Autonomous Emergency Braking for Vulnerable Road Users

Erik Rosén

Abstract A simple, but realistic, model of an autonomous emergency brake (AEB) system was studied. Using Matlab, the model was applied to 543 car-to-pedestrian and 607 car-to-bicyclist real-world collisions gathered from the highly detailed German In-Depth Accident Study Pre-Crash Matrix (GIDAS PCM) and weighted for representativeness. All collisions were to the front of the car. The aim was to investigate how AEB performance was influenced by varying some of the most relevant system parameters. A reference system was predicted to provide very high effectiveness in saving lives and mitigating severe injuries. However, the effectiveness was substantially impaired by imposing restrictions on functionality in darkness and high speeds. Further, effectiveness was highly sensitive to timing of brake activation and deceleration provided by the AEB system. Combining all these restrictions (darkness, high speed, timing and deceleration) led to a tenfold decrease of effectiveness compared to the reference system.

Keywords AEB, bicyclists, effectiveness, pedestrians, real-life

I. INTRODUCTION

A rapid development of pedestrian safety is in progress. With forward-looking sensor systems entering the vehicle fleet, the possibility to detect pedestrians in advance opens new possibilities to injury mitigation. Due to the sharp increase of injury risk with impact speed [1-3], autonomous emergency braking (AEB) based on forward-looking sensor systems has been predicted to offer a considerable reduction of pedestrian injuries [4-8]. Combining autonomous braking with driver warning or even autonomous emergency steering could increase the effectiveness further. Both driver warning and AEB systems are already available on the market. Test methods for such active safety systems are developing and will be implemented in consumer rating tests in the near future. For example, AEB for pedestrians will be tested by Euro NCAP from 2016.

Unwanted activations are an important aspect of AEB systems. Such activations could annoy and even pose a threat to car occupants. Hence, in order to limit the negative effects of unwanted activations, AEB will necessarily be limited in time and/or deceleration level. Further, some systems may have limited or no functionality in darkness and high speeds. With close to 50% of pedestrian fatalities occurring at impact speeds above 60 km/h [1, 2] and nearly 60% occurring in the night, dusk and dawn [9], these are important constraints. The importance of functionality in darkness and at high speeds for AEB systems was also pointed out in [6].

The aim of this paper was to study how such system parameters influence real-life effectiveness. Effectiveness was measured in terms of real-life reduction of fatalities and severe injuries defined as AIS3+F [10]. Frontal car-to-pedestrian and car-to-bicyclist collisions were studied in parallel, using the same AEB system. The data source was GIDAS Pre Crash Matrix (PCM), which is a rather novel extension of the well-known GIDAS database of real-life accidents [11]. In PCM, the final five seconds prior to collision are described in high detail including estimates of trajectories, velocities, accelerations, road layout, obstructing objects and tyre-to-road friction.

II. DATA

GIDAS data released January 2013 and GIDAS PCM version "20130218_GIDAS_PCM_2.1_2012_1" were used.

Weight factors

The GIDAS accident investigation teams operate in Dresden, Hanover and surroundings. The work shifts for the teams are specified by a statistically developed sampling plan and cover half the hours of each day and night [12, 13]. However, if a crash occurs within these regions but police suspect no injuries, GIDAS is not contacted. In these cases, possible pedestrian injuries would later be reported to the police. This phenomenon leads to an over-representation of severe and fatal accidents in GIDAS [13]. We compensated for this by considering

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German national statistics on road traffic accidents [14]. The inclusion criteria were similar for GIDAS and the national statistics. To weight the GIDAS data, we made explicit use of a police coded variable that was available in both data sets, which classified each person as uninjured, slightly injured, severely injured or fatally injured. The maximum injury severity in each accident was considered. By matching the proportions of “slight,” “severe” and “fatal” accidents in GIDAS (not only accidents with VRUs) to the corresponding national proportions from 1999 to 2012, weight factors were derived (see Table 1).

TABLE I
DERIVATION OF WEIGHT FACTORS FOR THE GIDAS DATABASE

	Fatal	Severe	Slight
GIDAS (1999–2012)	2.47%	28.0%	69.5%
National (1999–2012)	1.50%	20.4%	78.1%
Relative proportion	0.607	0.729	1.12
Relative weight	1.0	1.2	1.9

Darkness

For each accident, the GIDAS team at the accident scene makes a judgment whether the sun was up (day), setting (dusk), rising (dawn) or down (night). In this study, darkness was defined as night, dusk, and dawn according to the GIDAS coding. This means that an accident that occurred at night on a street with artificial lighting would be considered as darkness.

GIDAS PCM

Each accident in the GIDAS database is investigated on-scene when the involved participants are still available together with brake marks, vehicle end-positions and other evidence. Based on the collected information, each crash is reconstructed to generate estimates, for example, of car travel speed, driver braking and steering maneuvers, and car collision speed. Finally, a scaled sketch with estimated trajectories of car and VRU is drawn (see e.g. [2]). Recently, a subset of GIDAS accidents were re-analyzed (by GIDAS’ own experts) to provide a detailed and quantitative description of the trajectories (including velocities and accelerations) of both car and VRU during the final seconds prior to collision [11]. The cases in GIDAS PCM were selected to constitute a representative subset of the GIDAS database. The data are provided 100 times per second (100 Hz) and given for a time span of 5 s before the impact (but the first two seconds should only be used to initialize software for vehicle dynamics). Furthermore, exact locations of non-moving, obstructing objects are given, including standing vehicles in traffic. This extended database is called GIDAS PCM.

In GIDAS PCM, both cars and VRUs were modeled as rectangular objects. Exact car dimensions were available in each case. However, pedestrian rectangles had the size 0.8x0.5 m and cyclist rectangles 0.58x1.74 m, with the front of the VRU corresponding to the first side.

Pedestrian sample

The GIDAS database included 2467 pedestrians with recorded injuries that were involved in a road traffic collision between 1999 and 2012. Restricting the count to pedestrians that were struck once by a car, convertible, van or off-road vehicle this number decreased to 1843. Sixty-three percent of these were struck by the front of the vehicle, which included 86% of the fatalities and 76% of the AIS3+F injured pedestrians. Thus, restricting the sample to frontal collisions reduced the number of cases to 1347, of which 56/209 had fatal/AIS3+F injuries. In this sample, 28%/48%/24% were in the ages 0–14/15–59/60+ years, respectively. Further, there were 50% females and 50% males.

Of the 1347 frontal car-to-pedestrian collisions in GIDAS, detailed pre-crash data were available in GIDAS PCM for 543 cases, thus constituting our sample for analysis. This sample included 30/104 pedestrians with fatal/AIS3+F injuries. The sample included 38% accidents in darkness, of which two thirds were at night and one third at dusk or dawn. See Figure 1a for distribution of car impact speed.

Bicyclist sample

The GIDAS database included 5492 bicyclists with recorded injuries that were involved in a road traffic collision with one other vehicle (including other bicyclists) between 1999 and 2012. Restricting the count to bicyclists that were struck by a car, convertible, van or off-road vehicle this number decreased to 4274. Sixty-five percent of these were struck by the front of the vehicle, which included 85% of the fatalities and 77% of the AIS3+F injured bicyclists. Thus, restricting the sample to frontal collisions reduced the number of cases to 2761 of which 22/152 fatal/AIS3+F injuries. In this sample, 12%/68%/19% were in the ages 0–14/15–59/60+ years, respectively. Further, there were 45% females and 55% males.

Of the 2761 frontal car-to-bicyclist collisions in GIDAS, detailed pre-crash data were available in GIDAS PCM for 607 cases, thus constituting our sample for analysis. This sample included 8/43 bicyclists with fatal/AIS3+F injuries.

Further, only 2112 of the 2761 accidents had full information on bicyclist injuries, collision speeds of car and bicyclist, as well as bicyclist approach direction. This subset included 17/138 fatally/AIS3+F injured bicyclists and was used for the derivation of injury risk curves (see section III, Injury risk curves).

The sample included 18% accidents in darkness, of which half were at night and half at dusk or dawn. See Figure 1b for distribution of car impact speed.

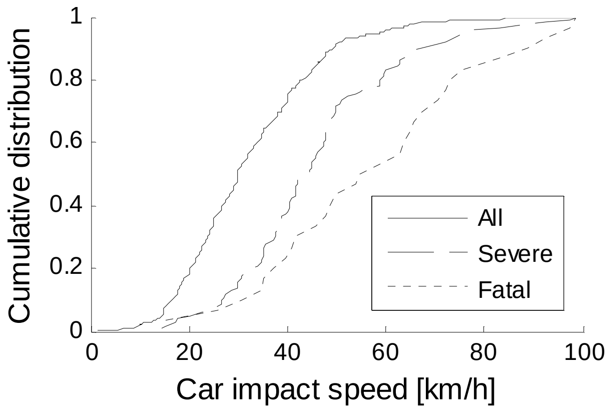

Fig. 1a. Cumulative distribution of car impact speed for pedestrians accidents.

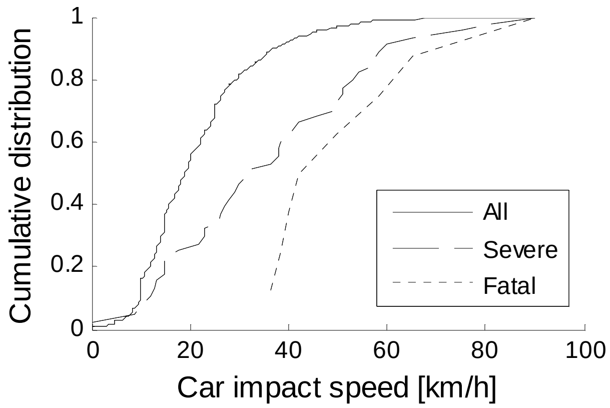

Fig. 1b. Cumulative distribution of car impact speed for bicyclist accidents.

III. METHODS

The autonomous emergency brake system

The autonomous emergency brake (AEB) system consisted of a forward-looking sensor mounted at the rear-view mirror, an electronic control unit and a brake system. The functionality of these devices was described by a number of system parameters. These were selected as reasonable parameter settings in current and future AEB systems. This is further discussed below.

The AEB system was described by the parameters in Table 2. See also Figure 2 and the decision algorithm described below. Values for a reference AEB system are given, as well as tested variations thereof. Note that only the most relevant parameters were varied.

The results of this study will be given for six distinct AEB systems. First, a reference system was defined by the reference value for each of the parameters in Table 2. A max brake/min brake system used the maximum/minimum value for the parameters TTC_{max}, a_{max}, w and FoV. One system used the reference values for all parameters, but was turned off at speeds above 60 km/h. One system used the reference values, but was turned off in darkness. The final system used the minimum brake values, but was also turned off at speeds above 60 km/h and in darkness. See Table 3 for a summary of the six systems.

The specific values of TTC_{max}, a_{max}, w, FoV and v_{max} were chosen according to the following: TTC_{max} is likely to fall within 0.5 to 1.5 s for most systems on the market today and in the years to come. The same is true for a_{max}. The choice of trigger width, w, is likely to depend on the travel speed of the VRU in real systems. Since bicyclists generally travel faster than pedestrians, w would be greater for bicyclists than for pedestrians. However, in this study we wanted to have exactly the same decision algorithms for both types of VRU. The reference and maximum value of w may seem overly large for pedestrians, while being more representative for bicyclists. Note that it only takes 0.9 s for a bicyclist traveling at 20 km/h to acquire a distance of 5 m. In real systems, the specific values of these parameters may of course vary with car travel speed and other relevant input variables. However, in this study we did not want to apply speed dependent parameters. In order to facilitate a trigger width of 5 m for the max brake system, the sensor FoV was increased to 90°. Otherwise, the trigger area would in many cases be outside the FoV. The cut-off speed, v_{max}, was inspired by the Euro NCAP road map [15], which indicated that AEB pedestrian tests will incorporate car travel speeds ranging from 10 to 60 km/h. Finally, the value of a_{driver} was chosen such that today's emergency brake assist systems (commonly referred to as EBA, BA or BAS) would not be activated before the AEB system. This occurs at approximately 0.4*g* in most cars.

TABLE 2
DESCRIPTION OF AEB SYSTEM PARAMETERS

FoV	Sensor field of view **Reference: 40°. Variations: 90°.**
R_{min}, R_{max}	Minimum and maximum range where a VRU could be detected **Reference: R_{min} = 7 m, R_{max} = 60 m. No variations.**
Frame rate	Rate at which images from the sensor is gathered **Reference: 25 Hz. No variations.**
$t_{classification}$	Time from first possible detection of VRU until it had been detected and classified as pedestrian or bicyclist. Only after this time period, AEB could be activated. **Reference: 3 frames = 120 ms. No variations.**
$t_{latency}$	Processing time at each frame **Reference: 1 frame = 40 ms. No variations**
a_{max}	Maximum brake acceleration provided by the AEB system. The acceleration in each particular accident was further constrained by the available tyre-to-road friction. **Reference: 0.7g. Variations: 0.5g, 0.9g.**
t_{ramp}	Ramp-up time from onset of brakes until max brake acceleration was provided **Reference: 300 ms. No variations.**
TTC_{max}	Maximum predicted time to collision, for an unbraked car, when the brake decision was taken. Note that brake onset would occur slightly later due to $t_{latency}$. **Reference: 1.0 s. Variations: 0.5 s, 1.5 s.**
w	Trigger width. The maximum lateral distance from car path to VRU at which braking was activated (see Figure 2 below). **Reference: 1 m. Variations: 0 m, 5 m.**
a_{driver}	AEB was not activated if the driver already braked harder than a_{driver} **Reference: 0.3*g*. No variations.**
v_{max}	Cut-off speed of car, above which AEB was not activated **Reference: unlimited. Variations: 60 km/h.**

TABLE 3
SUMMARY OF THE SIX AEB SYSTEMS UNDER STUDY. DEVIATIONS FROM REFERENCE SYSTEM IN BOLD FACE.

	Max brake	Reference	< 60 km/h	Daylight	Min brake	Minimal
TTC_{max}	**1.5 s**	1.0 s	1.0 s	1.0 s	**0.5 s**	**0.5 s**
w	**5 m**	1 m	1 m	1 m	**0 m**	**0 m**
FoV	**90°**	40°	40°	40°	40°	40°
a_{max}	**0.9*g***	0.7*g*	0.7*g*	0.7*g*	**0.5*g***	**0.5*g***
v_{max}	No limit	No limit	**60 km/h**	No limit	No limit	**60 km/h**
Darkness	Yes	Yes	Yes	**No**	Yes	**No**

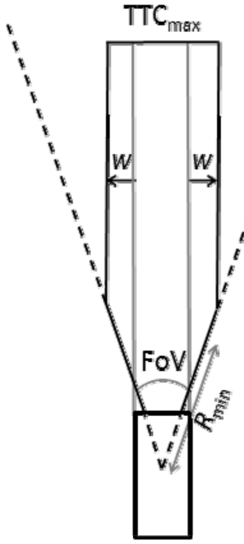

Fig. 2a. Specification of sensor system and parameters for decision algorithm. The area bounded by the solid contour was the trigger area.

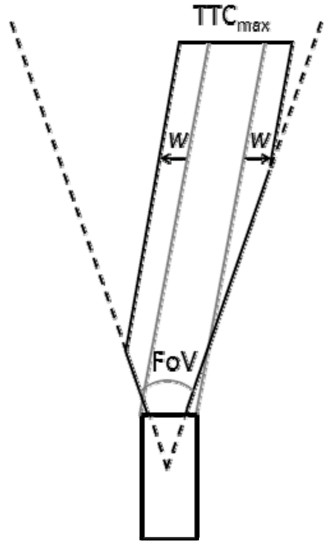

Fig. 2b. When the car turned, the predicted car path was in the momentary direction of travel of the vehicle front.

Decision algorithm

A simple geometric and deterministic decision algorithm was chosen for study, since it was most useful for illustrative purposes. However, conclusions should apply to physical and probabilistic decision algorithms as well (see for example [16, 17] for terminology related to different types of decision algorithms).

The AEB system was activated if, and only if, the following six requirements were satisfied:

1) *VRU visible and within sensor FoV and range during* $t_{classification}$ *(i.e. three consecutive frames)*
2) *Car predicted to collide with VRU*
3) *VRU within trigger width (at least partly)*
4) *Predicted TTC for unbraked car <* TTC_{max}
5) *Driver brake acceleration <* a_{driver}
6) *Car speed <* v_{max}

It can be shown that collision speed as a function of travel speed, v, brake acceleration, a, ramp-up time of brake acceleration, t_{ramp}, TTC at brake decision, and processing time of electronic control unit, t_{latency}, follows from $v_{\text{collision}} = [(v - at_{\text{ramp}})^2 - 2av(\text{TTC} - t_{\text{latency}} - t_{\text{ramp}}) - a^2 t_{\text{ramp}}^2/6]^{1/2}$, where speed is in m/s. (Note that this function provides imaginary numbers when braking to a full stop is possible.) Hence, the reference system was capable of braking to a full stop from travel speeds of nearly 40 km/h. The min brake and max brake systems could brake to a full stop from 11 and 83 km/h respectively.

Matlab implementation

The Matlab implementation of the decision algorithm was slightly different for pedestrians and bicyclists. First, the VRU must have been visible and within sensor FoV and range during $t_{\text{classification}}$. Visibility was calculated for all four pedestrian corners, while center of gravity, CoG, was used for bicyclists for practical reasons. The same holds true when determining if the VRU was within sensor FoV and detection range. Predicted TTC had to be less than TTC_{max} and at least one corner of the VRU had to be within the trigger width, w. Path prediction of ego vehicle and VRU was made as simple as possible by assuming constant linear motion at each particular frame. When the car turned, the predicted car path was in the momentary direction of travel of the vehicle front. Hence, it was still a straight line, but not parallel to the car longitudinal (see Figure 2b). AEB was only activated if the vehicle was predicted to collide with at least one VRU corner (see the decision algorithm above). See Figure 3 for a frame shot from a particular car-to-pedestrian accident in the GIDAS PCM data.

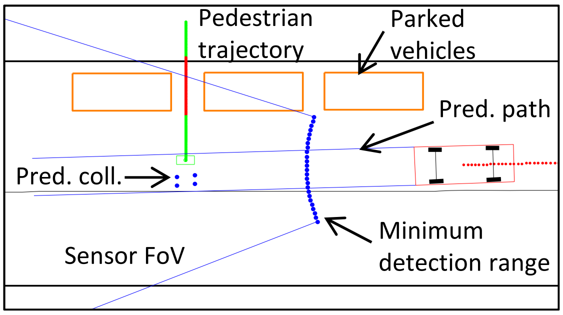

Fig. 3. Annotated frame shot of a car-to-pedestrian accident in GIDAS PCM. The pedestrian trajectory shifts color when the line of sight of the sensor changes from obstructed to unobstructed. The four dots show the predicted collision point for each pedestrian corner.

New impact speeds

Applying the AEB decision algorithm described above to the cases in GIDAS PCM implied the relative position and TTC at brake decision for each single accident. Straightforward classical mechanics then yielded a new impact speed for each accident based on the system parameters $t_{latency}$, t_{ramp}, a_{max} and available tyre-to-road friction. In this process, it was assumed that the car and VRU would both follow their original trajectories also when the AEB system was activated. We referred to the original impact speed as v and the new impact speed as v'. In cases where the driver had braked, the new impact speed was only used in the effectiveness calculations if it was lower than the original impact speed. A detailed description of the general steps of this process is provided in [11].

Injury risk curves

Pedestrian risk curves for fatal and severe injury (AIS3+F) were taken from [2] and [7] respectively: $P_{fatal} = 1/(1+\exp(6.9-0.090v))$, $P_{severe} = 1/(1+\exp(4.6-0.078v))$, where v is the car impact speed in km/h.

New risk curves were derived for bicyclists struck by the front of a car or van using weighted GIDAS data (see Table 1). Weight factors were normalized in this process. Logistic regression analysis was applied in order to derive an analytical expression for the pedestrian fatality risk and risk for severe or fatal injuries (AIS3+F). Various combinations of car impact speed, bicyclist impact speed and bicyclist approach direction were considered as predictors. Model fit investigations were based on Akaike's information criterion [18].

Effectiveness

The system effectiveness in terms of fatality reduction and reduction of severely injured was derived following a standard method applied for example in [7, 20, 21]. New impact speeds, v', (see above) implied reduced risks of fatal and severe injuries. Hence, the reconstruction data and the curve describing how risk varies with impact speed, $P_{fatal}(v)$, made it possible to estimate the effectiveness of the AEB system. The effectiveness was defined as $E=1-N'/N$, where N is the weighted number of fatalities in the sample and N' is the estimated weighted number of fatalities with the AEB system available. The calculations can be mathematically expressed as

$$E = 1 - \sum_{i=1}^{n} \mathrm{P}_{\mathrm{fatal}}(v'_i) w_i \Big/ \sum_{i=1}^{n} \mathrm{P}_{\mathrm{fatal}}(v_i) w_i \tag{1}$$

where n is the number of cases, v_i and v'_i the original and new impact speeds, and w_i the weight factor for the i:th pedestrian or bicyclist. Since the new impact speeds depended on the AEB decision algorithm and parameters described in Tables 2 and 3, so did N' and, hence, the effectiveness. This made it possible to study the effectiveness as a function of system parameters. The same analysis was conducted for severe injury. Weight factors were applied according to Table 1.

Sensitivity analysis – The jackknife

Having a small number of cases with fatal bicyclist accidents was not a direct problem, since the applied method considered the probability of death or severe injury for all cases and added these probabilities. However, having few high speed cases could be a problem, since these cases could then by highly influential due to the sharp increase of risk with speed. To investigate whether there were any highly influential cases in the pedestrian and bicyclist samples, the jackknife method was applied. Thus, one case at the time was left out from the analysis and the effectiveness in Equation (1) was re-calculated. This means that the fatal and severe effectiveness were re-calculated 543 times for the pedestrian sample and 607 times for the bicyclist sample, since they consisted of 543 and 607 cases respectively. If there was any highly influential case, the re-calculated effectiveness would differ substantially from the original estimate based on the full sample. The jackknife analysis was only applied to the reference system.

IV. RESULTS

Injury risk curves

Injury risk curves for pedestrians were available in the literature [2, 7]. However, for bicyclists, new injury risk curves were derived. The fatality risk for bicyclists struck by the front of a passenger car became $P_{\text{fatal}} = 1/(1+\exp(8.8-0.098v))$, where v is the car impact speed in km/h. Note that adding various combinations of bicyclist impact speed and approach direction did not improve the model according to Akaike's information criterion. The slope parameter (0.098) was comparable to that for pedestrians (0.090). However, the intercept was substantially higher, 8.8 compared to 6.9. This resulted in fatality risks that were remarkably low. We stress that further research is needed in order to understand why the fatality risks were so low. Note that in some collisions, the car hit the front or rear wheel of the bicycle but the cyclist only impacted the ground. This may, or may not, be an explanation of the low fatality risks. The risk curve for severe or fatal (AIS3+F) injury became $P_{\text{severe}} = 1/(1+\exp(4.7-0.065v))$. All injury risk curves are shown in Figure 4. Even though fatality risks for pedestrians and bicyclists may seem low at speeds below 50 km/h, there is an exponential increase of risk with impact speed.

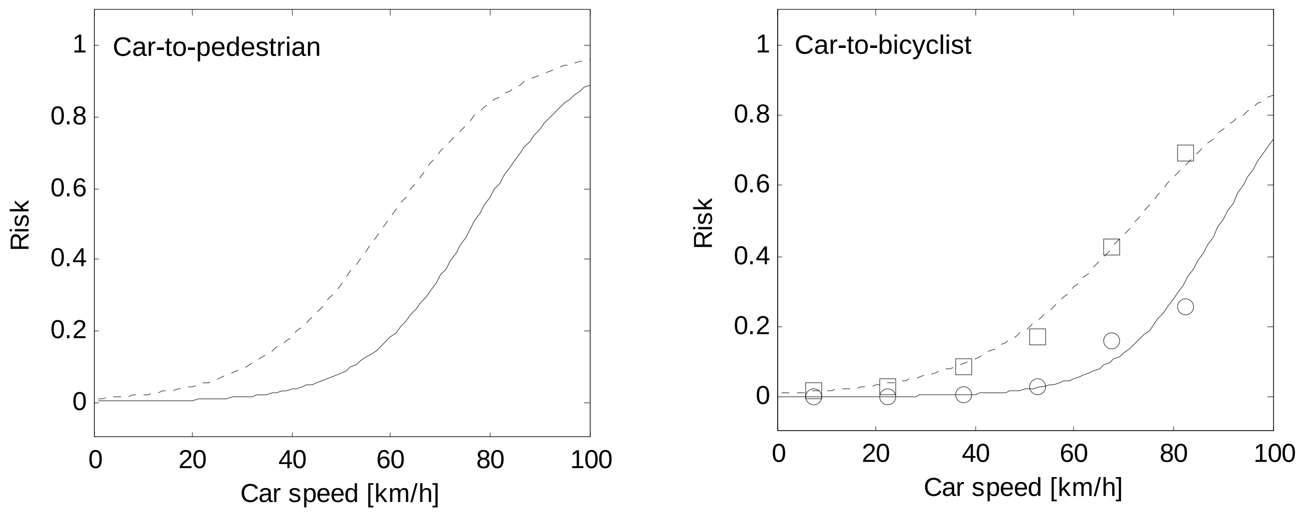

Fig. 4. Injury risk curves for frontal car-to-VRU collisions. Pedestrian risks from [2, 7]. Solid curves show fatality risk and dashed curves show risk for severe or fatal injury (AIS3+F). For bicyclists, empirical risks are displayed as circle and square markers.

Effectiveness

Figures 5 and 6 give the estimated reduction of fatally and severely injured VRUs for the six systems under study. It can be seen that the estimated effectiveness of the reference system was close to 50% for both pedestrians and cyclists. However, it should be noticed that all AEB systems in this study were assumed to have full functionality in rain and other adverse weather conditions, even the minimal system. Further, pedestrian detection rate was assumed to be 100% and tracking accuracy perfect. This implies that the estimates of effectiveness in this study were exaggerated. Nevertheless, it was worthwhile studying how effectiveness varied when imposing the various constraints offered by the other systems in Table 3.

We see in Figure 5 that the fatal effectiveness was substantially reduced by imposing restrictions on functionality in darkness and high speeds. But darkness was more important for pedestrians than bicyclists. Further, by limiting the brake parameters ($TTC_{\max}$, w, $a_{\max}$) from the reference system (1 s, 1 m, 0.7g) to the min brake system (0.5 s, 0 m, 0.5g) had a major impact on effectiveness. Combining the constraints on darkness, high speed and brake parameters (minimal system) decreased the effectiveness for fatalities from approximately 50% to 5% and the effectiveness for severely injured from approximately 40% to 4%. In other words, these constraints led to a tenfold decrease of effectiveness. The variation in effectiveness between the max brake system and the minimal system shows that the exact choice of system parameters will have a major effect on real-life effectiveness.

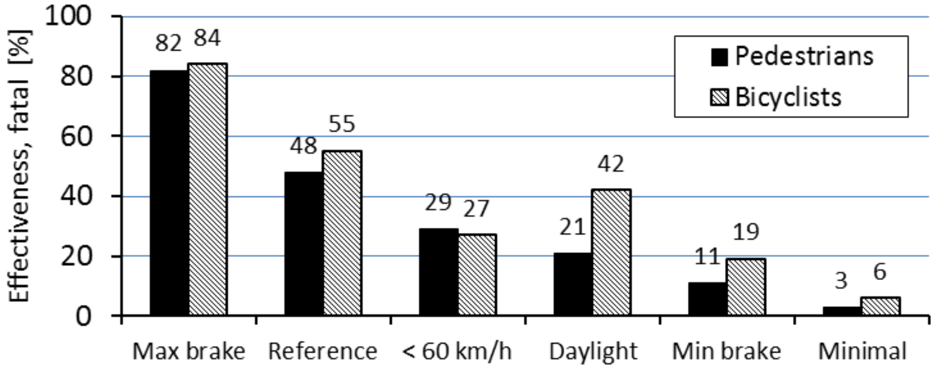

Fig. 5. Estimated effectiveness in terms of fatality reduction for various choices of system parameters (see Table 3).

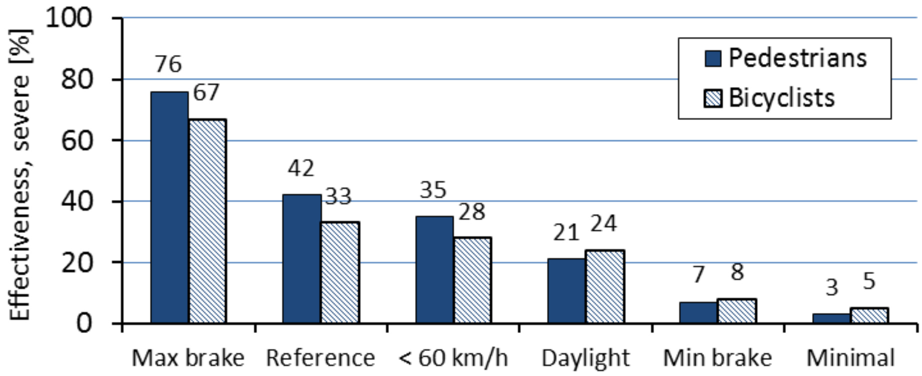

Fig. 6. Estimated effectiveness in terms of reduction of severely injured VRU's for various choices of system parameters (see Table 3).

Some further details are provided in Table 4. For pedestrian accidents, the activation rate of the reference system was 65% and the average collision speed decreased from 32 km/h without the system to 22 km/h with the system available. As already stated, this yielded an estimated reduction of fatally / severely injured pedestrians by 48% / 42%. Thus, even moderate reductions of average collision speed had a considerable effect on real-life benefit. On the other hand, imposing a cut-off speed at 60 km/h had only a minor effect on average collision speed while the effectiveness dropped markedly. This was explained by the fact that the high speed collisions were rare while still having a high effect on effectiveness, since injury risk increases sharply with speed. It is noticeable that the activation rate was generally lower for bicyclists than pedestrians, while effectiveness was at the same level. An explanation for this was that more accidents with bicyclists occurred when the car was turning. These scenarios required high FoV of the forward-looking sensor in order to detect the bicyclist, thus keeping activation rate low. At the same time, impact speed was generally low in these accidents, since the car was turning, and therefore they did not contribute substantially to fatal and severe injuries. The high frequency of turning scenarios explained that collision speed was considerably lower in accidents with bicyclists (22 km/h) than pedestrians (32 km/h).

TABLE 4

ACCIDENT AVOIDANCE AND SYSTEM ACTIVATION RATES AS WELL AS AVERAGE COLLISION SPEED OF THE CAR. ORIGINAL COLLISION SPEED AVERAGED TO 32 KM/H FOR PEDESTRIAN AND 22 KM/H FOR BICYCLISTS ACCIDENTS.

		Max brake	Reference	< 60 km/h	Daylight	Min brake	Minimal
Pedestrians	Avoidance	52%	17%	17%	12%	0%	0%
	Activation	85%	65%	59%	39%	45%	26%
	Avg. v_{coll}	10 km/h	22 km/h	22 km/h	26 km/h	31 km/h	32 km/h
Bicyclists	Avoidance	31%	10%	10%	7%	1%	1%
	Activation	68%	30%	28%	23%	26%	19%
	Avg. v_{coll}	8 km/h	16 km/h	17 km/h	18 km/h	21 km/h	21 km/h

Sensitivity analysis – jackknife

Using the jackknife method (see "Methods" above), the effectiveness for the reference system was re-calculated 543 times for the pedestrian sample and 607 times for the bicyclist sample by taking away one case at the time. The results are summarized in Table 5. It can be seen that the effectiveness for pedestrians did not vary much at all. For bicyclists, the fatal effectiveness varied slightly more, but much less than the differences between the various AEB systems compared in Figures 3 and 4. This was a strong indication that there were no highly influential cases biasing the analysis.

TABLE 5
RESULTS FROM JACKKNIFE ANALYSIS

		Original	Min jackknife	Max jackknife
Pedestrians	Fatal eff.	48%	47.8%	49.8%
	Severe eff.	42%	41.7%	42.4%
Bicyclists	Fatal eff.	55%	52%	58%
	Severe eff.	33%	32.2%	33.4%

V. DISCUSSION

This study confirmed the findings in [4-8] that AEB has a considerable potential to save lives and mitigate severe injuries in frontal car-to-pedestrian collisions. In line with [6] it was found that functionality in darkness and high speeds is essential to reach full system potential. Further, it supplemented previous findings by showing an equally high potential for car-to-bicyclist collisions, using the same AEB system. Nevertheless, the predicted real-life effectiveness for both pedestrians and bicyclists were highly sensitive to system parameters defining the brake capacity as well as functionality in darkness and high speed. The minimal system of this study (see Table 3), which combined all these restrictions, had an estimated effectiveness that was ten times lower than the reference system (see Figures 5 and 6). This should be important information to consumer rating organizations and car manufacturers considering AEB for vulnerable road users.

VI. CONCLUSIONS

Autonomous emergency braking (AEB) has a considerable potential to save lives and mitigate severe injuries for vulnerable road users in frontal collisions with passenger cars. However, this potential effectiveness is highly sensitive to parameters controlling the brake capacity of the AEB system. These include timing of brake activation and deceleration provided by the AEB system. Further, the effectiveness is sensitive to restrictions on functionality in darkness and high speeds. In particular, combining all these restrictions (darkness, high speed, timing and deceleration) would virtually eliminate the real-life effectiveness. It can be concluded that the exact choice of these system parameters will have a major effect on real-life effectiveness.

VII. LIMITATIONS

GIDAS PCM is a useful tool for accident analysis comprising a large number of accidents and high level of detail. However, it should be kept in mind that the data were not collected from event data recorders or GPS information. They were derived from normal accident reconstruction methods and thus comprise some inevitable inaccuracies. In [22] it was concluded that for car-to-pedestrian crashes, the GIDAS database was likely to have only a minor systematic error, while the amount of random error should have a standard deviation less than 15% of the true impact speed. Further, the data may not be representative for other countries than Germany. Clearly this had some effect on the estimates of effectiveness in this study. However, the main conclusions of this article, namely that effectiveness is sensitive to a number of system parameters, should be robust to these limitations.

VIII. ACKNOWLEDGEMENT

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