Head-on collisions between passenger cars and heavy goods vehicles: Injury risk functions and benefits of Autonomous Emergency Braking.

Johan Strandroth, Matteo Rizzi, Anders Kullgren, Claes Tingvall

Abstract This study focuses on frontal crashes between passenger cars and heavy goods vehicles (HGV) in Sweden. The objectives are to estimate how risk for moderate and severe injuries (MAIS2+) for passenger car occupants correlates with change of velocity (delta v) in this type of crashes and to estimate the potential benefits of Autonomous Emergency Braking (AEB) on HGV and passenger cars in reducing injury risk.

First risk curves were derived from Crash Pulse Recorder data from 85 real-world frontal collisions between passenger cars and HGV including 133 front seat occupants with AIS-coded injuries. Secondly, a case-by-case analysis was performed using 70 in-depth studies of fatal crashes collected by the Swedish Transport Administration. The possible additional braking time and impact speed reduction with AEB was calculated. Finally, the calculated speed reduction with AEB was applied on the derived risk functions in order to estimate the injury reduction.

Results showed that with a given delta v the injury risk for car occupants was higher in frontal collisions with HGV than in similar collisions with another passenger car. AEB activated on HGV and passenger cars in frontal collisions could possibly reduce the closing velocity by approximately 30 km/h on average, which would result in a 73% reduction of MAIS2+ injuries on the passenger car occupants.

Keywords Autonomous braking; CPR; Delta v; Heavy Goods Vehicle

I. INTRODUCTION

Strategies for improved road safety in Sweden have over the last decade been based on a model for a safe road transport system [1]. This model has been validated both regarding fatal and severe crashes and has proved to be a good predictor of how to create a safe system [2]. However there are some exceptions, especially regarding Heavy Goods Vehicles (HGV). The model allows a road to be defined as safe without median barrier if the speed limit is 80 km/h or lower. This has been found to be true for head-on collisions with car-to-car collisions, however not in car-to-HGV collisions [2]. Even in lower speeds, these collisions have a high severity outcome [3]. Hence, great challenges remain to include HGV in a safe system. While great improvements have been made in the road environment, it will not be possible to address all car-to-HGV crashes with infrastructural measures. Therefore more responsibility has to be placed on vehicle safety.

To tackle this and other road safety problems vehicle manufacturers have introduced collision avoidance systems both on passenger cars as well as on HGV. One example is Electronic Stability Control (ESC) that targets loss-of-control scenarios and has been found to reduce severe crashes on low-friction surfaces by 38 percent [4]. Other systems to avoid head-on collisions are Lane Keeping Assist (LKA) that supports the driver by warning or active steering to keep the car within its lane [5]. Systems like Autonomous Emergency Braking (AEB) that reduce the impact speed in order to avoid or mitigate a collision have also been introduced. There are a number of AEB systems on the market. So far, they are mainly focusing on car-to-pedestrian crashes and rear-end collisions and not yet on on-coming traffic [6]. So far, not much is to be found in the literature regarding real world benefits from AEB. However, case studies suggest a 24 percent reduction in pedestrian fatalities with Full Auto Brake and Pedestrian Detection [7]. In terms of AEB and rear-end collisions simulation studies have indicated a 40 percent reduction of impact severity [8] and a study from IIHS (Insurance Institute for Highway Safety) indicates a 51 percent reduction in claim frequency for bodily injury liability for cars fitted with the Volvo

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City Safety system aiming at mitigating low speed rear-end crashes [9]. Gabler [10] estimated that autonomous braking could potentially reduce the number of injured drivers who are belted by 19% to 57%.

Now, dealing with head-on crashes it is not obvious if the preferred way of avoidance and mitigation is braking or steering. Naturally this depends on the circumstances and characteristics in the chain of events leading to a crash. Brännström et al [11] concluded that braking is the preferred way of collision avoidance in lower speeds (typically in front to rear-end scenarios) while steering is preferred in high speeds (typically in on-coming scenarios). However, it could be noted that even after passing that moment in the accident sequence when the collision is unavoidable, there is still time for collision mitigation by braking [11].

When estimating the benefits of a pre-production safety system there are a couple of possible alternatives. One is the dose-response model that has successfully been used to study the effectiveness of systems aimed at mitigating crash severity. Dose in this model represents the input, in terms of impact severity, and the response is the injury outcome. The link deciding the response of the dose is the injury risk functions, where the risk for injury depending on delta v is illustrated [12]. Risk functions have been developed based on Crash Pulse Recorder data (CPR) and GIDAS data for e.g. car to pedestrian crashes as well as frontal and rear car-to-car collisions [12], [13], [14]. However, there is not much to find in the literature regarding risk curves on passenger cars in collisions with HGV.

The injury outcome in car collisions could be reduced in several ways. In general three ways are possible; (1) reduced number of crashes, (2) reduced injury risk (3) and/or reduced delta v [12]. The latter variant is illustrated in Fig. 1 below by shifting the exposure to the left and keeping the injury risk constant.

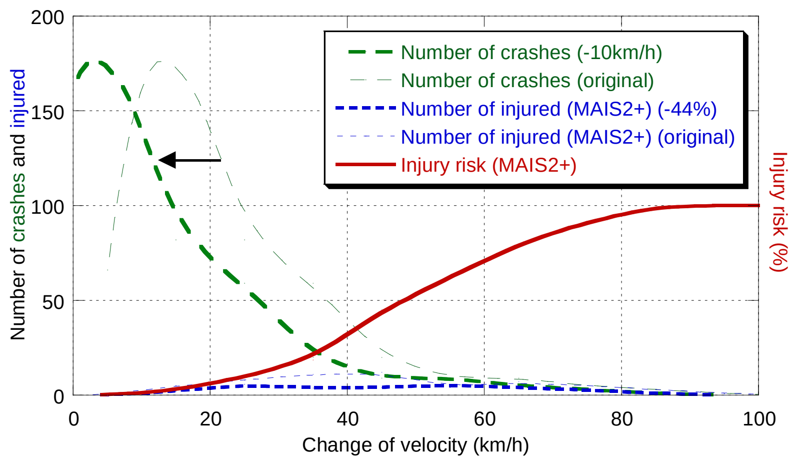

Fig. 1. Reduction in injured occupant due to reduced delta v [12].

Objective

New solutions addressing head-on collisions involving HGV need to be presented in order to include them in a safe road transport system. There could be a great potential for injury mitigation by braking when it is too late to steer to avoid a collision. For that reason *this study aims to estimate the benefit of AEB in reducing injuries in head-on collisions between passenger cars and HGV*. Since injury risk functions are a key factor in estimating the effectiveness of AEB, an additional objective is to *estimate how risk for severe injuries correlate with change of velocity in these crashes*.

II. METHODS

When estimating the effects of driver assistance systems there are a number of possible approaches. One that has proven to be feasible for pre-production systems is to use in-depth cases to investigate what type of crashes could be avoided or mitigated with a system with certain functionality. In-depth cases could also be used to gather detailed information about the crash sequence used in the benefit estimation. Crash data are used to find the exposure and risk functions to calculate the new reduced injury outcome. This principle for system benefit estimation which is commonly used is rather elementary and is described in Fig. 2 [10], [15]-[17].

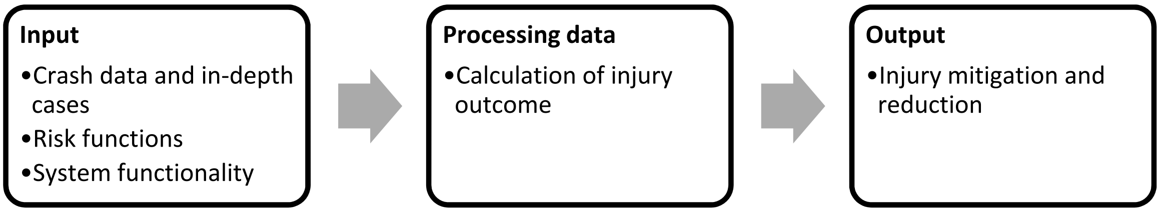

Fig. 2. Schematic description of method for estimating safety system benefits.

System functionality

In some studies using this method, the system functionality could be described in detail due to already developed algorithms and knowledge about the system components. In this present study, however, the system functionality is not yet available in detail and assumptions have to be made regarding system performance. The intended function of the AEB is to apply full braking on HGV, and, sometimes also on the passenger car, to mitigate frontal collisions with oncoming passenger cars. Activation of the AEB should occur when an oncoming passenger car approaches in the HGV's driving direction and when the collision is unavoidable, that is, at the minimum time to avoid the crash by steering (T_{steer}) [7], [11], [18]. Performance of the system is given by some system parameters, e.g. *sensor range*, *object identification time*, *activation time*, *system response time* and *acceleration level*. However, in a pre-production system like AEB for oncoming traffic some of these parameters are unknown. While reasonable assumptions with the help of the literature could be made regarding system response time (~0.2 s), sensor range (~150 m) and acceleration level (~8.0 m/s^2), it is more challenging to make assumptions of the algorithms controlling object identification [18], [11]. In this study the assumption is therefore made that the system is able to detect and identify an oncoming vehicle when it has passed the road markings in the middle of the road.

Crash data and in-depth cases

To find the distribution of injuries over delta v Crash Pulse Recorder (CPR) data from real world crashes was used. Approximately 240,000 CPRs have been fitted by Folksam in over twenty different passenger car models since 1992. The CPR measures change of velocity and acceleration in real-world crashes. In this study 85 head-on collisions with HGV and passenger cars were sorted out resulting in 113 car passengers with coded injuries (Table 1). Also 423 injuries from car passengers involved in 163 head-on collisions between passenger cars were used as reference.

TABLE I

	No. crashes	No. injuries	No. MAIS2+
Head-on with HGV	85	133	11
Head-on with pass. cars	163	423	55

The injuries from car-HGV crashes are distributed with regards to delta v according to Fig. 3.

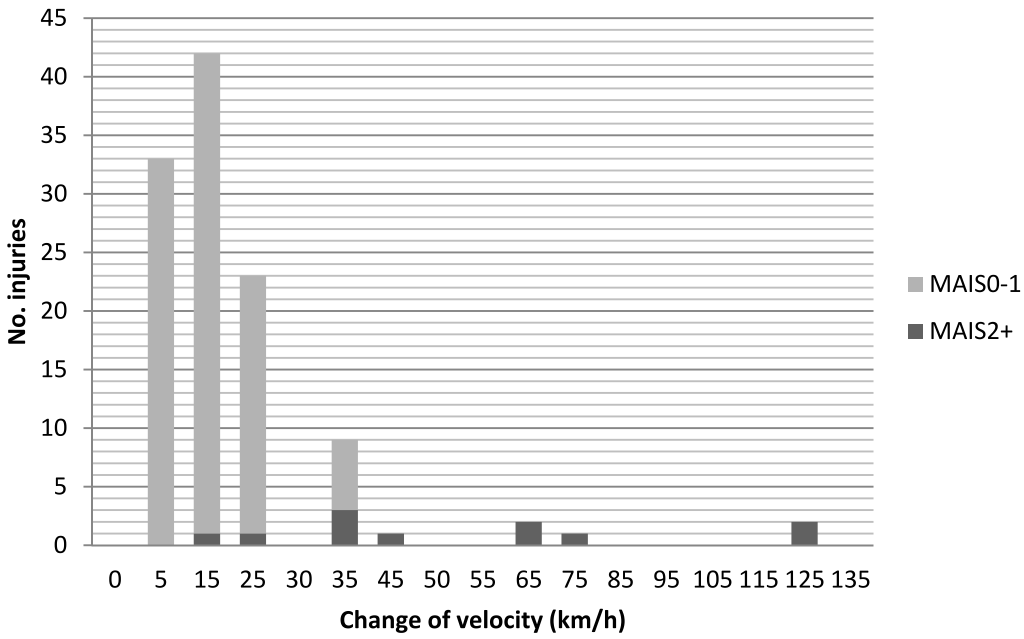

Fig. 3. Injury exposure in head-on collisions involving HGV and passenger cars.

To further investigate the accident scenario with head-on collisions involving HGV and passenger cars, and to collect the parameters needed for the benefit estimation, in-depth investigations of every fatal crash 2006-2007 (n=70) collected by the Swedish Transport Administration (STA) were analyzed. STA has been carrying out in-depth studies for each fatal road crash since 1997. Crash investigators at STA systematically inspect the vehicles involved in fatal crashes and record direction of impact, vehicular intrusion, seat belt use, airbag deployment, tire properties, etc. The crash site is also inspected to investigate road characteristics, collision objects, etc. Further information about injuries is provided by forensic examinations, questioning and witness statements from the police and reports from the emergency services.

Focus of the analysis was to investigate in which type of scenarios AEB, with the functionality described earlier, would work and their potential to mitigate the injury outcome. Comparisons between the STA in-depth studies and Folksam CPR-data were made according to direction of force, loss of control scenarios, offset and road type. The reason not to use only in-depth data from STA in the benefit estimation is that it contains only fatal accidents and that the information of delta v is rather limited.

The STRADA database (Swedish Traffic Accident Data Acquisition) is the base for the national statistics and is used in this study to find the potential benefits of the system in reducing relevant injuries in Sweden i.e. how many car passengers per year get a MAIS2+ injury in head-on collisions with a HGV.

Risk functions

The Folksam CPR data, earlier described in this study, with known delta v and coded injuries are used for deriving the risk curves in a similar way that has been done by Kullgren (2008) [12]. No mathematical injury risk functions were calculated. Instead the empirical injury risk was plotted and calculated as the proportion of injured occupants in intervals of change of velocity. To illustrate the shape of the injury risk versus impact severity, “smooth curve fits” in the software Kaleidagraph (2000) were used to connect the observations.

Calculation of speed reduction and injury outcome

Calculation of injury outcome is done through the exposure multiplied by the risk of injury, given by the risk function. To calculate injury reduction, this study used reduced delta v by reducing the impact speed through braking; that is, shifting the exposure curve in Fig. 1 to the left. In order to estimate how far to the left the curve could be shifted, the potential average speed reduction had to be calculated. This was done by in-depth analysis of fatal crashes where it was possible to simulate a scenario with AEB applied to real-life situations in order to find the potential speed reduction by AEB for every case.

First the potential extra brake distance with AEB was estimated. This was done by comparing the brake distance given by T_{steer} and other circumstances where T_{steer} is the minimum time to steer to avoid the crash. As mentioned, AEB should only be applied when it is no longer possible to avoid the collision by intervention from the driver or autonomous steering. T_{steer} then is a function of relative speed, lateral position and width of the vehicles and varies with collision type. In rear-end collisions, for example, as seen in Fig. 4, collision avoidance is a function of speed where braking is preferred in lower speeds and steering in higher speeds. Also T_{steer} is a function of speed, i.e. host vehicle speed. However, in on-coming collisions (Fig. 5) steering is always preferred for crash avoidance and braking only for mitigation. T_{steer} is also rather constant for host vehicle speed above 40 km/h. Hence, for this study dealing with head-on collisions mainly on rural roads, T_{steer} was set as a constant of 1.2 s (where 0.2 s is the brake system ramp-up time) [11].

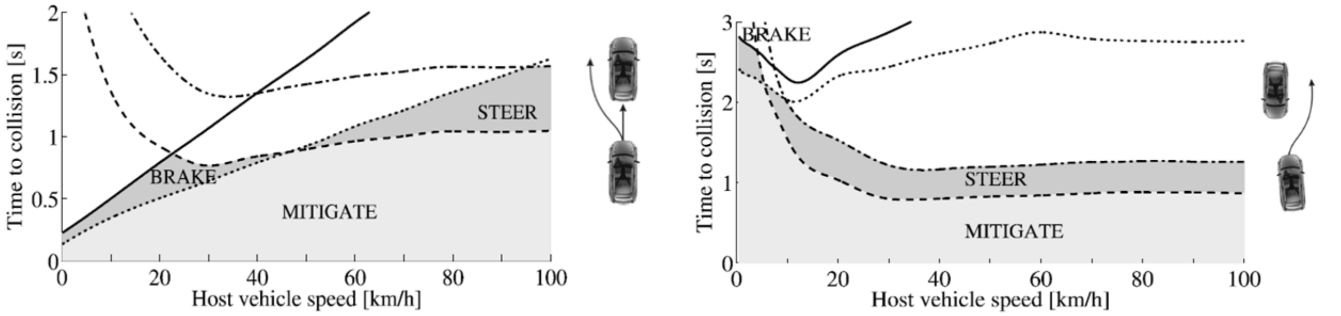

Fig. 4 and 5. Intervention criteria in rear-end and oncoming accidents as described in Brännström et al. [11]. The dotted line represents the latest time to initiate AEB for collision avoidance by braking and the dashed line the latest time to steer to avoid collision.

However, the circumstances in a crash do not always allow for 1.2 s of braking. The extra potential braking time by AEB was also determined by braking actions already taken by the drivers and also by when the oncoming vehicle passed the road markings in the middle of the road, e.g. lane departure. If this happened within the 1.2 s, the time for extra braking with AEB is of course shortened. Given this the time *t* with AEB was solved in equation 1 by setting *s(t)=0* at the time of collision:

$$v_{rel}(t) = v_1(t) + v_2(t)$$
$$v_{rel}(t) = v_{01} + v_{02} + \int \big(a_1(t) + a_2(t)\big)dt$$
$$s(t) = s_0 - (v_{01} + v_{02})t + \iint \big(a_1(t) + a_2(t)\big)dt\,dt \quad (1)$$

where v_1 and v_2 is the speed (*m/s*) of the two approaching vehicles, v_0 is initial speed (*m/s*), *a* is acceleration (m/s^2) and *s* is the distance (*m*) between the vehicles (set to 0 at the time of collision).

The circumstances regarding the sequence of events prior to collision also determined whether or not AEB was relevant in each case and if it could be applied only on the HGV or also on the oncoming passenger car. Activation of AEB on HGV was in this study assumed to be relevant in all head-on collisions except for when the collision somehow was involving loss-of-control or lane departure of the HGV, e.g. trailer skidding.

It was also assumed that AEB could be activated even on the oncoming passenger car in all cases except for loss-of-control scenarios and when the passenger car driver intentionally steered towards the HGV, e.g. suicide. Given the time for braking *t* by equation 1, the speed reduction v_{red} is given by equation 2:

$$v_{red} = at \quad (2)$$

where *a* is acceleration (or deceleration) (m/s^2) depending on friction coefficient of the road surface.

In these calculations, speed reduction (v_{red}) was considered to be equal to delta v reduction because of the very large weight differences between passenger cars and HGV. For more reading about decision making and braking prior to collision, see Lindman and Tivesten [16] and Brännström et al [11].

The output of the calculations was expressed in terms of MAIS2+ reduction in head-on collisions due to reduced impact speed as a result of AEB on HGV. The potential of the system in number of reduced MAIS2+ injuries in Sweden per year was also calculated by applying the potential reduction to national statistics.

In summary, the method could be described as follows:

1. Analyze in-depth data to find the possible closing speed and delta v reduction with AEB with a given functionality
2. Apply this delta v reduction to the exposure CPR-data (shifting the exposure to the left in Fig. 1)
3. Calculate the injury reduction based on the derived risk curve
4. Estimate the reduced number of severe accidents per year in Sweden through national statistics

III. RESULTS

Accident data and in-depth cases

The in-depth studies from STA were found to have all information needed to make the benefit estimations. In some cases it was found to be a challenge to judge the distance between the on-coming vehicles at the time of lane departure. However, in those cases conservative estimations were made. Also the Folksam data was found to match the data from the in-depth studies with good precision. One exception was the distribution of accidents by urban/rural areas, where the Folksam data had a larger share of crashes in urban areas.

Injury risk functions

Injury risk functions were derived regarding car occupants in collision with HGV, but also in collision with passenger cars for comparison (Fig. 6). Regarding the risk function relating to car-to-car crashes it seems to match the functions found in earlier studies based on larger data samples [12]. Comparing the two functions in Fig. 6 it was noted that for the same delta v the risk for suffering an MAIS2+ injury is higher for passenger car occupants in collision with HVG. For a delta v of 40 km/h the increased risk in a HGV collision is approximately 20%.

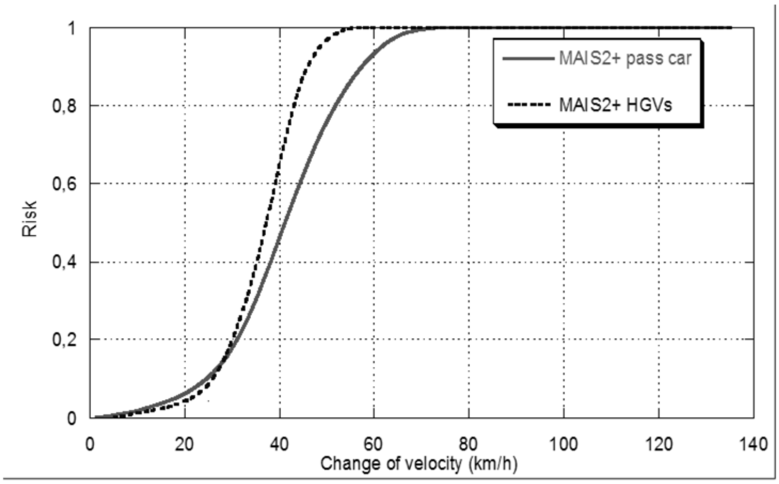

Fig. 6. Risk of MAIS2+ in the passenger car in car-to-car crashes (solid line) and car-to-HGV crashes (dashed).

Injury reduction

The analysis of in-depth studies found that in 64 out of 70 cases AEB would be relevant to activate on the HGV in order to mitigate the injury outcome. On average the potential extra braking time was 0.73 s, with a minimum of 0.23 s and a maximum of 1.00 s. However, the potential time with AEB differs with accident scenario as seen in Table II. For loss-of-control scenarios (LOC) such as over-steer and under-steer, the average time was 0.49 s while for non-LOC it was 0.77.

TABLE II

Accident scenario	*N*	*Average time for braking (s)*
Over-steer	8	0.50
Under-steer	3	0.45
Unintentional lane departure	43	0.77
Intentional lane departure (suicide)	16	0.76
All	70	0.73

In 40 cases the accident scenario allowed for AEB to be applied also on the passenger car. This results in an average speed reduction of 18 km/h with braking only on the HGV and 30 km/h with braking also on the passenger car where it was possible. By shifting the exposure curve 18 and 30 km/h to the left a new injury distribution was obtained. This new distribution gave a MAIS2+ injury reduction of 73 percent with 30 km/h with braking on both HGV and passenger cars, and 52 percent with 18 km/h delta v reduction with AEB only on the HGV (Table 3).

TABLE III

Effect on MAIS2+	*%*
with AEB only on HGV	-52
with AEB on HGV and pass. cars	-73

When applying these effects on national statistics it would mean a reduction of approximately 52 and 73 MAIS2+ injuries per year in Sweden. The total number of MAIS2+ in car-to-HGV-crashes per year in Sweden is around 100 which correspond to around 10 percent of all MAIS2+ in passenger cars. Hence, the effect of AEB would correspond to a total reduction of 4 and 6 percent respectively of all MAIS2+ injuries in passenger cars occurring in Sweden per year.

IV. DISCUSSION

In the design of a safe road transport system incompatibility is always a challenge. That becomes most apparent when dealing with HGV which due to their great mass cause severe damage to their collision partners. Head-on collisions involving HGV have for several decades been a major contributor to fatal and severe accidents in Sweden. As approximately 90 percent of these crashes start with a lane departure by the on-coming vehicle, ESC on passenger cars and median barriers has over the latest decade been effective in reducing the amount of severe accidents. However, it is not possible to build median barriers everywhere and there will always be accident scenarios in which the avoidance technologies are not enough to bring the vehicles from a critical event back to normal driving. Given those conclusions, it is of great interest to investigate the benefit of autonomous emergency braking the last second before collision when the crash is unavoidable.

In this study in-depth investigations of fatal crashes were analyzed in order to investigate the potential for extra braking with AEB in real-life scenarios. Both the Folksam CPR-data and the STA in-depth studies of fatal crashes were found to be very suitable for this type of study, even though the number of recorded car-to-HGV crashes was fairly low which gave a limited number of MAIS2+ injuries to derive the risk curve.

One disadvantage could be the subjectivity when conclusions are to be drawn from in-depth studies. The most difficult point was without question to judge the initial distance between the on-coming vehicles when one of them did a lane departure. In order to improve the estimations two persons investigated each crash separately and difficult cases were discussed in a consensus group.

The in-depth analysis showed that in 64 out of 70 fatal accidents (91 %) AEB would be relevant to apply on the HGV. In 40 cases (57 %) it would be relevant to apply AEB both on the HGV and the on-coming passenger car. AEB would thus add on average 0.7 s of extra braking time which would give on average 18 km/h and 30 km/h of impact speed respectively. *This supports the conclusion that AEB is relevant in most on-coming scenarios and has a great potential in closing speed reduction*. The potential in closing speed reduction is though highly dependent on the functionality of the system. For instance, sensor range and the possibility of the system algorithm to determine when a collision is unavoidable would be two factors with significant influence on the effectiveness of the system. Other AEB systems, with other characteristics than the one described in this study, would naturally have a different average speed reduction. Thus, the speed reduction calculated in the present study should be treated with some caution.

This study shows that the time available for emergency braking highly depends on the type of accident scenario, e.g. loss of control (LOC) as under-steer and over-steer, drifting or conscious steering. The difference in available time for braking ranges from 0.49 s in a LOC-scenario compared to 0.77 s in non-LOC. The accident scenario then is highly dependent on the presence of ESC according to previous studies [4]. Naturally many of the crashes in this study will in the future have a different accident scenario and therefore the overall potential for AEB will change in the future when vehicles are equipped with other kinds of avoidance technology than that available today. Therefore, knowledge of the characteristics of the future transport system will be of great importance. Therefore in the prediction of impact of safety technology it will not be sufficient to use only retrospective data.

It should also be noted that AEB has a larger potential in delta v reduction in car-to-HGV crashes than in car-to-car crashes. This is due to the fact that closing speed reduction in car-to-HGV collisions would automatically lead to almost the same delta v reduction due to the large weight differences whereas in a car-to-car crash, the impact speed reduction on one vehicle would only correspond to a delta v reduction by half, given equal masses of the cars. Thus, AEB is of special importance in collisions between vehicles with large weight differences. Other differences with car-to-HGV frontal crashes compared to car-to-car crashes are that T_{steer} is slightly higher in car-to-HGV crashes. That is due to the wider front of a truck that requires more time for steering to avoid the crash. Thus, in car-to-HGV frontal crashes AEB could be activated earlier than in a car-to-car frontal crash.

The link between the impact speed reduction and injury outcome is the risk function which in this study was derived from the Folksam CPR-data. By applying the 18 and 30 km/h impact speed reduction on the risk curve in Fig. 6, a 52 and 73 percent reduction of MAIS2+ injuries was realized. Since the number of MAIS2+ injuries used to calculate the risk curve was rather limited, one can assume some uncertainty in the shape of the curve. However, this was the first time the injury risk correlation to delta v in car-to-HGV crashes was illustrated and it is probably better to use this curve than the previous ones derived from car-to-car crashes.

It is also logical that the risk for injury is higher for a given delta v when colliding with an HGV. Earlier studies have shown that these collisions have a higher mean acceleration [19] which has been proved to be a good predictor of injury outcome [20]. Risk curves for car passengers in collisions with HGV are something that could be of importance in further research.

Another confounding factor could be the correlation between the Folksam CPR-data with known delta v and the STA in-depth studies. Since the CPR-data are collected from crashes that are more frequent in urban areas, the effect on injury reduction could be overestimated. If the real injury distribution correlating to the fatal accidents has a higher delta v on average than the CPR-data, the distribution would still be shifted to the left as much as before (Fig. 1), however on another part of the risk curve and maybe with a different power. However, it is not likely that the real distribution would differ to the extent that the power would change dramatically. In any case, it can be concluded that applying an 18 or 30 km/h closing speed reduction on any risk curve would have an enormous effect on injury reduction. The closing speed reduction will most probably also have large effects on fatality reduction since the power of the fatality risk curve is even steeper with a power of approximately 3.5 [21].

Even if this study focused on on-coming scenarios with passenger cars and HGV, the principle results could of course be applied to other accident scenarios in the future. That could make the overall potential of AEB even higher. The most important finding though is that AEB could have a real benefit in reducing injuries. Therefore, it should be included as the last action in the chain of events leading to a crash. Even if steering or other maneuvers are preferred for accident avoidance, there is always a reason for braking just prior to the crash. It is also evident that by optimal use of that last second prior to the crash, there are great safety improvements to gain. For example, if it would be possible to decelerate more than 1G, the benefit of braking could increase even more.

V. CONCLUSIONS

- The average potential time with Autonomous Emergency Braking (AEB) in car-to-HGV frontal crashes is 0.7 s on average, but ranges from 0.45-0.77 s depending on the accident scenario.
- AEB on HGVs would possibly reduce the closing speed in head-on collisions between passenger cars and HGVs with approximately 18 km/h.
- If AEB also would be applied on the passenger car, the possible closing speed reduction would be approximately 30 km/h.
- The corresponding potential reduction of MAIS2+ injuries would be 52-73 percent in head-on crashes.

VI. ACKNOLEDGEMENTS

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