ESTIMATION OF EFFECT OF CROSSING SCENARIO AEB SYSTEM TO HELP REDUCE TRAFFIC ACCIDENTS

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ABSTRACT

Advanced safety technologies such as automated emergency braking (AEB) systems are key technologies for helping to reduce traffic accidents. This study quantifies crossing scenario accident types by analyzing traffic accident databases from various countries. It then calculates the delta-V reduction collision velocity obtained by a proposed crossing scenario AEB system, and estimates the benefit of the proposed crossing scenario AEB system.

INTRODUCTION

To help reduce traffic accident fatalities and casualties, national governments, industries, and manufacturers are working with the guidance of regulations and assessments to enhance vehicle safety and to popularize devices and systems that help to ensure an even safer traffic environment [1]. In recent years, several advanced safety technologies have begun to enter wider use, including automatic emergency braking (AEB) systems that detect vehicles or pedestrians in front of the driver's vehicle, as well as lane departure warning (LDW) and lane keeping support (LKS) systems that help the driver to keep the vehicle inside the driving lane. Some vehicle models are also installed with AEB systems that provide support when driving through intersections (in this paper, these systems are referred to as "crossing scenario AEB systems").

This paper focuses on crossing scenarios and discusses the effects of crossing scenario AEB systems in helping to further reduce accidents, fatalities, and casualties. First, this paper analyzes accident data from various countries, and quantifies the types of crossing scenario accidents and the speed distributions of vehicles involved in frontal and side impact collisions. It then uses the National Automotive Sampling System Crashworthiness Data Set (NASS CDS) from the U.S. to identify the relationship between collision velocity and the rate of severe injuries in vehicles damaged at the side. Finally, this paper proposes specifications for an AEB system and calculates the changes in collision velocity with and without system activation in a crossing scenario. These results can be combined to estimate the reduction in severe injuries due to system activation, providing greater impetus to the development of future AEB systems capable of further mitigating damage in crossing collision scenarios.

RESEARCH INTO CROSSING ACCIDENTS

This section analyzes accident data from various countries and discusses the characteristics of crossing scenario accidents.

Country-by Country Breakdown of Fatalities and Casualties

Accident fatality and casualty data of people involved in accidents in three different countries (Japan, the U.S., and Germany) is analyzed below. First, Figs. 1 and 2 compare the proportions of accidents resulting in a fatality or casualty in each country.

It is evident that accident proportions are different even in developed countries. Since vehicle safety performance and education levels in these countries are similar, differences in the road environment may be assumed as a possible cause. For example, in the case of fatal accidents, Japan has a high proportion of pedestrian fatalities (37%), whereas car occupants account for a high proportion of fatalities in the U.S. (66%). The results for Germany are between Japan and the U.S. Accordingly, accident investigations were conducted in each country to help enhance vehicle safety from a global standpoint.

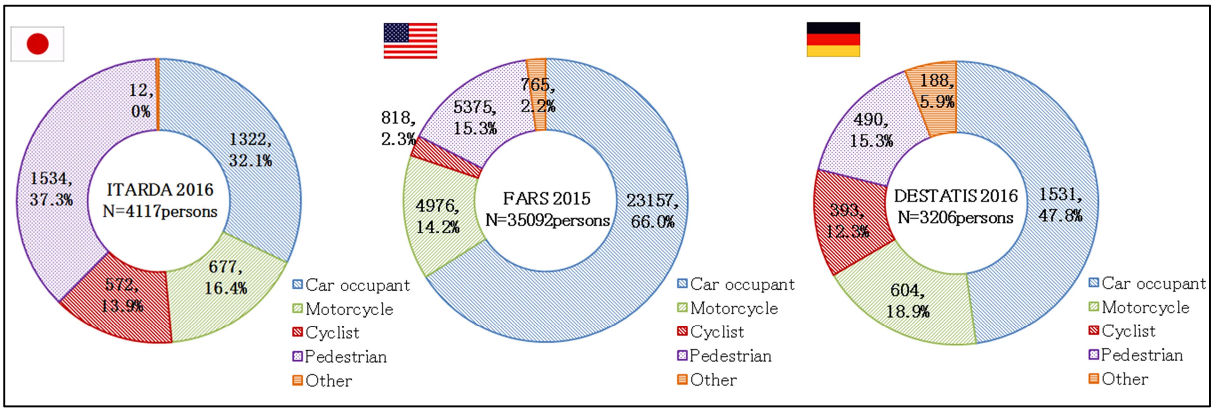


Figure 1. Comparison of proportion of fatalities in Japan, the U.S., and Germany.

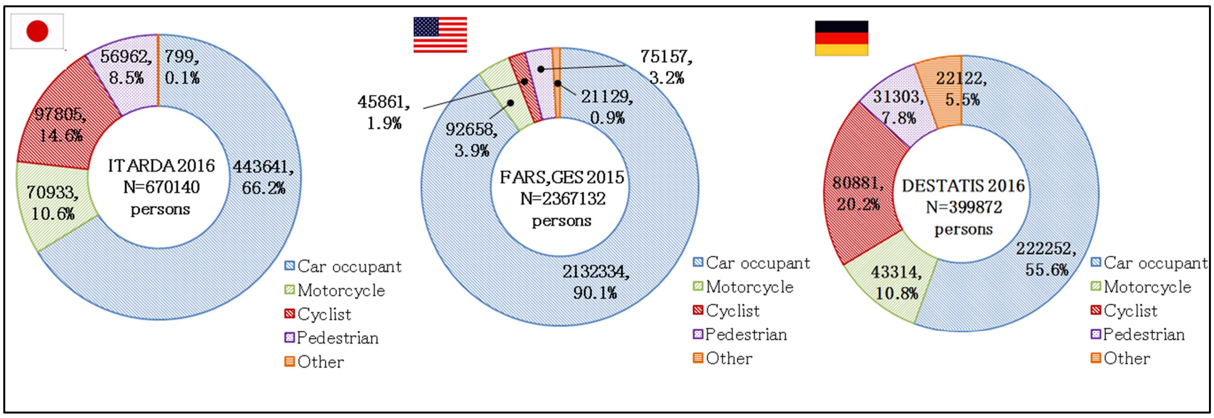


Figure 2. Comparison of proportion of casualties in Japan, the U.S., and Germany.

Proportions of Accidents Leading to Fatalities and Casualties in each Country

Figures 3 and 4 show the proportions of accident types leading to fatalities and casualties. These graphs break down the accident proportions shown in Figs. 1 and 2 into more detailed accident type information. The proportions of crossing scenario accidents involving cars are highlighted in red.

Figure 3 shows the proportions of accident types resulting in a fatality, with the most prevalent type on the left. In the U.S., the proportion of fatal crossing scenario accidents involving cars is approximately 8%, higher than in Japan and Germany, in which the proportion is approximately 4%. Figure 4 shows the proportions of accident types resulting in a casualty, with the most prevalent type on the left. In Japan, the proportion of crossing scenario accidents involving cars and resulting in a casualty is 12%. This is the second most common accident type, after rear-end collisions. In the U.S., the figure is 19%, which is also second only to rear-end collisions. In Germany, the proportion of this accident type is 10%, the third most common accident type after rear-end collisions and loss of control. These figures indicate that crossing scenario accidents result in a comparatively high number of accidents in all countries.

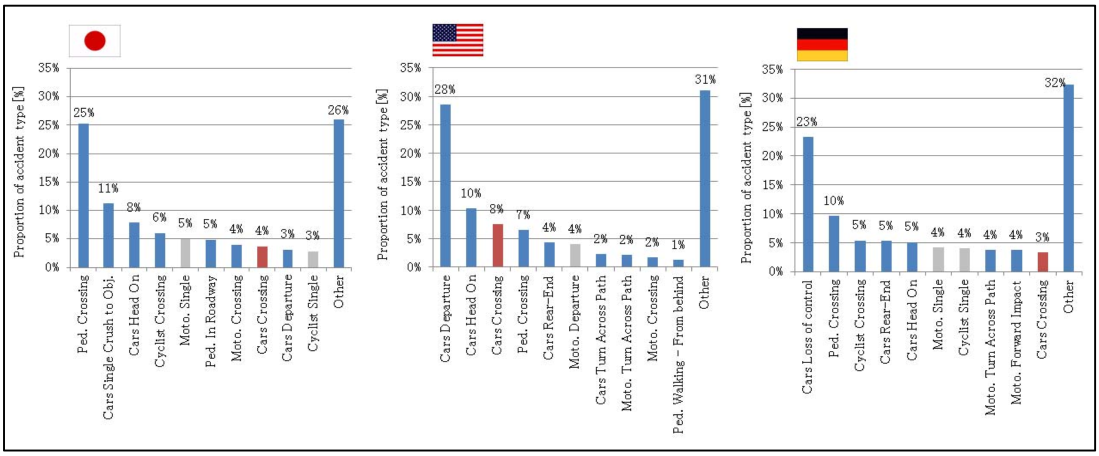


Figure 3. Fatalities: proportion of accident types.

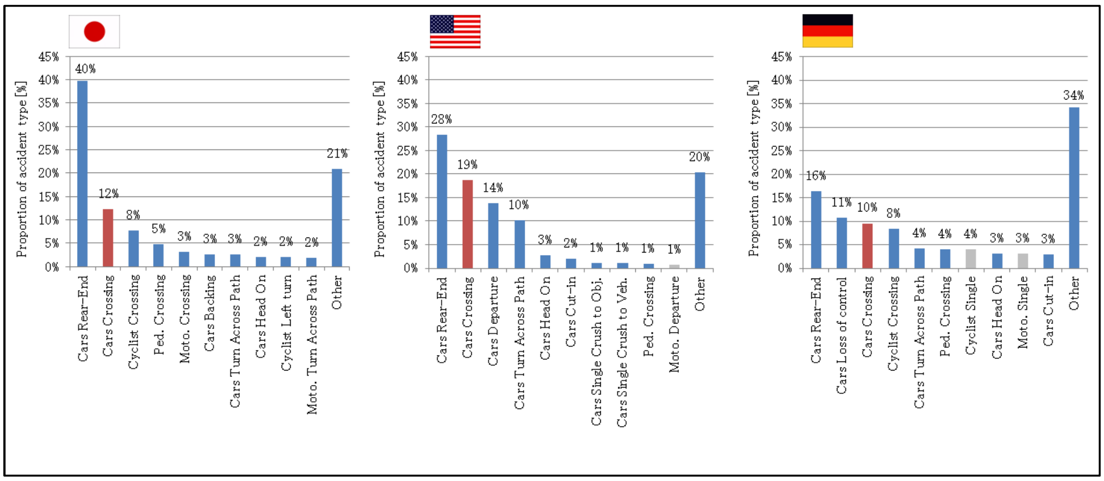


Figure 4. Casualties: proportion of accident types.

Locations of Crossing Scenario Accidents

To identify the circumstances of crossing scenario accidents in more detail, Fig. 5 shows the locations of such accidents that result in a casualty. In all three countries, a high proportion of these accidents occurs at intersections, with only a limited proportion occurring elsewhere. This result highlights the importance of prioritizing accidents at intersections in efforts to mitigate crossing scenario accidents.

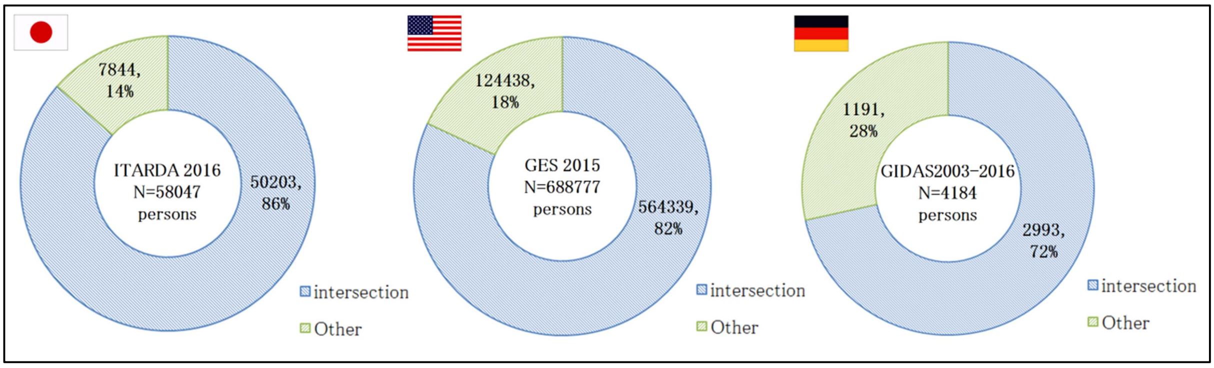


Figure 5. Comparison of proportion of crossing scenario accident locations.

Vehicle Speeds in Crossing Scenario Accidents

Finally, the distribution of vehicle speeds in crossing scenario accidents was analyzed. The results described above found that crossing scenario accidents accounted for a high proportion of casualties in all three countries, as well as a relatively high proportion of fatalities in the U.S. Subsequently, to supplement the fatality data and obtain a sufficiently large data set, this research analyzed accident data from the U.S. with a maximum abbreviated injury scale score of 3 or higher (MAIS3+) and accident data from Germany of people killed or seriously injured (KSI).

Figure 6 shows the distribution of vehicle speeds in crossing scenario accidents resulting in KSI. The X axis shows the speed of the vehicle damaged at the side and the Y axis shows the speed of the vehicle damaged at the front. The data for Germany covered fourteen years of accidents and was converted to show the number of casualties on an annual basis. In many cases in both the U.S. and Germany, the speed of the vehicle damaged at the front exceeded the speed of the vehicle damaged at the side.

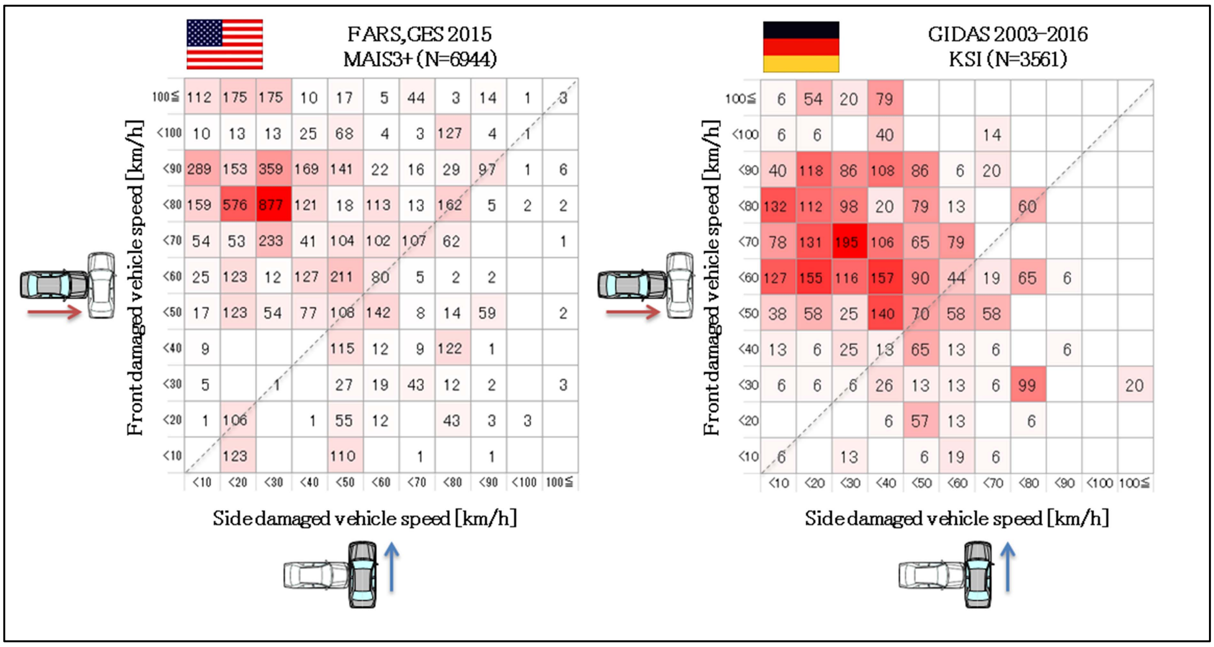


Figure 6. Speed distribution of crossing vehicles in the U.S. and Germany.

ESTIMATION OF EFFECT OF CROSSING AEB SYSTEM

This section calculates the potential effect of a crossing scenario AEB system based on the relationship between changes in collision velocity and the risk of severe injury. Using the results described above, an AEB system capable of mitigating crossing scenario accidents would require additional forward monitoring sensors for vehicles traveling at high speed that can detect potential collision objects in front of the vehicle at longer distances, and wider angle forward or side sensors for vehicles traveling at a lower speed that may be struck in the side. As of 2018, forward sensors have achieved wider commercialization than side sensors. Furthermore, if a vehicle brakes before a potential side impact collision but cannot avoid the collision, then the collision point will change. This will affect the damage caused by the collision in accordance with the positional relationship with the occupant compartment. This means that braking by a vehicle before a potential side impact collision requires more accurate collision point prediction technology. Therefore, this section focuses on AEB activation by vehicles traveling at high speed before a potential frontal collision. In addition, the angle of view of most current forward sensors is between ±20 and ±30 degrees, and it is feasible that this may expand to ±45 degrees in the near future. Assuming the widespread adoption of such advanced sensors, an AEB system was proposed that activates in scenarios in which the other vehicle is driving toward the same location as the driver's vehicle at the same relative speed or lower. The potential effect of such a crossing scenario AEB system is calculated below.

Relationship between TTC Judgment of Crossing Scenario AEB System and Deceleration

This section calculates the relationship between the TTC judgment of the proposed crossing scenario AEB system and the amount of deceleration.

This study assumed the following braking characteristics. Figure 7 shows the time sequence characteristics.

Time from judgment to brake activation: 0.2 sec

Jerk to maximum deceleration: 18.0 m/s^3

Maximum deceleration: 9.0 m/s^2

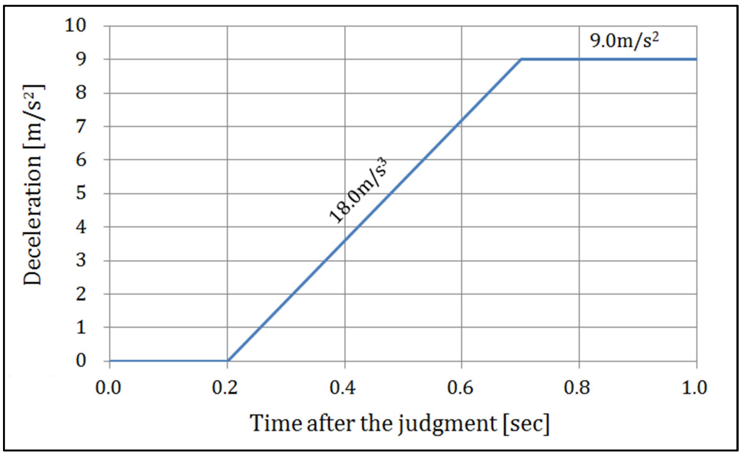
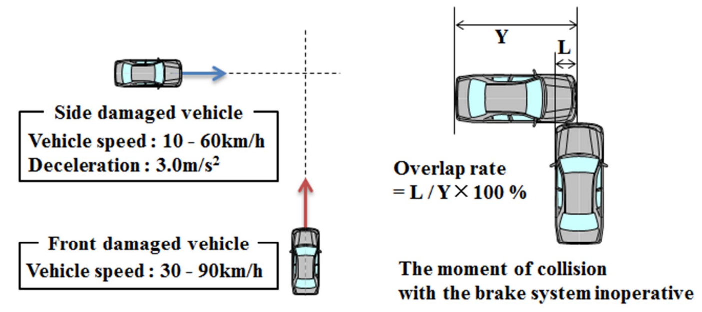


Figure 7. Assumed braking characteristics.

The activation timing of the crossing scenario AEB system was determined as follows. In the case of a crossing scenario, the other vehicle might stop before the potential path of the driver's vehicle. The judgment timing for this eventuality depends on the speed of the other vehicle and the relative vehicle position. Assuming that a collision can be avoided by the other vehicle reducing speed, the time to collision (TTC) with the driver's vehicle was estimated regardless of the behavior of the other vehicle. The estimation was carried out using the conditions shown in Fig. 8. Figure 9 shows the results. When the speed of the other vehicle and the overlap rate are low, it is necessary to delay the AEB activation judgment until a relatively shorter TTC. Assuming brake activation occurs at an overlap rate of 20% or higher, the TTC was estimated as 0.9 sec under the most severe conditions (speed of other vehicle: 10 km/h, overlap rate: 20%). Consequently, the AEB activation timing was set to TTC = 0.9 sec.



	Front damaged vehicle	Side damaged vehicle
Size	mid-size sedan	mid-size sedan
Overall width	1.8 m	1.8 m
Overall length	4.9 m	4.9 m

Figure 8. Defined overlap rate.

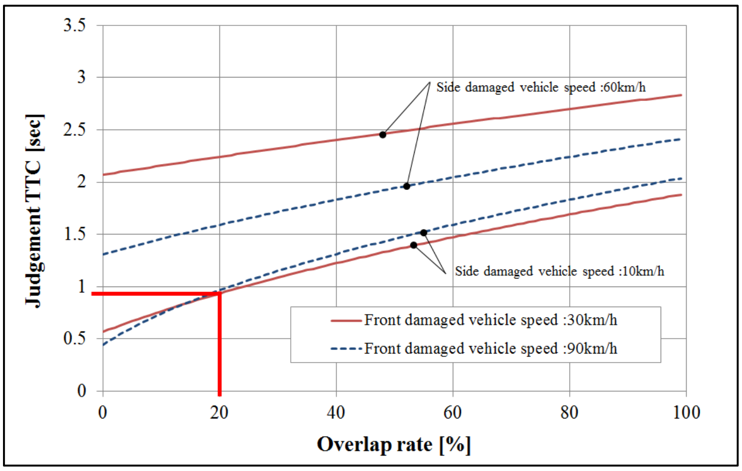


Figure 9. Relationship between overlap rate and TTC judgment.

Next, the relationship between the initial speed and amount of deceleration was estimated. This estimation assumed the braking characteristics shown in Fig. 7 and an activation timing of TTC = 0.9 sec. Under these conditions, a collision can potentially be avoided when the driver's vehicle is traveling up to a speed of 30 km/h. At higher speeds, the proposed system can potentially reduce the collision velocity.

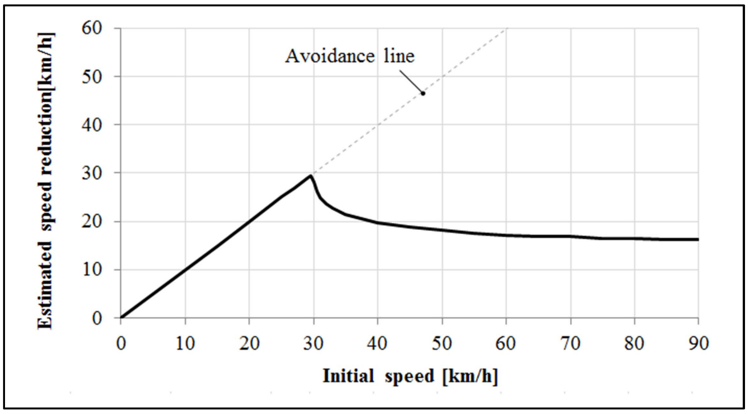


Figure 10. Defined deceleration characteristics.

Change in Collision Velocity and Calculation of Approximate Severe Injury Risk Reduction Effect

This section assumes a case in which the crossing scenario AEB system reduced the collision velocity but could not completely avoid a collision. To estimate the potential damage mitigation effect, the relationship between the collision delta-V (ΔV) and severe injury risk was analyzed. Although similar research has been carried out in the past [2][3], this paper uses NASS CDS data from 2009 to 2013. Reflecting the recent spread of side airbags, this relationship was analyzed based on MAIS3+ accidents in which the side airbags deployed.

First, the data was filtered under the conditions listed in Table 1. These conditions narrow down the analyzed accidents to near side collisions with occupants present in the front seats. The analysis was also limited to models from the 2007 model year or newer, which are expected to have a relatively high side collision performance, and included only accidents in which the side airbags deployed. After filtering, data from 108 injured people was analyzed in accordance with the change in collision velocity.

The thin line in Fig. 11 shows the results of severe injury rate analysis using this methodology. In addition, the severe injury risk P (ΔV) was approximated using the method of maximum likelihood from the logistic regression line calculated by Equation 1. This approach uses the analytical methodology described in a previous report [4]. This result is shown by the thick line in Fig. 11.

$$P(\Delta V) = \frac{1}{1+e^{-b(\Delta V - c)}} \qquad \text{(Equation 1) [4]}$$

The severe injury rate increases from ΔV = 25 km/h, and the reduction effect eases once the ΔV value exceeds 50 km/h.

Table 1.

Filtering Code of Near Side VTV Collisions with Occupants in Front Seats

TOWPAR	1		Towed	
VEHFORMS	2		2 vehicle forms	
EVENTS	1		1 event	
ROLLOVER	0		No rollover	
DOF1	8,9,10,49,50,68,69,70,88,89,90	2,3,4,62,63,64,82,83,84	Struck Leftside	Struck Rightside
GAD1	L	R		
MODELYR	2007-2014		Later than '07MY	
SEATPOS	11	13	Driver's seat	Front Passenger seat
BAGDEPOT	1		Air bag deployed,other than first seat frontal	

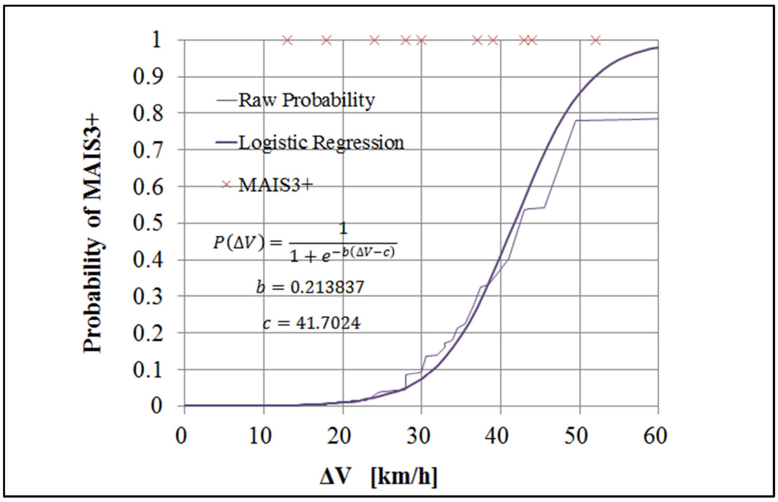


Figure 11. Relationship between normalized collision ΔV and probability of MAIS3+.

Calculation of Approximate Severe Injury Reduction Effect of Crossing Scenario AEB System

This section estimates the potential effect of the crossing scenario AEB system in reducing the number of severe injuries in vehicle-to-vehicle (VTV) side impact collisions by lowering the collision velocity.

The calculation assumptions were as follows. The crossing scenario AEB system was activated in only the driver's vehicle (i.e., the vehicle damaged at the front), the activation object was defined as other vehicles approaching at the same relative speed as the driver's vehicle or lower, the activation timing was set to TTC =

0.9 sec, the deceleration was set based on Fig. 10 to avoid a collision at a maximum speed of 30 km/h, and the amount of deceleration was set to 16 km/h or more from a maximum speed of 90 km/h.

Since the severe injury probability described in the previous section was analyzed based on ΔV, estimation of the reduction in severe injuries must be converted from collision velocity to ΔV. This conversion was carried out based on the assumptions shown in Fig. 12.

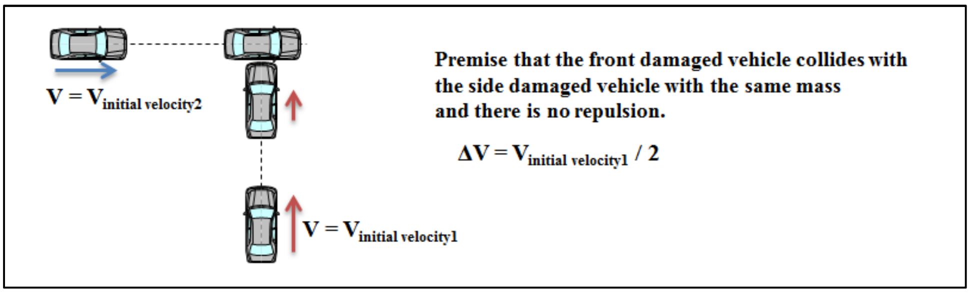


Figure 12. Defined collision ΔV.

Next, the circumstances immediately before the collision were investigated to examine the proportion of conditions in which the AEB system might have a potential effect. First, 2015 data from the Fatality Analysis Reporting System (FARS) run by the National Highway Traffic Safety Administration (NHTSA) in the U.S. was filtered as shown in Table 2. This procedure obtained data pertaining to 830 people. Additionally, as shown in Table 3, the data was categorized in accordance with the presence of avoidance maneuvers by the driver and vehicle stability immediately before the collision. Figure 13 shows these results. This figure indicates that the driver performed no avoidance maneuvers and that the vehicle was stable in 64.1% of accidents. Factoring in this figure, the AEB system activation rate in the U.S. was set to 64%.

Table 2.

Filtering Code of Near Side VTV Collisions (FARS 2015)

INJ_SEV	3,4	Suspected Serious Injury,Fatal Injury
BODY_TYP	1,2,3,4,5,6,7,8,9,10,11,14,15,16,17,19,20,21,22,28,29, 30,31,32,33,39,40,41,45,48,49,50,51,52,55,58,59, 60,61,62,63,64,66,67,68,71,72,78,79,	Passenger Cars,Light Trucks&Vans, Large Trucks,Buses
Ego's IMPACT1	1,11,12	Front
Opposite's IMPACT1	8,9,10,2,3,4	Left or Right
VE_FORMS	2+	VTV
P_CRASH3	1,2,3,4,5,6,7,8,9,10,11,12,98	No Avoidance Maneuver, Braking,Steering,Accelerating,Other Actions

Table 3.

Classification Code for Pre-Event Driver Maneuvers and Vehicle Stability (FARS 2015)

P_CRASH3	P_CRASH4	
1	1	No avoidance maneuver and no skidding
1	2,3,4,5	No avoidance maneuver and skidding
2,3,4,5,6,7,8,9,10,11,12,98	1	avoidance maneuver and no skidding
2,3,4,5,6,7,8,9,10,11,12,98	2,3,4,5	avoidance maneuver and skidding
Other Combination		Others

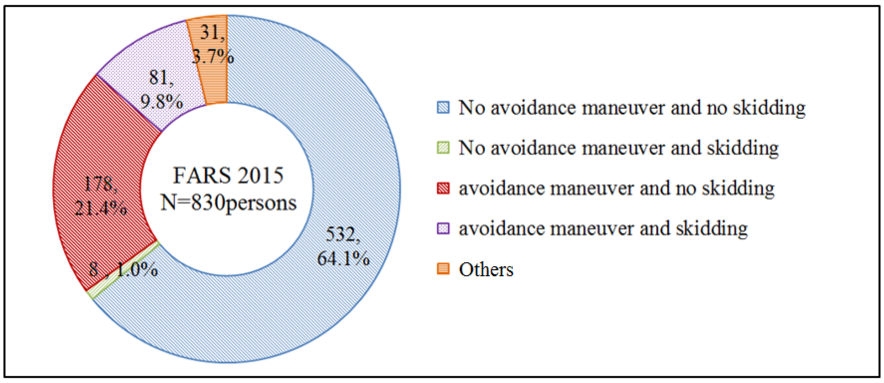


Figure 13. Proportion of KSI by pre-event in near side VTV collisions (FARS 2015).

In the same way, German In-Depth Accident Study (GIDAS) data from 2016 was used to estimate the AEB system activation rate. The GIDAS 2016 data was filtered as shown in Table 4, and data pertaining to 226 people was obtained. As shown in Table 5, the data was categorized in accordance with the presence of avoidance maneuvers by the driver and vehicle stability immediately before the collision. The results are shown in Fig. 14. This figure indicates that the driver performed no avoidance maneuvers and that the vehicle was stable in 40.7% of accidents. Therefore, the AEB system activation rate in Germany was set to 41%.

Table 4.

Filtering Code of Near Side VTV Collisions (GIDAS 2016)

PVERL	4,5	seriously injured,killed
FART	3,4,5,6	passenger cars,HGV,bus,agricultural tractor
Ego's VDI2	1	Front
Opposite's VDI2	2,4	Left or Right
ANZBETFZ	2+	VTV
REAKTGAS	0,1,2,3,4,8	No Avoidance Maneuver,Accelerating,Other Actions
REAKTBR	0,1,2,8	No Avoidance Maneuver,Braking,Other Actions
REAKTLE	0,1,2,3,4,8	No Avoidance Maneuver,Steering,Other Actions

Table 5.

Classification Code for Pre-Event Driver Maneuvers and Vehicle Stability (GIDAS 2016)

REAKTLE	REAKTBR	REAKTGAS	SCHLEU	
2	2	2	2	No avoidance maneuver and no skidding
2	2	2	1	No avoidance maneuver and skidding
1,3,4	1	1,3,4	2	avoidance maneuver and no skidding
1,3,4	1	1,3,4	1	avoidance maneuver and skidding
Other Combination				Others

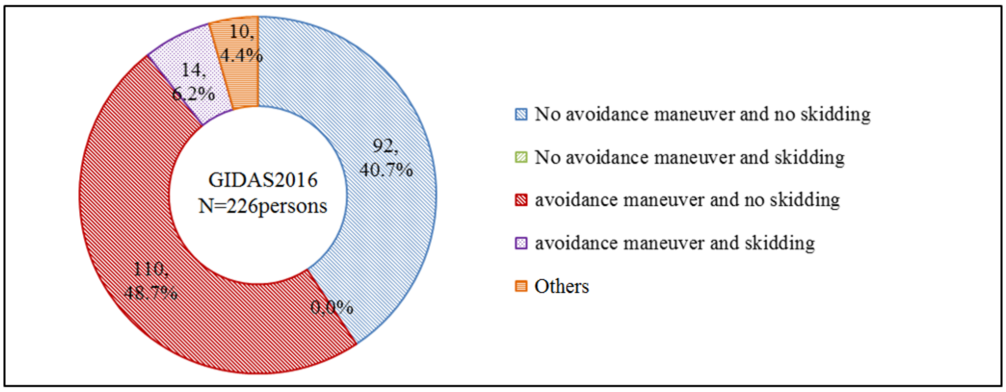


Figure 14. Proportion of KSI by pre-event in near side VTV collisions (GIDAS 2016).

Figure 15 shows the distribution of severe injuries and fatalities at each vehicle speed when the crossing scenario AEB system activated. This distribution uses the relationship between the change in collision velocity and severe injury risk shown in Fig. 11. After comparing the results in Figs. 6 and 15 with the speed of the driver's vehicle (i.e., the vehicle damaged at the front) on the horizontal axis, Fig. 16 shows the potential severe injury reduction effect. This figure indicates that the number of KSI caused by crossing scenario accidents fell after the application of the AEB system. Specifically, the number of KSIs in the U.S. fell by 2,394 people out of a total of 6,944, and in Germany by 873 people out of a total of 3,561.

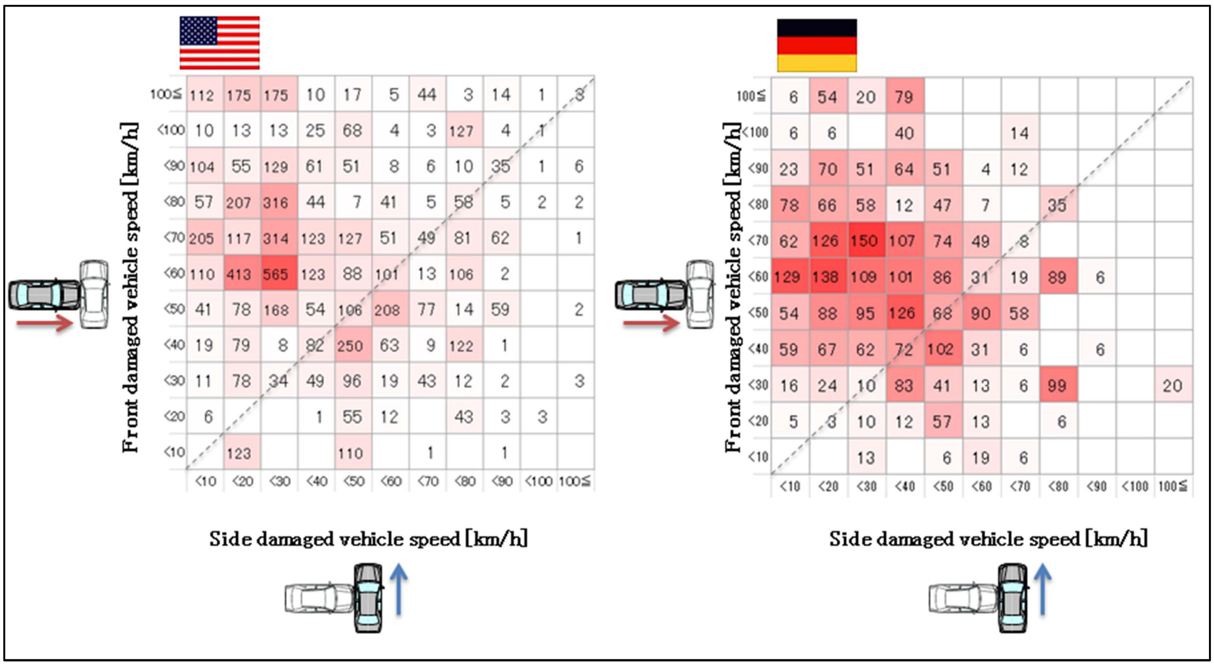


Figure 15. Speed distribution of crossing accidents before and after application of AEB system.

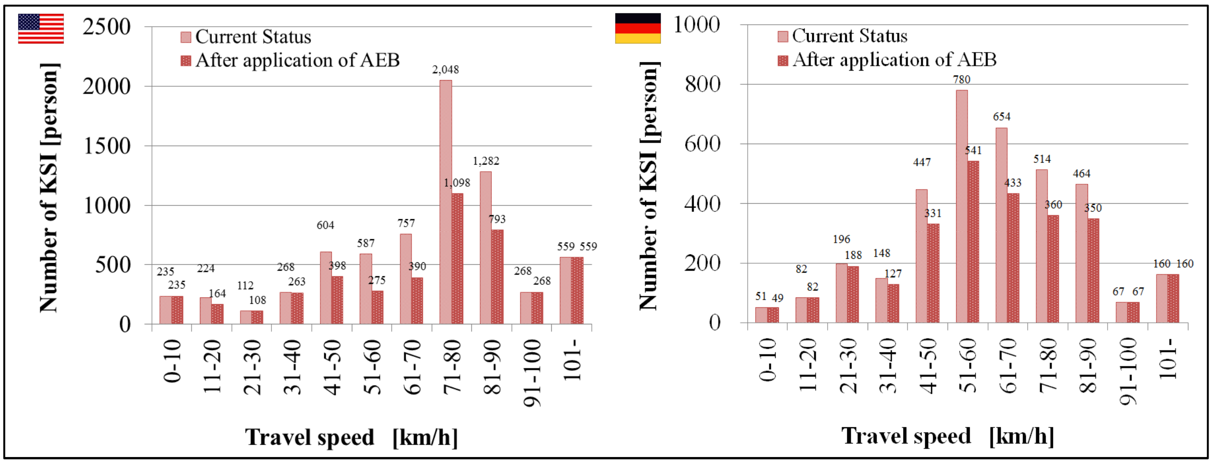


Figure 16. Comparison of number of KSIs before and after application of AEB system.

CONSIDERATIONS

According to Fig. 16, the AEB system has the potential to reduce the number of severe injuries by 2,394 people (34.5%) in the U.S. and by 873 people (24.5%) in Germany. Since the system only has the potential capability to avoid a collision at 30 km/h or less, the potential severe injury reduction rate is limited compared to the total number of severe injuries. However, since it is capable of reducing the collision velocity when the vehicle is traveling between 60 and 90 km/h (i.e., a speed range that covers a large proportion of accidents), this system may be regarded as potentially effective.

According to Fig. 14, the driver performed avoidance maneuvers and the vehicle remained stable (i.e., skidding did not occur) in 48.7% of accidents. In many of these cases, the vehicle was already braking (90.9% or 100/110 cases). Since the driver was already braking the vehicle, a braking assist system that speeds up the AEB activation timing may have an even greater effect.

LIMITATIONS

This paper showed the potential effect of a crossing scenario AEB system. However, any reduction in the number of severe injuries depends greatly on the braking activation timing and activation characteristics, the activation rate of the AEB system, the surrounding environment, and other factors. Additionally, the estimations in this paper are based on a number of assumptions described above. More detailed estimations would require the definition of specific sensor specifications and judgment logic through future AEB system development. As a result, it is entirely possible that the estimated effect described in this paper may change.

Although these estimations were carried out based on accident data, various statistical methodologies were applied. For this reason, there is no guarantee that the estimated system effect would be generated in the case of individual real-world accidents.

CONCLUSIONS

This paper obtained the following conclusions from an analysis of accident databases in various countries and paper estimations of crossing scenario traffic accidents.

Analysis of fatal accident types in these countries found that the proportion of fatal crossing scenario accidents involving cars is approximately 8% in the U.S., higher than in Japan and Germany, in which the proportion is approximately 4%. Furthermore, the rate of crossing scenario accidents involving cars and resulting in a casualty is approximately 12% in Japan, approximately 19% in the U.S., and approximately 10% in Germany.

Analysis of the vehicle speed distribution in crossing scenario accidents resulting in a casualty identified that, in many cases in both the U.S. and Germany, the speed of the vehicle damaged at the front exceeded the speed of the vehicle damaged at the side.

An AEB system was proposed for crossing scenario accidents based on these analysis results. Based on the relationship between the change in collision velocity and severe injury risk, the proposed AEB system is capable of potentially avoiding collisions at low speeds and reducing the collision velocity at medium speeds. The proposed AEB system has the potential to reduce the number of KSIs by 2,394 people (34.5%) in the U.S. and by 873 people (24.5%) in Germany.

REFERENCES

[1] National Agency for Automotive Safety & Victims' Aid (NAVSA): New Car Assessment, http://www.nasva.go.jp/mamoru/about/about.html (retrieved on January 1, 2019)

[2] Gabauer, D.J. and Gabler, H.C. 2006. "Comparison of Delta-V and Occupant Impact Velocity Crash Severity Metrics Using Event Data Recorders." In 50th Annual Proceedings of the Association for the Advancement of Automotive Medicine

[3] Richards, D. and Cuerden, R., 2009. "The Relationship between Speed and Car Driver Injury Severity."

[4] Hasegawa, T. 2017. "Clarification of Priority Factors for Reducing Traffic Accident Fatalities in the U.S. and Benefit Estimation of AEB System for Oncoming Vehicles." 25th ESV, Paper Number 17-0171

TITLE: EVALUATION OF AUTOMATIC EMERGENCY BRAKING IN HELPING PREVENT FRONT-TO-REAR CRASHES AMONG TOYOTA MODELS

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Paper Number 19-0146

ABSTRACT

This study estimated the effectiveness of Toyota Safety Sense (TSS) in helping prevent front-to-rear collisions among three Toyota models (Avalon, Prius, RAV4). TSS, offered as an option in model year 2016 vehicles, includes a pre-collision warning system with automatic emergency braking (AEB), in addition to lane departure alert and automatic high beam. This study addresses the hypothesis that TSS-equipped vehicles will be less likely to experience a front-to-rear crash (as the striking vehicle) compared to those not equipped with TSS.

Using Toyota-supplied production data linked to police reported crash data from 5 US states (Florida, Louisiana, Michigan, Pennsylvania, Texas) for crash years 2014-2016, the study compared crash rates (crashes per 10,000 vehicle months) of TSS equipped (n= 23,394) versus non-equipped (n= 294,931) vehicles. TSS equipment present per vehicle was identified based on VIN. This study evaluated the impact on front-to-rear crashes where the Toyota was the striking vehicle.

Exposure, using vehicle-months, was computed based on aggregate vehicle sales in the five study states for TSS equipped and non-equipped model year 2014 to 2016 vehicles. The crude rate ratio (CRR) of front-to-rear crash rates where the Toyota was the striking vehicle was calculated as the front-to-rear crash rate for TSS-equipped vehicles divided by the crash rate for non-equipped vehicles.

Given that TSS is optional, it is possible that customers who choose to purchase these safety systems also exhibit different driving and risk-taking behaviors compared to those who do not purchase the safety systems. To address a possible selection bias, sensitivity analysis examined the control outcome of front-end damage in a multi-vehicle crash, excluding the types of crashes targeted by AEB (front-to-rear).

Of the TSS-equipped vehicles, 2.46 per 10,000 vehicle-months (95%CI:1.75-3.17 per 10,000 vehicle-months) experienced a front-to-rear crash as the striking vehicle, compared to 4.55 per 10,000 vehicle-months (95%CI:4.37-4.73 per 10,000 vehicle-months) of the non-equipped vehicles. Therefore, study Toyotas equipped with TSS were 46% less likely to experience a front-to-rear crash as the striking vehicle compared to non-equipped (CRR=0.54; 95%CI:0.40-0.67).

The study found that when the outcome was broadened to include all vehicles with front-end damage in multi-vehicle crashes, TSS-equipped vehicles experienced 17% fewer crashes than non-equipped vehicles (CRR=0.83; 95%CI:0.71-0.94) . However, no significant difference was observed if front-to-rear crashes were excluded (CRR=1.02; 95%CI:0.86-1.16) suggesting that selection bias did not play a significant role in this study.

The TSS option was only available in model year 2016 vehicles, limiting the sample size and follow-up time of TSS-equipped vehicles. Future research that includes additional state data, models and model years, will increase sample sizes and may allow for estimates by model and other crash types.

In conclusion, vehicles equipped with TSS, were nearly half as likely to be the striking vehicle in a front-to-rear crash compared to non-equipped vehicles. This study contributes to the growing evidence of the effectiveness of AEB in helping prevent a significant number of front-to-rear crashes.

INTRODUCTION

The National Motor Vehicle Crash Causation Survey, administered by the National Highway Traffic Safety Administration found that driver error was the critical reason for 94% of crashes [1]. These errors included recognition error (e.g. driver inattention and inadequate surveillance), decision error (e.g. driving too fast for conditions, misjudgment of gap or other's speed), and performance (e.g. overcompensation, poor directional control) and non-performance (e.g. falling asleep) errors.

Advanced Driver Assistance Systems (ADAS) are in-vehicle technologies developed to counteract these driver errors and help prevent crashes or mitigate the severity if a crash occurs. These systems provide drivers timely warnings and some will actively and automatically intervene to help avoid hazardous situations. Examples of ADAS technologies include lane departure warning and active lane keep assistance, blind spot detection, forward collision warning and automatic emergency braking (AEB). In vehicles with pre-collision warning and AEB, the driver is alerted if the speed of the equipped vehicle and the vehicle ahead and the distance from the vehicle or object ahead indicate that a collision is possible. AEB will finally apply the brakes if the system predicts a high probability of a crash to help prevent the collision regardless of driver response.

Many manufacturers offer these technologies as options or standard on some their vehicles. ADAS technologies are the precursor to autonomous vehicles and, depending on the combination of ADAS equipment installed in a vehicle, can allow level 1 through level 3 autonomous driving at the present time [2].

While controlled track and simulated testing of ADAS technologies suggest that they will greatly impact crash involvement rates, real world evidence that characterizes their effectiveness is still limited. Previous evaluations of AEB and other ADAS have found reductions in both injury-involved and, to a lesser extent, all-severity (injury and non-injury) crashes. An evaluation of police-reported crashes in the United States found that vehicles equipped with AEB experienced a 42% reduction in injury front-to-rear crashes and a 39% reduction in all-severity front-to-rear crashes compared to non-equipped vehicles [3]. A meta-analysis of pooled data from multiple countries determined that AEB was associated with a 38% reduction in real-world rear-end crashes [4].

In Toyota vehicles the Toyota Safety Sense (TSS) package includes a pre-collision warning system with AEB, in addition to lane departure alert and automatic high beam. TSS was first offered as an option in some model year 2016 vehicles and standard in most model year 2017 Toyota and Lexus passenger vehicles. Toyota is the frontrunner among manufacturers in the number of model year 2017 vehicles equipped with AEB: 1.4 million vehicles, 56% of its model year 2017 fleet [5].

This study evaluates the effectiveness of TSS among three Toyota models (Avalon, Prius, RAV4) in helping prevent the types of collisions AEB is designed to address: striking another vehicle in a front-to-rear collision. This study hypothesizes that vehicles equipped with AEB will be less likely to be involved in a front-to-rear crash as the striking vehicle compared to non-equipped vehicles.

METHODS

This retrospective cohort study of three Toyota models (Avalon, Prius, RAV4), model years 2014-2016, compares rates in vehicles with TSS versus without TSS in order to estimate the effectiveness of TSS in helping prevent front-to-rear crashes.

Toyota production data was used to compute the aggregate number of vehicles sold in the five study states by model, model year and TSS equipped/non-equipped. Some model year 2014 and 2015 vehicles are equipped with a previous version of the Pre-Collision System. These are not included in the comparison between TSS-equipped vehicles and non-equipped vehicles. Exposure was computed in vehicle-months: the number of vehicles sold multiplied by the estimated number of months on the road. We assumed an average seven months of exposure for the first year of a model year platform; e.g. Model year 2014 vehicles had an average seven months exposure during calendar year 2014.

The study used state police crash reports from five states (Florida, Louisiana, Michigan, Pennsylvania, Texas) for crash years 2014-2016. Vehicles in these five states make up an estimated 23% of U.S. vehicle miles travelled.

The TSS options data were linked at the individual VIN level to the five state police crash report data files, identifying which crashed vehicles were TSS-equipped and which were not. The state police reported crash data included information on the crash type (e.g. front-to-rear, side swipe, angle, etc.) and the location of vehicle damage per vehicle involved.

The outcome evaluated in this study was the subset of crashes targeted by AEB: front-to-rear crashes where the Toyota was the striking vehicle. Using the state police reported crash files, a striking vehicle in a front to rear crash was identified as a vehicle involved in a front-to-rear collision where the Toyota was coded with front-end damage (the striking vehicle) and at least one other vehicle was coded with rear-end damage (the struck vehicle). Figure 1 describes the process. Of all Toyota vehicles involved in a crash ([1] in Figure 1), those involved in multi-vehicle crashes ([2] in Figure 1) were identified. Of the vehicles involved in multi-vehicle crashes, those that experienced front-end damage where identified ([3] in Figure 1). Of these, those involved in a front-to-rear crash ([4] in Figure 1) were defined as the striking vehicle in a front-to-rear crash. Crashes where the Toyota was first involved in a front-to-rear crash as the struck vehicle (rear damage) and subsequently struck a second vehicle from the rear as the striking vehicle were excluded from the evaluation.

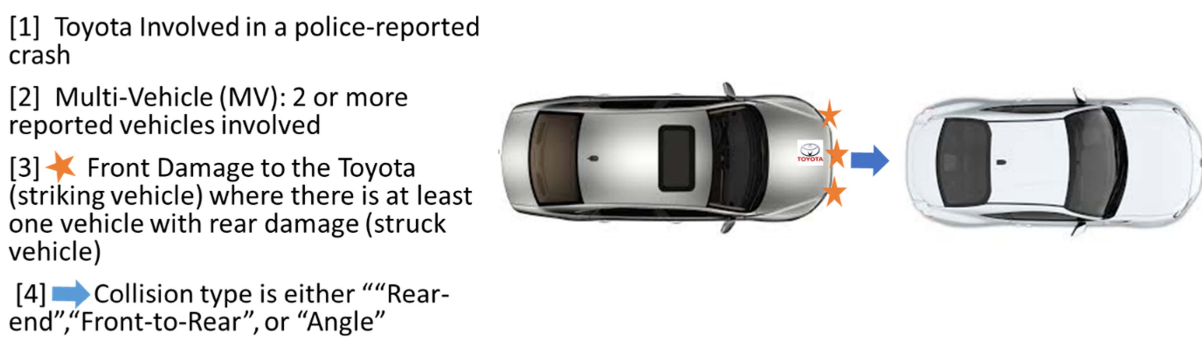

Figure 1. Process for Identifying Crash-Involved Toyotas where Toyota is the Striking Vehicle in a Front-to-Rear Crash

The rate of vehicle involvement in a front-to-rear crash as the striking vehicle was computed as the total number of crashes divided by the total number of vehicle months. Crash rates were computed separately for TSS-equipped and non-equipped vehicles. The state data are a census of police-reported crashes and therefore not subjected to sampling variability. However, to account for random variation, confidence intervals were computed based on the method described by Arias and Smith, 2003 [6].

The crude rate ratio (CRR) for TSS-equipped versus non-equipped vehicles was calculated as the front-to-rear striking vehicle crash rate for TSS-equipped vehicles divided by the crash rate for non-equipped vehicles. Crude rate ratios are interpreted to describe the percent reduction in front-to-rear crashes associated with TSS.

Given that TSS was optional, it is possible that customers who choose to purchase these safety systems also exhibit different driving and risk-taking behaviors compared to those who don't purchase the safety systems. To address a possible selection bias, sensitivity analysis examined two additional outcomes: the broad outcome of front-end damage in a multi-vehicle crash and the subset of these crashes excluding the types of crashes targeted by AEB (front-to-rear where Toyota is the striking vehicle). This control analysis tests the hypothesis that differences in crash rates for TSS (thus, AEB)-equipped vehicles are only observed in front-to-rear crashes.

RESULTS

A combined total 318,325 Toyota Avalon, Prius and RAV4 vehicles, model year 2014-2016, were sold in the five study states. Of these, 23,394 (29%) of the model year 2016 vehicles (the first year TSS was offered as an option) were equipped with TSS (Table 1). Take-rates in model year 2016 vehicles varied; 24% for the Avalon, 28% for the RAV4 and 38% for the Prius.

Table 1
Number of Toyotas Sold in the Study States, by Model Year and TSS Option

Model Year	Without TSS	With TSS	Total
2014	86,401	-	86,401
2015	127,310	-	127,310
2016	81,220	23,394	104,614
Three Model Total	294,931	23,394	318,325

The five state police reported crash files from years 2014-2016 captured 18,454 vehicles involved in crashes among the study cohort of 318,325 vehicles ([1] in Table 2). Of these, 17,402 were vehicles involved in multi-vehicle crashes ([2] in Table 2). Of the vehicles involved in multi-vehicle crashes, 6,076 experienced front-end damage ([3] in Table 2). Of these, 2,749 were involved in a front-to-rear crash ([4] in Table 2), i.e. the striking vehicle in a front-to-rear crash. This outcome was evaluated in this study. Table 2 further presents the number of crashes by state.

Table 2
Number of Crash-Involved Toyotas among the Vehicles Sold in the Study States, by Crash Population and Crash State

Crash Population	Total 5 States	FL	LA	MI	PA	TX
[1] All Crash-Involved Toyotas	18,454	9,534	1,296	1,355	1,116	5,153
[2] Toyotas involved in a Multi-Vehicle (MV) crash	17,402	9,168	1,255	1,130	937	4,912
[3] Toyotas involved in a MV crash with Front-end damage	6,076	3,069	442	472	417	1,676
[4] Outcome Evaluated: Toyota involved in a MV front-to-rear crash with front-end damage (striking vehicle)	**2,749**	**1,282**	**164**	**199**	**155**	**949**

Among the study cohort of 318,325 vehicles, 2,617 (0.82%) were involved in a front-to-rear crash as the striking vehicle. Of the TSS-equipped vehicles, 46 (0.20%) experienced a front-to-rear crash as the striking vehicle, compared to 2,571 (0.87%) of the non-equipped vehicles (Table 3).

To compare crash risk among TSS equipped versus non-equipped, crash rates were computed to account for the overall greater exposure (vehicle-months) of the non-equipped vehicles. Of the TSS-equipped vehicles, 2.46 crashed per 10,000 vehicle-months (95%CI:1.75-3.17), compared to 4.55 crashes per 10,000 vehicle-months (95%CI:4.37-4.73) among the non-equipped vehicles (Table 3).

Therefore, study Toyotas equipped with TSS were 46% less likely to be a striking vehicle in a front-to-rear crash compared to non-equipped (CRR=0.54; 95%CI:0.40-0.67) (Table 3).

Table 3
Number and Rate of Vehicles involved in a Front-to-Rear Crash as the Striking Vehicle, by TSS equipment; Crude Rate Ratio of Vehicles With versus Without TSS

	Number of Striking Vehicle in a Front-to-Rear Crash (A)	Vehicle-Months (B)	Rate Per 10,000 Vehicle-Months C=(A/B)*10,000	Crude Rate-Ratio $(C_{withTSS}):(C_{withoutTSS})$
Equipped with TSS	46	187,215	2.46	0.54
Not equipped with TSS	2,571	5,650,834	4.55	

The study found that when the outcome was broadened to include all front-end damaged vehicles in multi-vehicle crashes, TSS-equipped vehicles experienced 17% fewer crashes than non-equipped vehicles (CRR=0.83; 95%CI:0.71-0.94) (Table 4). However, no significant difference was observed for the control crash population where the subset of crashes targeted by AEB (front-to-rear) was excluded (CRR=1.02; 95%CI:0.86-1.16). Table 4 also presents CRR for all crashes and multi-vehicle crashes.

Table 4
Crude Rate Ratio for Crashing Among Vehicles With Versus Without TSS, by Crash Population

Crash Population	Crude Rate Ratio	95% Confidence Interval
[1] All Crash-Involved Toyotas	1.01	(0.94 to 1.08)
[2] Toyotas involved in a Multi-Vehicle (MV) crash	1.00	(0.93 to 1.08)
[3] Toyotas involved in a MV crash with Front-end damage	0.83	(0.71 to 0.94)
[4] Outcome Evaluated: Toyota involved in a MV front-to-rear crash with front-end damage (striking vehicle)	**0.54**	**(0.40 to 0.67)**
Control crash population: MV crash with front-end damage [3] excluding front-to-rear crashes	1.01	(0.86 to 1.16)

CONCLUSIONS

Vehicles equipped with TSS, were 46% less likely to be a striking vehicle in a front-to-rear crash compared to non-equipped vehicles. This study contributes to the growing evidence of the effectiveness of AEB in helping prevent a significant number of crashes.

The control analysis found that differences in crash rates for TSS-equipped vehicles were only observed in front-to-rear crashes. Therefore, selection bias (customers who opt for TSS are safer drivers) did not likely play a significant role in this study. Further research is warranted to explore if the crash reductions in AEB-equipped vehicles found by this and other studies persist once these technologies are offered standard.

This study uses real-world data of a cohort of Toyota vehicles linked to crash events. The strengths of this study include the large sample size of a well-defined vehicle cohort, the ability to identify the individual options for each vehicle, and a well-defined outcome measure.

A limitation of the study is the short (less than one year) follow up of model year 2016 vehicles, limiting the sample size of TSS-equipped vehicles and crashes. In addition, this study uses estimated vehicle-months based on aggregate counts of vehicles by model year.

The current study served as the pilot for a more rigorous Phase 2 study, currently ongoing. Phase 2 uses retail dates of each vehicle to accurately estimate vehicle-months. In addition, Phase 2 expands the field study by incorporating additional Toyota and Lexus models (Highlander, Corolla, Lexus ES and Lexus RX), more recent model years (model years 2015 to 2017; TSS was standard on model year 2017 vehicles), more recent crash data (years 2015 to 2017) and an additional three states' police reported data. Using the increased sample sizes and accurate computation of exposure at the vehicle level, phase 2 incorporates regression modeling techniques that control for exposure and time and compute adjusted risk ratios to quantify effectiveness. These findings will be reported in the near future.

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REFERENCES

[1] Singh S. Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. (Traffic Safety Facts Crash Stats. Report No. DOT HS 812 115). Washington, DC: National Highway Traffic Safety Administration. 2015.

[2] SAE International. Standard J3016 titled Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems. Society of Automotive Engineers. 2014.

[3] Cicchino JB. Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. Accident Analysis and Prevention. 2017;99(Pt A):14-152.

[4] Fildes B, Keall M, Bos N, Lie A, Page Y, Pastor C, Pennisi L, Rizzi M, Thomas P, Tinvall C. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. Accident Analysis and Prevention. 2015;81:24-29.

[5] NHTSA, National Highway Traffic Safety Administration (2017). NHTSA-IIHS Announcement on AEB: Manufacturers make progress on voluntary commitment to include automatic emergency braking on all new vehicles (accesed online, February 1, 2019 at https://www.nhtsa.gov/press-releases/nhtsa-iihs-announcement-aeb)

[6] Arias, E., & Smith, B. L. (2003). Deaths: Preliminary data for 2001. National vital statistics reports (vol. 51, No. 5). Hyattsville, MD: National Center for Health Statistics