2019
22nd Presentation Session for Traffic Accident Investigations, Analysis, and Research

Analysis of the effects of collision damage mitigation brakes (Automatic Emergency Brakes (AEB)) by generation

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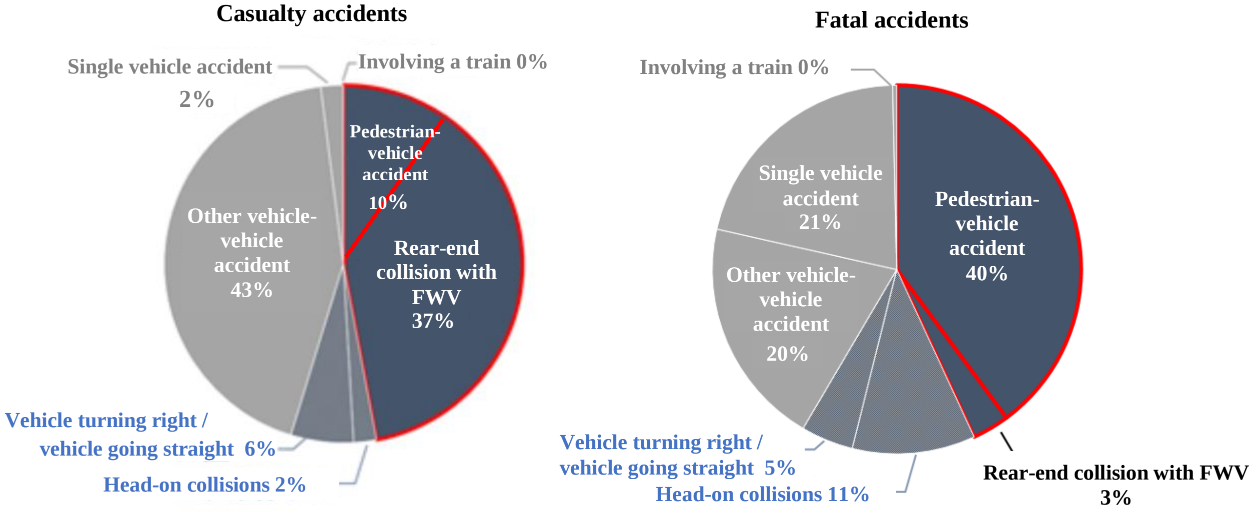
1. Introduction

Collision damage mitigation brakes (Automatic Emergency Brakes (AEB)) are a driving assist system that drivers rely on to avoid accidents or to mitigate the damage when accidents do occur. They operate by urging the driver to brake or by undertaking brake control in lieu of the driver in response to errors related to cognition, decision-making, and operation, which are counted among the human factors that serve to cause traffic accidents (Fig. 1).

Fig. 1. Image of an AEB system activating (Source: Suzuki's homepage)

In the initial stages of the dissemination of AEB, the dominant variety consisted of AEB systems that used laser radar (or millimeter wave radar) as their sensors (hereinafter referred to as the "first generation"). These mainly served to detect the rear of the four-wheel vehicle out ahead of the vehicle in question, and would activate in conditions where the vehicle speed was between 5 - 30 (5 - 80) km/h. In recent years, AEB equipped with more sophisticated sensors than what were initially disseminated (hereinafter referred to as the "second generation") have been making it possible to improve the activation speed and detect pedestrians and other road object. AEB are mainly designed to activate for rear-end collision accidents with four-wheel vehicle and pedestrian-vehicle accidents. When the proportion of the total number of accidents that these account for where the primary party was driving a four-wheel vehicle is taken into consideration, they were found to account for 47% of casualty accidents and 43% of fatal accidents over the five-year period from 2014 - 2018 (Figs. 2 and 3). Moreover, recently AEB that can respond to head-on collisions with four-wheel vehicles and accidents involving collisions between a vehicle turning right and a vehicle going straight, and that can handle detecting bicycles, have begun to be practically implemented. As such, the expectations placed on AEB to mitigate the damage from accidents continues to widen in scope.

The objective of this report will be to determine the accident damage mitigation effects for each generation of AEB systems (first / second generations) by type of accident status and driver's property for rear-end collision accidents with four-wheel vehicles and pedestrian-vehicle accidents, and to propose a course of action for further enhancing their effectiveness.



N=2,281,108 N=14,814

Figs. 2 / 3: Status of traffic accidents by type of accident
(2014 - 2018, primary party driving a four-wheel vehicle)

2. Analytical methods

Sections 2.1 - 3 calculated the number of accidents per 100,000 vehicles owned by three groups based on the AEB system status of the primary party's vehicle (first generation-equipped vehicles, second generation-equipped vehicles, and vehicles without AEB).

2.1. Aggregating the number of accidents

The following guidelines were used to aggregate the number of accidents.

Target years: 2016 - 2018 (three years)

Target vehicles: Vehicle of the primary party that is a privately owned kei sized passenger vehicle with AEB set up on it (69 models total)

Type of accident (accident details): Rear-end collision accidents with four-wheel vehicles (casualty accidents) and pedestrian-vehicle accidents (casualty accidents, fatal and serious injury accidents)

This report took accidents in which the primary party was driving a kei sized vehicle as the subject of its analysis. The accident database that uses information on AEB systems focuses on kei sized vehicle models that went on sale in January 2006 and thereafter. Since accidents caused by vehicles sold from 2012 onward, which is when the first generation AEB systems began to be disseminated to kei sized vehicles in earnest, are included, this offers conditions conducive to analyzing accidents based on the AEB generation (for medium and small sized vehicles, the focus was placed on vehicles sold in or after April 2015, the majority of which came outfitted with second generation AEB).

When it comes to the accident details, most rear-end collisions with a four-wheel vehicle comprise slight injury accidents, and so the decision was made to look at trends in whether or not accidents occurred from the number of casualty accidents. With pedestrian-vehicle accidents, ideally the number of casualty accidents as well as fatal accidents should be focused on in order to view damage mitigation trends. However, since an adequate number of fatal accidents alone could not be obtained, trends with the number of fatal and serious injury accidents were observed.

The number of accidents obtained from this aggregation were classified into three groups based on the AEB system status of the primary party's vehicle (first generation-equipped vehicles, second generation-equipped vehicles, and vehicles without AEB). In order to identify the generation of AEB, information on the model of the primary party’s vehicle and the date of the initial inspection was used. In addition, the following rules were used to sort these.

1) For models on which AEB was equipped in the middle of their sales period, accidents caused by vehicles that were registered in the period prior to AEB being equipped on said model were not included in the aggregation.
2) Regarding models that were sold with both first and second generation AEB, the actual shift in the share of vehicle registrations from first generation to second generation systems is thought to have happened gradually, but it was difficult to get a grasp of the actual status of this shift. Therefore, all vehicles that were registered starting from the next month after second generation AEB was added were regarded as having switched over to the second generation (this was processed by including accidents by first generation vehicles in with some of the accidents caused by second generation vehicles).

2.2. Aggregating the number of vehicles owned

The number of vehicles owned in the middle of the year was used to calculate the number of accidents per 100,000 vehicles owned. The numbers of vehicles owned as of the ends of 2015 - 2018 categorized into the three groups mentioned above (Table 1) were used to calculate the numbers of vehicles from the middle of the three-year period from 2016 - 2018 (Table 2). The following rules were used in order to aggregate and categorize the number of vehicles owned, similar to how the number of accidents was aggregated.

1) For models on which AEB was equipped in the middle of their sales period, the number of vehicles owned that were registered in the period prior to AEB being equipped on said model were not included in this aggregation.
2) Regarding models that were sold with both first and second generation AEB, all vehicles that were registered starting from the next month after second generation AEB was added were regarded as having switched over to the second generation.

Table 1. Number of vehicles owned by AEB system status at the end of each year from 2015 – 2018

AEB	Specs	End of 2015	End of 2016	End of 2017	End of 2018
Equipped	First generation	1,894,171	2,280,620	2,603,003	2,781,735
	Second generation	178,978	610,825	1,303,190	2,332,757
Not equipped	-	1,722,532	2,159,032	2,475,216	2,623,811

Table 2. Number of vehicles owned by AEB system status in the middle of the period from 2016 - 2018 (total for the three years)

AEB	Specs	Middle of the period from 2016 - 2018
Equipped	First generation	**7,221,576**
	Second generation	**3,169,883**
Not equipped	-	**6,807,420**

2.3. Estimating the number of vehicles owned by the driver's age

In order to analyze the number of accidents per 100,000 vehicles owned by the driver's age, the number of vehicles owned by drivers of each age group ought to be used for the analysis. However, this data is hard to come by. As an alternate method, traffic exposure that uses the number of secondary parties (who are not at fault when traffic accidents occur) was used to estimate the number of vehicles owned by each age group. Specifically, the number of vehicles on the receiving end of a rear-end collision (numbers in the top row of Table 3) driven by drivers not at fault (secondary party) over the three-year period from 2016 - 2018 corresponds to traffic exposure. The number of vehicles aggregated in Section 2.2. was distributed according to the composition rate for the number of vehicles by age group (numbers in the bottom row of Table 3) (Table 4). These figures were used to calculate the number of accidents per 100,000 vehicles owned by the driver's age. The traffic exposure is based on the thinking that when the probability of a single vehicle becoming involved in an accident without the driver being at fault is treated as a constant, the number of accidents is indicative of the usage frequency for road traffic [Research Material 1].

Table 3. Number of vehicles on the receiving end of a rear-end collision where the driver was not at fault by AEB system status and driver's age from 2016 - 2018
(upper row: number of vehicles; bottom row: composition rate)

AEB	Specs	- 29	30 - 49	50 - 64	65 - 74	75 -
Equipped	First generation	3,361 20.3	7,482 45.2	4,000 24.2	1,375 8.3	341 2.1
	Second generation	1,397 21.9	2,843 44.5	1,528 23.9	501 7.8	114 1.8
Not equipped	–	3,256 20.4	7,425 46.5	3,653 22.9	1,312 8.2	309 1.9

Table 4. Estimated number of vehicles by AEB system status and driver's age from the middle of the period from 2016 – 2018

AEB	Specs	- 29	30 - 49	50 - 64	65 - 74	75 -
Equipped	First generation	1,465,772	3,262,989	1,744,447	599,654	148,714
	Second generation	693,769	1,411,872	758,825	248,803	56,614
Not equipped	–	1,389,217	3,167,978	1,558,603	559,783	131,839

3. Results and considerations

3.1 Rear-end collisions with a four-wheel vehicle (casualty accidents)

Fig. 4 shows the number of casualty accidents involving rear-end collisions with a four-wheel vehicle per 100,000 vehicles owned by group. The blue indicates the number of accidents by vehicles without AEB, the yellow is the number by vehicles with first generation AEB, and the orange is the number by vehicles with second generation AEB. The numbers at the top of the graphs indicate the rate of decline from first generation and second generation vehicles versus those without AEB. The two (one) asterisks at the top of the graphs indicate that a significance level of 1% (5%) or over was maintained in statistical tests of the difference in the ratio between the two groups. Graphs for which significance could not be obtained are indicated in gray. The listing of the rate of decline and significance level follows the same standards in the subsequent graphs as well. As for the error bar, when the distribution of the average values has been assumed to be identical to the F distribution, then this indicates a confidence interval of 99%. This reveals that the number of accidents declines significantly with vehicles equipped with first and second generation AEB versus those without it. The rate of decline is higher with the second generation than with the first generation.

The number of casualty accidents per 100,000 vehicles owned is shown in Fig. 5 by whether the accident occurred during the day or at night. The number declined significantly for both vehicles with first generation and second generation AEB, with the rate of decline higher for vehicles with the first generation over the second generation both during the day and at night.

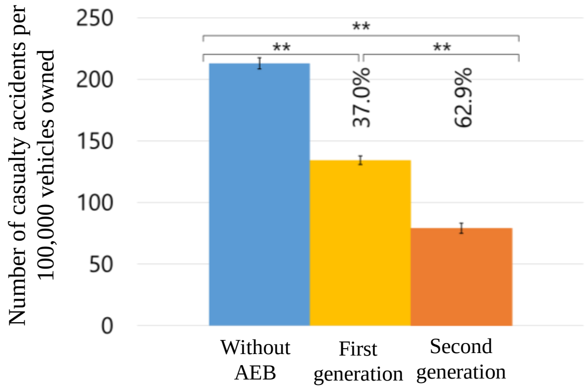


Fig. 4. Number of casualty accidents per 100,000 vehicles owned

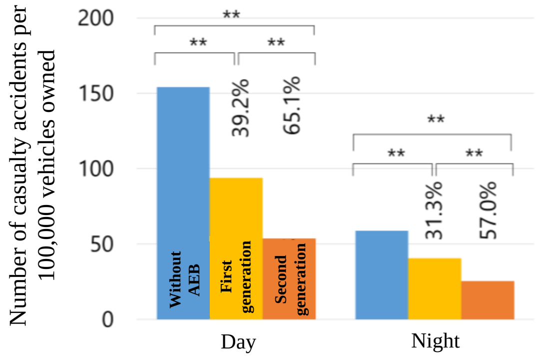


Fig. 5. By day / night

Fig. 6 shows the number of casualty accidents per 100,000 vehicles owned by the danger perception speed of the primary party vehicle. With vehicles with first generation AEB this was primarily in a speed range from 0 - 30km/h, while for the second generation declines were observed in the speed ranges from 0 - 30km/h, up to 60km/h, and over 61km/h. Since every model of kei sized vehicle with first generation AEB were equipped with laser radar (with an activation speed range of 5 - 30km/h), the effects obtained showed that both the first and second generation were largely consistent in terms of the specifications for their activation speeds.

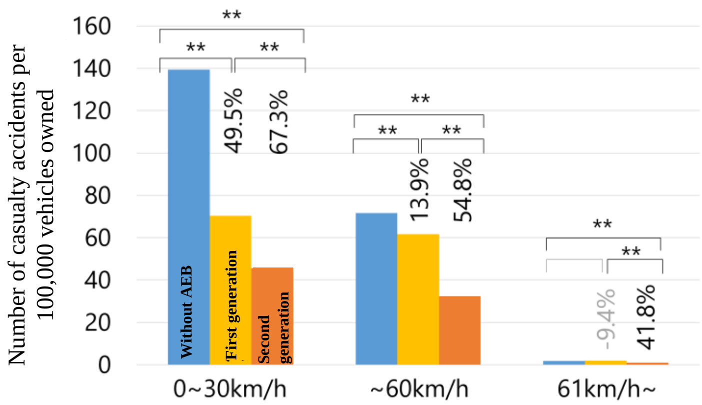


Fig. 6. By danger perception speed of the primary party

The number of accidents per 100,000 vehicles owned as classified by the type of movement of the primary party revealed that going straight and starting up accounted for most types of movement at the time of the accident, regardless of whether AEB was equipped or not and differences in the specifications (Fig. 7). Next, this will be analyzed by linking the driving behavior when the accident occurred (when going straight, when starting up) and the human factors at this time (human error).

Supplementary explanations of the contents of the human factors dealt with in this report are provided in Table 5. Descriptions concerning the human factor items not dealt with in this report have been omitted.

A graph of the number or accidents per 100,000 vehicles owned by human factor when going straight is shown (Fig. 8). The number of accidents for the three items with the highest composition rates among the human factors (intrinsic failure to pay attention forward, extrinsic failure to pay attention forward, and failure to observe surrounding traffic movement when going straight) and for total when going straight have been indicated. The rate of decline for human factors that are decreasing over and above the totals for when going straight have been listed in red. The effects obtained showed that the rate of decline was higher with the second generation compared to with the first across each of the human factors. Since the speed range of vehicles when going straight is spread out across a broad range from low to high speeds, the assumption is that second generation AEB would be more effective given their broader activation speed range. One characteristic point is that even under the same category of failure to pay attention forward, the decline was more significant with an extrinsic failure to pay attention forward than with an intrinsic failure to pay attention forward. No difference in braking distance arises due to the automatic activation of the brakes by the AEB, regardless of whether the failure to pay attention forward was due to intrinsic or extrinsic causes. Therefore, this presumably indicates that with this difference there is a shorter length of time from when the AEB emits a warning at the state prior to automatically activating the brakes until the driver steps on the brake with an extrinsic failure to pay attention forward, thus making it easier to avoid accidents (which approximately correlates to making it easier to cover for errors).

As for the number of accidents by human factor per 100,000 vehicles owned when starting up (Fig. 9), extrinsic failure to pay attention forward, failure to observe surrounding traffic movement, and operating error account for a large share of these. A rate of decline was obtained from first generation AEB that is approaching that from the second generation. This is presumably because vehicle speed when starting up is often in low speed ranges, making it easier to receive the effects of both first and second generation AEB.

Table 5: Supplementary explanations for human factors

Human factor		Definition	Sample conditions
Cognitive errors	Intrinsic failure to pay attention forward	A failure to pay attention forward due to a psychological or physiological factor	Dozing off Lost in thought Aimless driving
	Extrinsic failure to pay attention forward	Failure to pay attention forward resulting from motion	Distracted Trying to retrieve something
	Failure to confirm safety factors	Failed to confirm everything possible despite decelerating to a speed where confirmation was possible	Failure to confirm safety Inadequate safety confirmation
Decision-making errors	Failure to observe surrounding traffic movement	Detected (became aware of) the other party, but neglected to pay attention to the movement of said party	Driver thought the other party would stop and took their eyes off them
Operating errors	Driving operation errors	Improper operation or hesitating in operating the vehicle due to surprise	Misapplication of the pedals Late in applying brakes

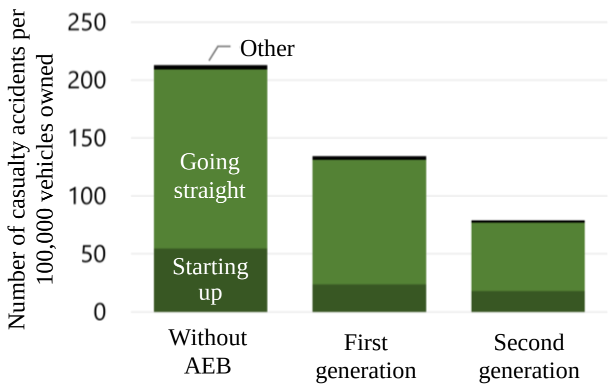


Fig. 7. By type of movement of the primary party

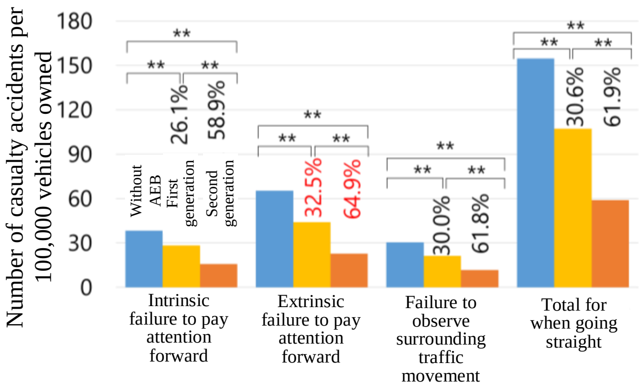


Fig. 8. By human factor when going straight

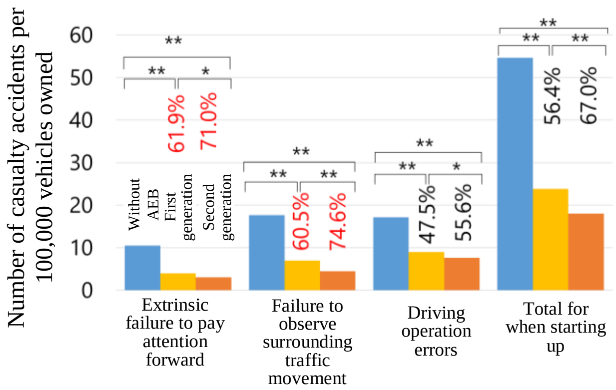


Fig. 9. By human factor when starting up

The number of accidents per 100,000 vehicles owned by the driver's age differs from the results indicated thus far, with the number of vehicles owned by the driver's age obtained from Section 2.3 having been used as the number of vehicles owned (Fig. 10). Regardless of whether or not the vehicle is equipped with AEB, the overall trend indicated that young people age 29 and younger and elderly people age 75 and older had a large number of accidents. However, decreases were seen across every age group for both first and second generation AEB.

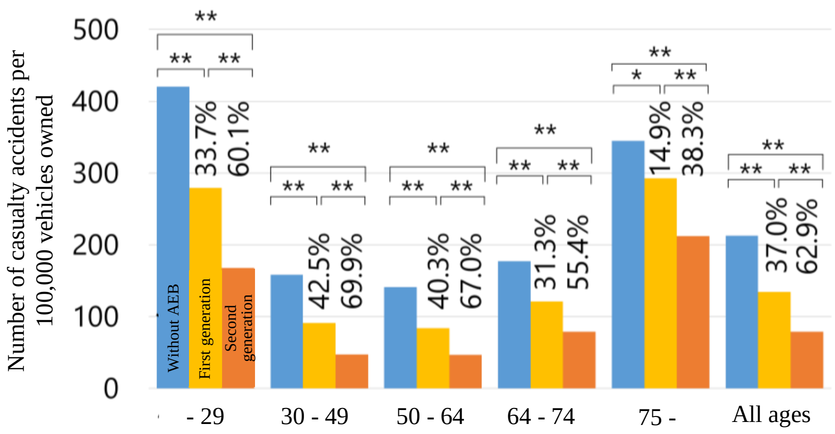


Fig. 10. By age of the primary party

As for rear-end collisions with a four-wheel vehicle, the main cases where the effects of AEB were seen have been compiled into Table 6 by AEB generation. From the accident statuses confirmed for both generations, the accident damage mitigation effects were found to be greater with the second generation than with the first. The difference in the rate of decline was particularly pronounced in a speed range of up to 60km/h when viewed by danger perception speed. When viewed by human factor, the errors mainly covered by the first and second generations were the same.

Table 6. Cases where effects were mainly seen: Rear-end collisions with a four-wheel vehicle

Specifications	First generation		Second generation
Time of day	Day, night		⇐
Danger perception speed	0 - 30km/h		0 - 30km/h - 60km/h 61 km/h -
Type of movement x Human factors	When going straight	Extrinsic failure to pay attention forward	⇐
	When starting up	Extrinsic failure to pay attention forward, failure to observe surrounding traffic movement	⇐
Driver age	All age groups		⇐

In considering what will be necessary to further improve the effects of AEB in regard to rear-end collision accidents with four-wheel vehicles, since effects have been observed as things currently stand with accident statuses that account for a high share of the total, still greater effects could be obtained by improving the basic performance of AEB. Proposals for improving its basic performance that could be mentioned include improving the detection accuracy for the vehicles up ahead by adopting 79 GHz millimeter wave radar, or electrifying the brake system in order to improve braking efficiency.

3.2 Pedestrian-vehicle accidents (casualty accidents, fatal and serious injury accidents)

Figs. 11 and 12 show the number of casualty accidents and the number of fatal and serious injury accidents per 100,000 vehicles owned by group. The blue shows the number of accidents by vehicles without AEB and the orange shows the number from vehicles with second generation AEB. Vehicles with first generation AEB were unable to detect pedestrians and demonstrated trends similar to vehicles without AEB in terms of their analytical results, and thus were omitted. Vehicles with second generation AEB showed significant declines versus vehicles without AEB systems for both casualty accidents and fatal and serious injury accidents. Pedestrian-vehicle accidents include accidents caused by pedestrians rushing out where, even if it is assumed that the AEB was able to detect the pedestrian faster to some extent, it was unable to apply the brakes in a physical sense in time to prevent the accident. This is a point that requires attention. Since it is difficult to isolate out these accidents, they were not categorized for this report.

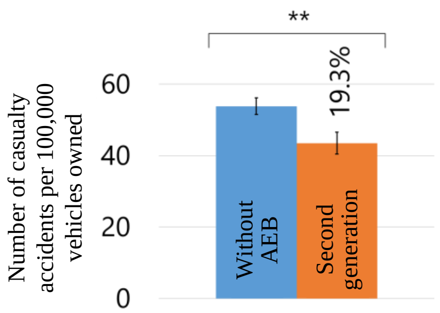


Fig. 11. Number of casualty accidents per 100,000 vehicles owned

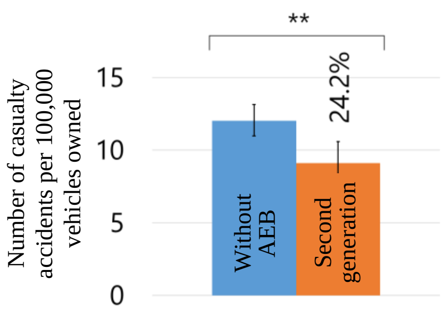


Fig. 12. Number of fatal and serious injury accidents per 100,000 vehicles owned

Figs. 13 and 14 show the number of casualty accidents and the number of fatal and serious injury accidents per 100,000 vehicles owned by the time of day the accident occurred. While casualty accidents declined in both the day and at night, conversely with fatal and serious injury accidents only a significant decrease was observed at night. There is no information in the macro data on the extent of the illumination from street lamps and the like for accidents at night. However, with current kei sized vehicles the number of models capable of detecting pedestrians at night is limited, and so there is the conceivable possibility that other methods besides AEB like automatic high beams that activate at nighttime also contribute to reducing accidents at night.

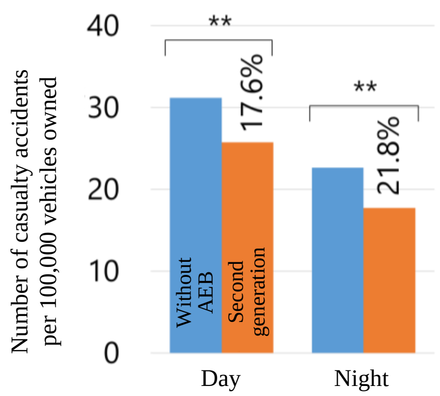


Fig. 13. Casualty accidents by time of day

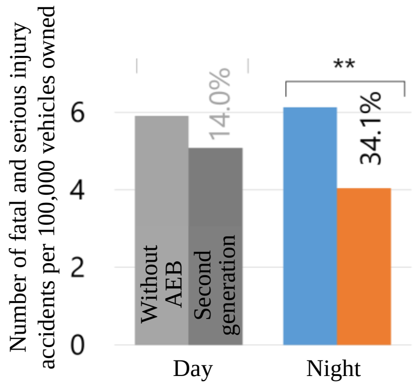


Fig. 14. Fatal and serious injury accidents by time of day

As for the number of accidents per 100,000 vehicles owned categorized by the type of movement of the primary party vehicle (Figs. 15 and 16), accidents when going straight or turning right account for the vast majority of both casualty accidents and fatal and serious injury accidents, regardless of whether the vehicle was equipped with AEB. Human factors were linked with this to perform the analysis on accidents when going straight and when turning right.

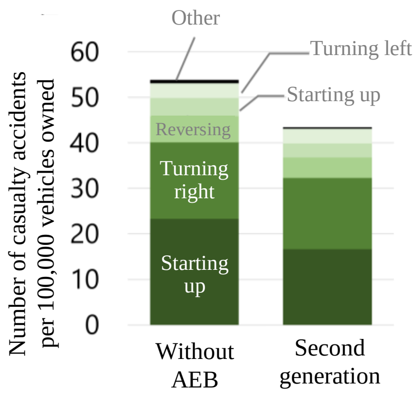


Fig. 15. Casualty accidents by type of movement of the primary party

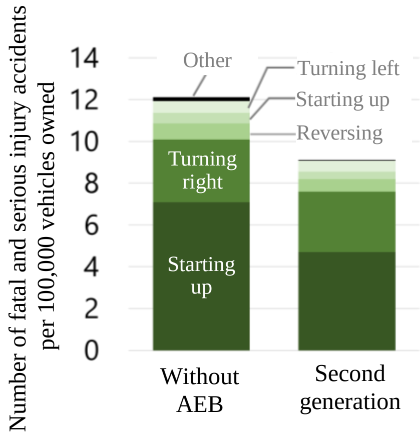


Fig. 16. Fatal and serious injury accidents by type of movement of the primary party

For the number of accidents per 100,000 vehicles owned by human factor when going straight, for the three items with the highest composition ratio (intrinsic failure to pay attention forward, extrinsic failure to pay attention forward, and failure to confirm safety factors) and for total when going strait were indicated for both casualty accidents and fatal and serious injury accidents (Figs. 15 and 16). Accidents caused by an intrinsic or extrinsic failure to pay attention forward had a rate of decline that exceeded the total for accidents when going straight. It is believed that this suggests that errors in situations in which a person is in the field of view of the sensor and driver but the driver fails to see them can be covered by the AEB. Conversely, with accidents caused by a failure to confirm safety factors this resulted in a relatively low rate of decline. Accidents caused by a failure to confirm safety factors include accidents that cannot be covered for by AEB as things currently stand, which is thought to be why they were less prone to receiving the benefits. Examples of such accidents include cases where a pedestrian moves from outside to inside the sensor's field of view, such as when they rush out, or cases where accidents occur when the pedestrian is outside of said field of view.

For the number of accidents per 100,000 vehicles owned by human factor when turning right, the three items with the highest composition ratio for both casualty accidents and fatal and serious injury accidents were intrinsic failure to pay attention forward, extrinsic failure to pay attention forward, and failure to confirm safety factors. Failure to confirm safety factors accounted for the majority, but no significant differences were seen based on whether the vehicle had AEB or not for any of the human factors. This is similar to accidents when going straight, in that it is believed that there is a mismatch between the field of view of the vehicle's sensor and the position of the pedestrian, and it is thus unable to detect the pedestrian.

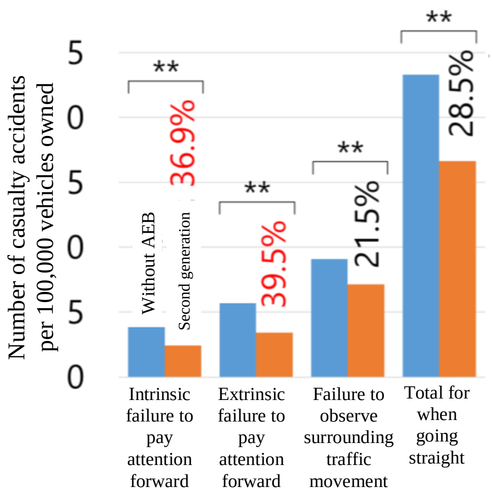


Fig. 17. Casualty accidents by human factor when going straight

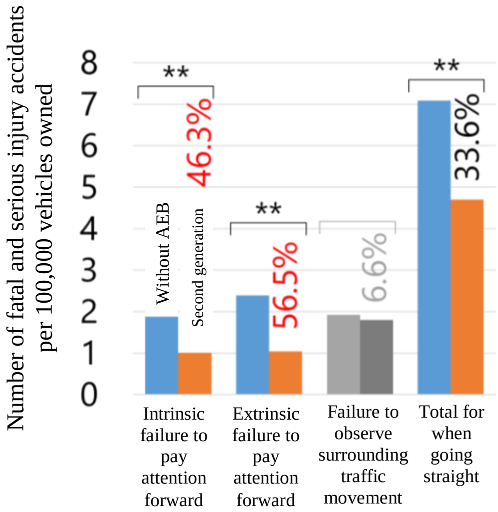


Fig. 18. Fatal and serious injury accidents by human factor when going straight

The number of accidents per 100,000 vehicles owned by type of accident for pedestrian-vehicle accidents (categorized by relative position of the vehicle and the person and the direction of motion of the person; Figs. 19 and 20) reveals a significant decline in accidents under certain conditions. Said conditions include casualty accidents while the pedestrian is walking facing the vehicle or while walking parallel to the vehicle and other cases where the person is out ahead of the vehicle, which is to say, often when the person is within the sensor's field of view. On the other hand, for fatal and serious injury accidents there has been a greater decline in accidents while crossing compared to with casualty accidents. This suggests that there are a certain number of accidents where the AEB was unable to fully avoid the accident, but was able to mitigate the damage down to a slight injury accident.

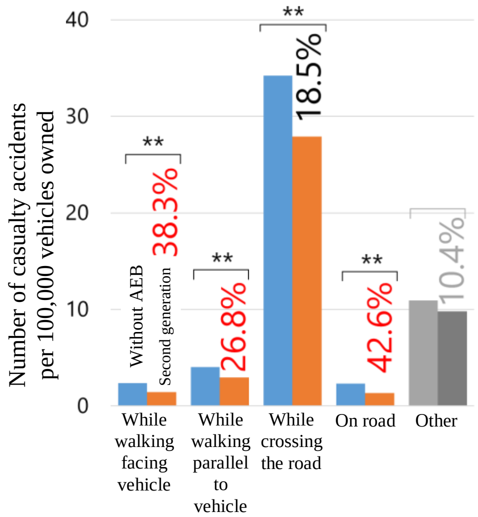


Fig. 19. Casualty accidents by detailed type of accident

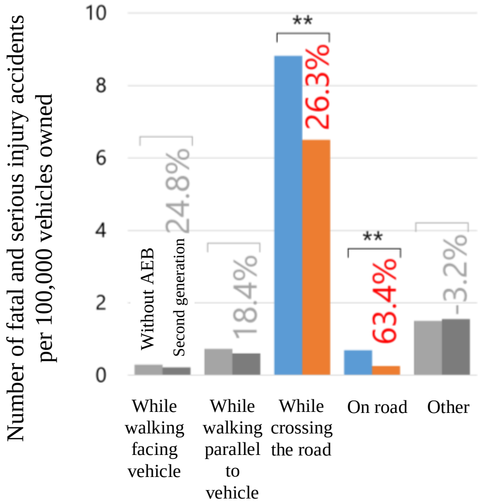


Fig. 20. Fatal and serious injury accidents by detailed type of accident

The number of accidents per 100,000 vehicles owned by the driver's age has shown a tendency towards a larger number of accidents the higher up in age one goes, with this holding true for both casualty accidents and fatal and serious injury accidents regardless of whether or not the vehicle had AEB (Figs. 21 and 22). There are some age groups with a limited number of accidents where no significant difference was seen, but on the whole a downward trajectory was seen across all age groups.

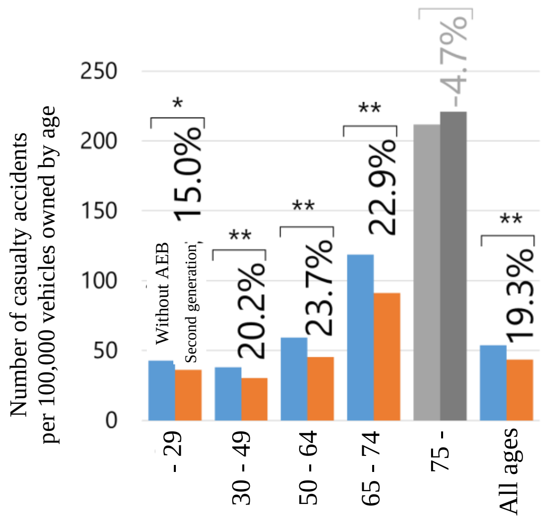


Fig. 21. Casualty accidents by age of the primary party

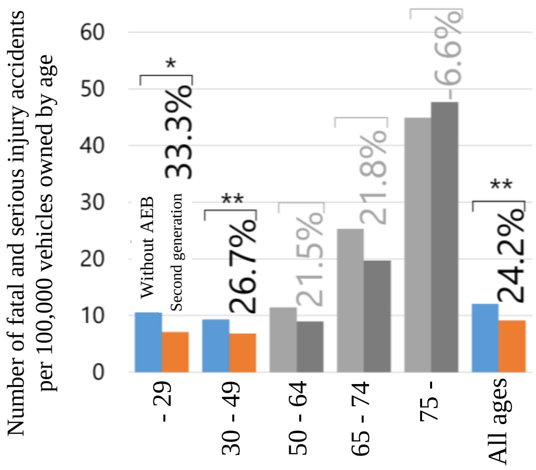


Fig. 22. Fatal and serious injury accidents by age of the primary party

With regard to pedestrian-vehicle accidents, cases where the effects were mainly seen were summarized in Table 7. With second generation AEB, effects were observed in the form of a decline in both pedestrian-vehicle casualty accidents and fatal and serious injury accidents. When viewed by status, effects were oftentimes noted with cases where the person is within the sensor's field of view. As for accidents at nighttime, the thinking is that automatic high beams and other ASV devices could potentially have the effect of mitigating damage.

Table 7. Cases where effects were mainly seen: Rear-end collisions with a four-wheel vehicle

Accident details	Casualty accidents		Fatal and serious injury accidents
Time of day	Day, night(*1)		Night(*1)
Type of movement x Human factors	When going straight	Intrinsic failure to pay attention forward Extrinsic failure to pay attention forward	⇐
Driver age	All age groups(*2)		⇐
Type of accident (person's location, movement)	While crossing the street, while walking facing the vehicle, while walking parallel to vehicle, on road		While crossing the road, on road

With regard to pedestrian-vehicle accidents, when one considers what will be necessary in order to further improve the effects from AEB systems, it would presumably be beneficial to expand the detection range for pedestrians (particularly around angles). This could be done via the adoption of LiDAR (Light Detection and Ranging) to make it possible to detect pedestrians located outside of the field of view of the sensors on current vehicles. Conversely, accidents where the AEB is unable to apply the brakes in time in a physical sense no matter how quickly it detects the pedestrian cannot be prevented by AEB. As such, the thinking is that it will be necessary to combine it with accident prevention systems that activate in a quicker time frame than AEB does, such as ITS [Reference Material 2], in order to eliminate pedestrian accidents.

Given the current analytical conditions, it was impossible to analyze the results from conditions corresponding to the conditions in which AEB activate to a certain extent for pedestrian-vehicle accidents compared with rear-end collision accidents. As such, conceivably there were scenarios in which it was difficult for the effects of AEB to be become apparent. Presumably, it will be necessary in the future to set in place an environment for analyzing accidents that would make it possible to analyze the results of ASV, including AEB, in a detailed manner.

4. Conclusion

This report determined the effects of mitigating the damage from rear-end collision accidents against four-wheel vehicles and pedestrian-vehicle accidents by the different specification of AEB.

1) Regarding rear-end collisions with a four-wheel vehicle

   Regarding the accident damage mitigation effects, greater effects were obtained with the second generation of AEB than with the first

   Ideally, the effects can be further improved by enhancing the sensitivity and braking efficiency of AEB systems

2) Regarding pedestrian-vehicle accidents

   Second generation AEB systems that can detect pedestrians demonstrated effects in terms of mitigating the damage from accidents

   It will be necessary to develop AEB that can cover pedestrians outside of the field of view of the current sensors in order to further improve upon their effects

   In order to reach zero pedestrian accidents, it will be necessary to combine AEB with accident prevention systems that activate in a quicker time frame than AEB does

[参考資料]

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