Injury crash reduction of low-speed Autonomous Emergency Braking (AEB) on passenger cars

Matteo Rizzi, Anders Kullgren, Claes Tingvall

Abstract Low-speed Autonomous Emergency Braking (AEB) is a safety system designed to support passenger car drivers to avoid or mitigate the consequences of rear-end crashes, mostly in urban road environments. This study set out to evaluate the effectiveness of this technology in reducing real-life crashes, based on Swedish police-reported injury crashes 2010-2014. Cars with standard AEB were compared with non-AEB cars from the same manufacturer as well as from others. Both groups were chosen to be of similar types and weights.

The statistical analysis used odds ratio calculations with an induced-exposure approach. In this case, striking rear-end crashes were considered sensitive to AEB. The non-sensitive crash types used in the analysis were struck rear-end crashes as well as all crossing crashes. Only two-car collisions were included.

The results showed that the reduction of striking rear-end crashes in 50 km/h speed areas ranged between 54% and 57%. The reduction of all striking rear-end crashes, regardless of speed area, ranged between 35% and 41%. These findings were in line with previous research, although of greater magnitude as the striking and the struck car could be identified and separated. However, it should be noted that the present study calculated the overall benefits of AEB, in terms of both crash avoidance and injury mitigation.

Keywords AEB, effectiveness, rear-end, injury, crash

I. INTRODUCTION

Passenger car safety has improved considerably during the latest 30 years. During this period most injury preventive countermeasures were focused on vehicle crashworthiness. Compared with passenger cars introduced in the early 1980s, the fatality risk with cars launched in the late 2000s decreased by almost 90% and the risk for permanent impairment by approximately 50% [1].

Furthermore, many vehicle safety systems have been aiming at avoiding or mitigating crashes. For instance, several studies have shown that Electronic Stability Control (ESC) reduces injury and fatality crash involvement risk by 20%-35% [2-7]. In 2012, almost 100% of new cars in Sweden were equipped with ESC [8]. Another technology with increasing implementation rates is Autonomous Emergency Braking (AEB). There are different AEB specifications: some are designed for low-speed scenarios while others are active at higher speeds [9]. These systems also vary in their ability to address different crash types. These can be car-to-car crashes in various configurations but also crashes with vulnerable road users, for instance, pedestrians and cyclists. While some manufacturers offer these technologies as standard fitment, most often they are optional [9].

The most commonly available system to date is low-speed AEB, which is designed to support passenger car drivers to avoid or mitigate the consequences of rear-end crashes, mostly in urban road environments [10]. If the driver does not react in critical rear-end situations, the system applies the brakes automatically and, within the lowest speed ranges, can fully avoid the collision. The brake lights are simultaneously activated to warn other traffic users [11]. At the present stage, this technology has been introduced by different car manufactures on a number of size classes [9]. Volvo was the first one that introduced this technology (Volvo City Safety) for low-speed rear-end crashes as a standard fitment [11]. A Swedish study based on insurance claims indicated a 23% reduction of rear-end crashes involving Volvo XC60 fitted with City Safety [11], while a study by the Highway Loss Data Institute in the USA [12] showed a 20% reduction in crash involvement risk for the Volvo XC60 and 33% reduction in bodily injury liability.

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While the benefits in terms of crash severity mitigation have not yet been investigated in real-life crashes, estimations of injury crash reductions suggest that the trauma savings are likely to be significant [13-14]. Therefore the present study attempted to address this issue by evaluating the overall benefits of AEB in terms of reduction of injury rear-end crashes in Sweden.

II. METHODS

Material

The Swedish Transport Accident Data Acquisition (STRADA) is managed by the Swedish Transport Agency and includes police records that can be merged with hospital data. Crashes occurring on public roads and having caused at least one injured person are recorded by the police. Four injury levels are assigned by the police officer attending the crash scene: fatal, serious, slight and uninjured.

Police-reported car crashes that occurred between January 2010 and February 2014 were used for the analysis. Passenger cars with standard AEB from Volvo were compared with two different groups: Volvo cars without AEB as well as non-AEB cars from other manufacturers. Both groups were chosen to be of similar types and weights; Table 1 shows the car models included in the three groups. A total of 3,922 injury crashes involving these car models were available for analysis.

TABLE I
CAR MODELS INCLUDED IN THE CALCULATIONS

AEB Volvos	non-AEB Volvos	non-AEB others	
Volvo S60/V60 10-	Volvo S60 06-09	Audi A6 11-	Mercedes E-Class 09-
Volvo S80 12-	Volvo S80 07-11	Audi Q5 09-	Nissan Qashqai 07-
Volvo V40 12-	Volvo V70 07-11	BMW 3 Series 09-12	Opel Insignia 09-
Volvo V70 12-	Volvo XC70 07-11	BMW 5 Series 10-	Skoda Superb 09-
Volvo XC60 08-	Volvo XC90 06-	Ford Kuga 08-	Toyota Avensis 09-
Volvo XC70 12-		Ford Mondeo 10-	Toyota RAV4 08-
		Hyundai IX35 10-	VW Passat 08-
		Kia Sportage 11-	VW Tiguan 08-

Methods

An analysis using induced-exposure can be used when true exposure is not available [6] [15-16]. With this approach, the key point is to identify at least one crash type in which the countermeasure under analysis can be reasonably assumed (or known) not to be effective. In the present study, cars with and without low-speed AEB were compared. If the only noteworthy difference in terms of involvement in rear-end crashes is AEB, the relation between cars with and without AEB in that non-sensitive situation would be considered as the true exposure relation. This means that any deviation from the relation in non-sensitive situations is considered to be a result of AEB.

The analysis focused on two-car rear-end crashes in which at least one person was injured - not necessarily the occupants of the cars with or without AEB. Striking rear-end crashes were considered to be sensitive to low-speed AEB. Struck rear-end crashes were assumed to be non-sensitive to AEB (see Figure 1), as the City Safety technology is designed to brake very late, i.e. when a collision becomes imminent [17]. While police reports do not explicitly include details on whether a specific car was striking or struck, this information was manually obtained in the description or in the sketch of the crash.

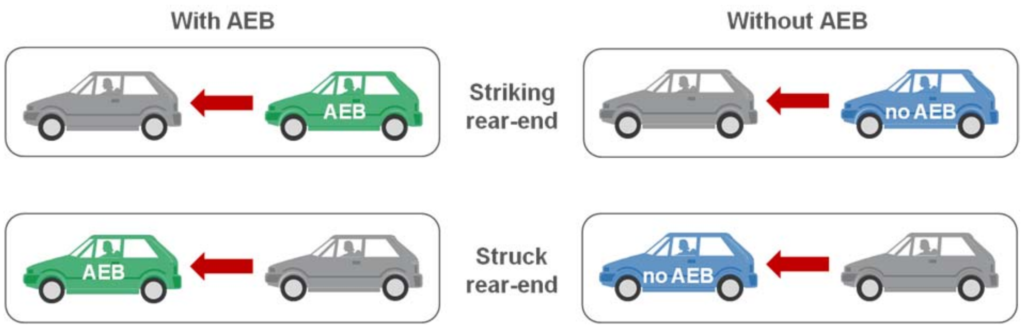

Fig. 1. The induced-exposure approach: analyzing the relation between striking and struck rear-end crashes, with and without AEB.

As a further control, two-car crossing crashes were also tested as non-sensitive, as these should not be systematically addressed by low-speed AEB technologies. While these crashes normally involved side collisions, information for identifying the striking or struck parts in those crashes was not available. In total, 660 rear-end crashes and 500 crossing crashes were available for the calculations, which were performed according to Eq. 1 and 2 below. Further details on the material included in the analysis per car model are shown in the Appendix.

$$R_1 = \frac{Striking_{AEB}}{Struck_{AEB}} \div \frac{Striking_{no\ AEB}}{Struck_{no\ AEB}} \qquad (1)$$

$$R_2 = \frac{Striking_{AEB}}{Crossing_{AEB}} \div \frac{Striking_{no\ AEB}}{Crossing_{no\ AEB}} \qquad (2)$$

$Striking_{AEB}$ = number of striking rear-end crashes, involving AEB cars
$Striking_{no\ AEB}$ = number of striking rear-end crashes, involving non-AEB cars
$Struck_{AEB}$ = number of struck rear-end crashes, involving AEB cars
$Struck_{no\ AEB}$ = number of struck rear-end crashes, involving non-AEB cars
$Crossing_{AEB}$ = number of crossing crashes, involving AEB cars
$Crossing_{no\ AEB}$ = number of crossing crashes, involving non-AEB cars

For each equation, the effectiveness in terms of injury reduction can be expressed as:

$$E_{1,2} = 100 \times (1 - R_{1,2})\% \qquad (3)$$

The standard deviation of each effectiveness was calculated on the basis of a simplified odds ratio variance, according to Equation 4. This method gives symmetric confidence limits but the effectiveness is not overestimated.

$$Sd = \sqrt{\sum_{i=1}^{4} \frac{1}{m_i}} \qquad (4)$$

where m is the number of crashes of each type. The 95% confidence limits for each effectiveness are given in Equation 5.

$$E \pm \Delta E = E \pm (100 \times R \times Sd \times 1.96) \qquad (5)$$

The effectiveness calculations were performed in relation to both non-AEB groups. Controls were also made on a number of factors such as driver age, curb weight ratios, etc in order to make sure that the only significant difference between the crashes involving the analyzed car models was the fitment of low-speed AEB.

III. RESULTS

Crash type distributions

Tables II, III and IV below show the distributions of crash types across different speed areas for the AEB and non-AEB cars, respectively. Rear-end and crossing crashes were broken down depending on the number of vehicles involved, as mentioned above.

TABLE II
CRASH TYPE DISTRIBUTION PER SPEED AREA – VOLVOS WITH AEB

	≤50 km/h	60-70 km/h	≥80 km/h	Total
Crossing crashes, 2 cars only	7%	3%	1%	11%
Other crashes at intersections	6%	3%	1%	10%
Pedestrian/bicycle	9%	1%	0%	10%
Head-on	2%	3%	2%	7%
Single-vehicle	4%	3%	6%	13%
Rear-end, 2 cars only	6%	4%	7%	17%
Rear-end, 3+ vehicles, no HGV involved	3%	6%	7%	16%
Rear-end, 3+ vehicles, involving HGV	2%	3%	5%	10%
Others	2%	2%	2%	6%
Total	41%	28%	31%	100%
n crashes	248	165	202	615

TABLE III
CRASH TYPE DISTRIBUTION PER SPEED AREA – VOLVOS WITHOUT AEB

	≤50 km/h	60-70 km/h	≥80 km/h	Total
Crossing crashes, 2 cars only	10%	3%	1%	14%
Other crashes at intersections	7%	3%	1%	11%
Pedestrian/bicycle	11%	1%	0%	12%
Head-on	3%	3%	5%	11%
Single-vehicle	3%	4%	5%	12%
Rear-end, 2 cars only	7%	4%	5%	16%
Rear-end, 3+ vehicles, no HGV involved	3%	4%	5%	12%
Rear-end, 3+ vehicles, involving HGV	1%	1%	3%	5%
Others	2%	2%	3%	7%
Total	47%	25%	28%	100%
n crashes	717	368	401	1486

TABLE IV
CRASH TYPE DISTRIBUTION PER SPEED AREA – NON-VOLVOS WITHOUT AEB

	≤50 km/h	60-70 km/h	≥80 km/h	Total
Crossing crashes, 2 cars only	9%	3%	1%	13%
Other crashes at intersections	6%	2%	1%	9%
Pedestrian/bicycle	12%	1%	0%	13%
Head-on	3%	3%	3%	9%
Single-vehicle	3%	3%	4%	10%
Rear-end, 2 cars only	9%	4%	6%	19%
Rear-end, 3+ vehicles, no HGV involved	4%	5%	6%	15%
Rear-end, 3+ vehicles, involving HGV	2%	3%	2%	7%
Others	2%	1%	2%	5%
Total	50%	25%	25%	100%
n crashes	889	459	473	1821

It was found that, in speed areas up to 50 km/h, two-car crossing crashes accounted for 7% of all crashes with AEB Volvos. However, these accounted for 10% and 9% of all crashes involving Volvos without AEB and non-Volvos without AEB. It was also found that two-car rear-end crashes accounted for 6% of all crashes involving AEB cars. The non-AEB groups had 7% and 9%, respectively. While in higher speed areas the distributions of two-car rear-end and crossing crashes were not dissimilar; AEB cars had a greater share of rear-end crashes involving Heavy Good Vehicles (HGV).

Effectiveness in rear-end crashes

The findings for the analysis of rear-end crashes are shown in Table V below. As it can be seen, the striking-struck ratios were quite constant for the non-AEB cars across different speed areas, and generally close to 1. However, this was not the case for AEB Volvos, which were found to have lower ratios, especially in speed areas up to 50 km/h. The number of crashes in each category is shown in the Appendix.

TABLE V

STRIKING-STRUCK RATIOS IN REAR-END CRASHES, PER SPEED AREA

	≤50 km/h	60-70 km/h	≥80 km/h	>50 km/h	Total
AEB Volvos	0.42	0.60	0.80	0.71	0.59
non-AEB Volvos	0.96	1.03	1.06	1.05	1.01
non-AEB others	0.90	0.92	0.91	0.92	0.91

Table VI below shows the calculated reductions of striking rear-end crashes, based on the ratios in Table V. The findings for the two non-AEB groups were generally consistent. The reductions of striking rear-end crashes in speed areas up to 50 km/h were statistically significant and ranged from 54% to 57%. No statistically significant results were found for other speed areas or all speed areas above 50 km/h grouped together. However, the overall reductions (regardless of speed areas) of striking rear-end crashes were statistically significant and ranged from 35% to 41%.

TABLE VI

REDUCTION OF STRIKING REAR-END CRASHES WITH AEB, PER SPEED AREA - IN RELATION TO STRUCK REAR-END CRASHES

	≤50 km/h	60-70 km/h	≥80 km/h	>50 km/h	All speed areas
non-AEB Volvos	57% ± *36%*	42% ± *56%*	25% ± *61%*	32% ± *42%*	41% ± *29%*
non-AEB others	54% ± *37%*	35% ± *61%*	12% ± *67%*	22% ± *46%*	35% ± *31%*

Table VII below shows the results for the calculations with crossing crashes as non-sensitive. The reductions of striking rear-end crashes were somewhat lower than those in Table VI. However, no statistically significant results were found with exception of non-Volvos without AEB in speed areas up to 50 km/h. In that case, the reduction of striking rear-end crashes was well in line with the previous one (50%). The number of crashes in each category is shown in the Appendix.

TABLE VII

REDUCTION OF STRIKING REAR-END CRASHES WITH AEB, PER SPEED AREA - IN RELATION TO CROSSING CRASHES

	≤50 km/h	60-70 km/h	≥80 km/h	>50 km/h	All speed areas
non-AEB Volvos	31% ± *52%*	26% ± *70%*	22% ± *87%*	13% ± *59%*	8% ± *43%*
non-AEB others	50% ± *37%*	27% ± *68%*	10% ± *92%*	16% ± *54%*	25% ± *34%*

Tables VIII and IX below show the distributions of SUVs across the AEB and non-AEB groups, as well as the ratios between the analyzed cars and the other cars involved in the crashes with regard to the share of male drivers, mean driver age and curb weight. While non-AEB Volvos included fewer SUVs, the curb weight ratio was in line with the other analyzed cars. The distribution of road surfaces was not dissimilar across the AEB and non-AEB groups.

TABLE VIII

OVERVIEW OF ALL ANALYZED TWO-CAR REAR-END CRASHES (STRIKING AND STRUCK)

	AEB Volvos	non-AEB Volvos	non-AEB others
% SUVs	21%	4%	20%
Driver mean age, study/other car	0,99	0,99	1,06
% male driver study/other car	1,15	1,12	1,18
Curb weight study/other car	1,23	1,18	1,11
% crashes on dry asphalt	61%	55%	55%
% crashes on wet asphalt	29%	23%	26%
% crashes on ice or snow	11%	21%	17%

TABLE IX
OVERVIEW OF THE ANALYZED STRIKING REAR-END AND CROSSING CRASHES

	AEB Volvos	non-AEB Volvos	non-AEB others
% SUVs	25%	2%	25%
Driver mean age study/other car	0,94	0,97	0,98
% male driver study/other car	1,11	1,20	1,11
Curb weight study/other car	1,20	1,17	1,12
% crashes on dry asphalt	54%	47%	58%
% crashes on wet asphalt	25%	22%	19%
% crashes on ice or snow	19%	31%	22%

IV. DISCUSSION

Overall Findings

The findings of the present study showed that the risk of being the striking part in an injury rear-end crash could be halved by low-speed Autonomous Emergency Braking in speed areas up to 50 km/h. The overall reduction in all speed areas was in the 35%-40% range. The present results are in line with the two previous studies [11-12], albeit of greater magnitude, as it was possible to identify the active and passive cars in those crash scenarios that low-speed AEB is designed to address. In other words, it should be noted that the calculated reductions of rear-end crashes referred to striking cars only, which should theoretically be twice as high as the reduction of all two-car rear-end crashes.

As shown in Table V, the striking-struck ratios for non-AEB cars were generally close to 1, regardless of speed area. This seems logical as cars without AEB should have in principle a 50% risk of striking and a 50% risk of being struck. Furthermore, urban speed areas could be analyzed separately. Since the low-speed AEB technology analyzed in the present study is deactivated at higher speeds, it is not unreasonable to expect that larger benefits should be found in those speed areas where driving speeds are more often below that cut-off speed, and vice versa.

The findings of the present study as well as the previous ones clearly show that AEB systems have a significant potential to reduce road traffic casualties. It could be argued that low-speed AEB only addresses a relatively small part of all existing crash scenarios in terms of impact directions and closing speeds. However, it should be noted that this technology addresses a much larger proportion of all road traffic injuries, since whiplash-associated disorders account for 60% of injuries leading to permanent impairment among passenger car occupants [18]. Furthermore, it is important to add that 50% of these occur in rear-end crashes [19], and the vast majority in low speed crashes below 50 km/h [20].

Considering the substantial benefits in terms of trauma savings, it is important that proper actions are taken by stakeholders to increase the implementation rate of this technology. To date low-speed AEB systems are most often optional, although some manufacturers offer them as standard fitment. While Volvo was the first one that introduced this technology as standard fitment [11], many other manufacturers have followed [9].

Furthermore, other AEB technologies are present [9]. The development is ongoing in this field, and the existing systems are continuously further improved. While the potential for large injury reductions in other crash types than low-speed rear-end crashes seems significant [13-14], further research is needed to rapidly evaluate the effectiveness of other AEB technologies.

Research Strengths and Limitations

The present research used an induced-exposure approach, as shown in several previous studies [6] [15-16]. Other exposures could also be used for this kind of evaluation, for instance the number of registered vehicles with and without the analyzed technology. However, these may include confounding factors for which an induced-exposure approach would normally compensate, as the result is given by the relative differences within the AEB and non-AEB groups.

The present method, however, is based on some assumptions that are important to discuss. The most critical step in the analysis is to determine the non-sensitive crash type. In the present study, struck rear-end crashes were first used as non-sensitive. It could be argued that this assumption could lead to an overestimation of the actual benefits of low-speed AEB: theoretically, there is a risk that AEB cars could be struck more often than those without. In other words, the calculated benefits of AEB with this method could be an effect of a decreased risk of striking another vehicle from the rear, but also of an increased risk to be struck in the rear. However, it should be noted that the results based on crossing crashes were not dissimilar, although these were not statistically significant. Furthermore, the question could be raised of whether crossing crashes are completely non-sensitive to AEB. By comparing Table II with Tables III and IV, it seems that these could also be slightly reduced with low-speed AEB. In other words, it could be argued that it may not be impossible that AEB systems could be activated in low-speed crossing scenarios when the AEB vehicle was the striking one. While the present study could not further investigate those crossing scenarios to identify the active and passive car, this seems to suggest that a systematic increase in the risk of being struck with low-speed AEB is unlikely and, if at all present, small.

A critical step was to properly match the AEB and non-AEB cars. It should be kept in mind that some of the Volvo cars included in the study might have been equipped with an optional “driver support” safety package, including a number of technologies such as Adaptive Cruise Control (ACC), Lane Departure Warning (LDW), DAC (Driver Alert Control), Pedestrian Detection and Blind Spot Information System (BLIS). It could be argued that take rates are probably higher among Volvos with AEB (i.e. Volvo XC60) than those without, thus affecting the findings. However, take rates are still relatively low in Sweden, and therefore this was not expected to affect the analysis to any large degree. Future research, however, will need to address this issue.

Data quality also represents a limitation of the present study that needs to be discussed. Police-reported crashes were used, and these are well-known to suffer from a number of quality issues. This aspect was especially important in the case of defining the striking and struck cars for the calculations using the induced-exposure technique. To improve the quality this classification was done manually, based on the description of the crashes made by the police officer at the crash scene. Also, injury severity measures relied on police assessments, which have been previously shown to have limitations [21]. While these are clear limitations, it was assumed that these aspects would equally affect both the AEB and non-AEB groups, and therefore it was not expected to affect the analysis to any large degree.

A further limitation of the present analysis was that the available material was limited. Future research should address this issue, perhaps by merging crash data from several countries, as previously done in other studies [22]. It should be also noted that the present method could not separate the crash avoidance effects of low-speed AEB from the injury-mitigating benefits. While the overall reductions of striking rear-end crashes were impressive, it was not possible to estimate how many collisions did not occur at all, and how many did occur although at such low speeds that no injuries were police-reported. Therefore, it is recommended that future research should attempt to isolate the injury-mitigating effects of low-speed AEB, possibly with a matched pairs approach.

In conclusion, even though there are several factors that could influence the findings of the present study, the benefits found were large. The more noise there is in the data material the lower effectiveness will be found [23]; therefore, there is reason to believe that the true effect of low-speed AEB may be even larger than those presented in the present paper.

V. CONCLUSIONS

- The positive effect of low-speed AEB in reducing striking rear-end crashes in speed areas up to 50 km/h was statistically significant and ranged from 54% to 57%.
- The overall reduction (regardless of speed areas) of striking rear-end crashes was statistically significant and ranged from 35% to 41%.
- It can be concluded that the effectiveness of AEB in low-speed crashes is very large, thus showing that it is one of the most important systems to address whiplash-associated disorders. The potential for other AEB systems aimed at higher speed and other impact types seems very promising and should be evaluated as soon as possible.

VI. ACKNOWLEDGMENTS

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VIII. APPENDIX

TABLE A

NUMBER OF REAR-END AND CROSSING CRASHES INVOLVING VOLVO CARS WITH AEB

	rear-end	crossing
Volvo S60/V60 10-	30	25
Volvo S80 12-	0	0
Volvo V40 12-	3	2
Volvo V70 12-	33	16
Volvo XC60 08-	20	17
Volvo XC70 12-	8	8
Total	94	68

TABLE B

NUMBER OF REAR-END AND CROSSING CRASHES INVOLVING VOLVO CARS WITHOUT AEB

	rear-end	crossing
Volvo S60 06-09	10	16
Volvo S80 07-11	19	22
Volvo V70 07-11	175	129
Volvo XC70 07-11	23	34
Volvo XC90 06-	10	4
Total	237	205

TABLE C

NUMBER OF REAR-END AND CROSSING CRASHES INVOLVING NON-VOLVO CARS WITHOUT AEB

	rear-end	crossing
Audi A6 11-	12	7
Audi Q5 09-	15	8
BMW 3 Series 09-12	37	17
BMW 5 Series 10-	24	12
Ford Kuga 08-	3	1
Ford Mondeo 10-	3	7
Hyundai IX35 10-	4	5
Kia Sportage 11-	1	5
Mercedes E-Class 09-	23	19
Nissan Qashqai 07-	27	20
Opel Insignia 09-	3	5

Skoda Superb 09-	12	15
Toyota Avensis 09-	18	11
Toyota RAV4 08-	2	6
VW Passat 08-	137	81
VW Tiguan 08-	15	13
Total	336	232

TABLE D

NUMBER OF STRIKING AND STRUCK REAR-END CRASHES USED IN THE CALCULATIONS, PER SPEED AREA

	≤50 km/h		60-70 km/h		≥80 km/h		>50 km/h		All speed areas	
	striking	struck	striking	struck	striking	struck	striking	struck	striking	struck
AEB Volvos	10	24	9	15	16	20	25	35	35	59
non-AEB Volvos	49	51	31	30	35	33	66	63	115	114
non-AEB others	73	81	36	39	51	56	87	95	160	176

TABLE E

NUMBER OF STRIKING REAR-END AND CROSSING CRASHES USED IN THE CALCULATIONS, PER SPEED AREA

	≤50 km/h		60-70 km/h		≥80 km/h		>50 km/h		All speed areas	
	striking	crossing	striking	crossing	striking	crossing	striking	crossing	striking	crossing
AEB Volvos	10	45	9	16	16	7	25	23	35	68
non-AEB Volvos	49	152	31	41	35	12	66	53	115	205
non-AEB others	73	165	36	47	51	20	87	67	160	232