THE EFFECT OF P-AEB SYSTEM PARAMETERS ON THE EFFECTIVENESS FOR REAL WORLD PEDESTRIAN ACCIDENTS

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ABSTRACT

The objective of this ACEA funded study was to determine the effect of different pedestrian autonomous emergency braking (P-AEB) systems on the collision speeds of real world pedestrian accidents originating from three different accident databases. The precrash phases of real world passenger car to pedestrian frontal accidents from the in-depth accident databases were investigated using different pre-crash simulation tools. Collision parameters were compared between the original real-world cases and cases with treatment conditions. For treatment simulations, the car was equipped with a virtual generic P-AEB system, triggered at a time to collision (TTC)$\leq$ 1 s. The range of the generic sensor was 80 m and the opening angle was varied between 60°, 90° and 120°. For the braking system, two different brake gradients (24.5 m/s^3 and 35 m/s^3) were modelled with different decelerations of 0.8 g and 1.1 g. Accidents from the Austrian in-depth accident database CEDATU (n=50), the German GIDAS (n=1084) and Swedish V_PAD (n=68) were used for the baseline. The effect of using different data samples was compared to the effect of assuming different generic AEB system parameters. The best performing P-AEB system (120°, innovative brake system) avoided 42% of the CEDATU cases, while the baseline P-AEB system (60°, standard brake system) avoided 18%. The best performing AEB System was able to avoid 79.4% of the V_PAD sample. The baseline P-AEB avoided in V_PAD at least 66.2% compared to GIDAS with 39.5%. The lower the mean collision speed of the sample, the higher was the benefit of the P-AEB system, as a higher percentage of cases can be avoided. The study shows that system parameters and the selection of accidents can greatly affect the outcome in prospective traffic safety analyses. As a significant reduction of collision speeds was seen in all three data sources, the study highlights the need for a combined vehicle safety assessment instead of a separate evaluation of active and passive pedestrian safety measures.

INTRODUCTION

Pedestrians accounted for 21% of the total road fatalities in the European Union in 2016 [1]. Safety measures addressing pedestrians have not been as effective as those for car occupants. While the total number of road fatalities decreased by 41% in the period from 2007 and 2016, it was only reduced by 36% for pedestrians [1]. It is expected that active safety systems, such as pedestrian autonomous emergency braking (P-AEB) systems will help to avoid or mitigate pedestrian accidents. Studies agree, however, that all accidents cannot be avoided, which is the reason why passive safety systems will be still needed in the future [2–8]. In the Euro NCAP VRU assessment active and passive safety measures are evaluated separately, i.e. in a non-integrative way. However, active safety measures influence the boundary conditions of accidents which were not avoided by the active safety measure. The question is raised of what targets for passive safety measures are relevant for vehicles with P-AEB systems in the future.

The present study was conducted in the framework of the project ProPose, which is funded by ACEA (European Automobile Manufacturers' Association) and addresses the following questions:

1. How many real-world accidents can be avoided with P-AEB systems?
2. Is there a need to consider an update of the speed range addressed by passive safety measures in the future?
3. How does the sensor opening angle and brake characteristic affect the effectiveness of the P-AEB system?

The effect on collision speed for different crash data samples was analyzed in order to suggest input to future pedestrian crash test setups, relevant for the design of passive safety measures. In contrast to other studies, the analyses were examined by comparing results based on three different accident databases.

METHOD

The effectiveness of the conceptual P-AEB systems was determined by means of comparing baseline- (the crash situations without the AEB) with treatment (the same situations but with a concptual P-AEB system) virtual simulations.

Collision parameters of the original real-world cases (w/o P-AEB) were compared to those with a conceptual P-AEB system. The method used in this study is referred to as 'virtual pre-crash simulation'. In the last couple of years this type of investigation gained importance for the evaluation of effectiveness of active safety systems [9–14].

To analyse the effectiveness of P-AEB systems it is crucial that the velocity-time-history is known for the entire duration of the pre-crash phase, where the P-AEB deploys.

Input Data

In this study, the pre-crash phase of real-world passenger car to pedestrian frontal collision accidents from three different in-depth accident databases (Table 1) were investigated using different pre-crash simulation tools. Within the accident databases, the reconstructed accidents including the pre-crash phase are available. In CEDATU (Central Database for In-Depth Accident Study) [15,16] accidents are reconstructed with the software PC Crash on the basis of police-, medical-, witness and court reports, photos and photogrammetric analysis of the accident side. In V_PAD [17] (Volvo Cars Pedestrian Accident Database), the information considered by the crash investigator at Volvo's Traffic Accident Research Team is compiled and the pre-crash phase is digitized in order to provide vehicle paths in relation to vehicle velocities and to the surroundings in a numerical time history data (THd) format. The GIDAS (German In-Depth Accident Study) accidents are recorded on scene and therefore often provide additional information [18]. Apart from regional differences, the three databases are also differing in terms of their case selection criteria: In CEDATU Austrian accidents with at least one injured road user are included, for which access to the court file is given [16]. In GIDAS accidents are selected according to a statistical sampling process [18] from the area around Hannover and Dresden. The V_PAD sample [17] consists of Swedish pedestrian accidents reported to the insurance company Volvia (IF P&C Insurances), where all new Volvo passenger cars in Sweden are insured for at least three years. The different inclusion criteria for the databases are clearly reflected in injury distributions and speed statistics, see Table 1.

Table 1: Comparison of applied data sources, simulation tools and variations

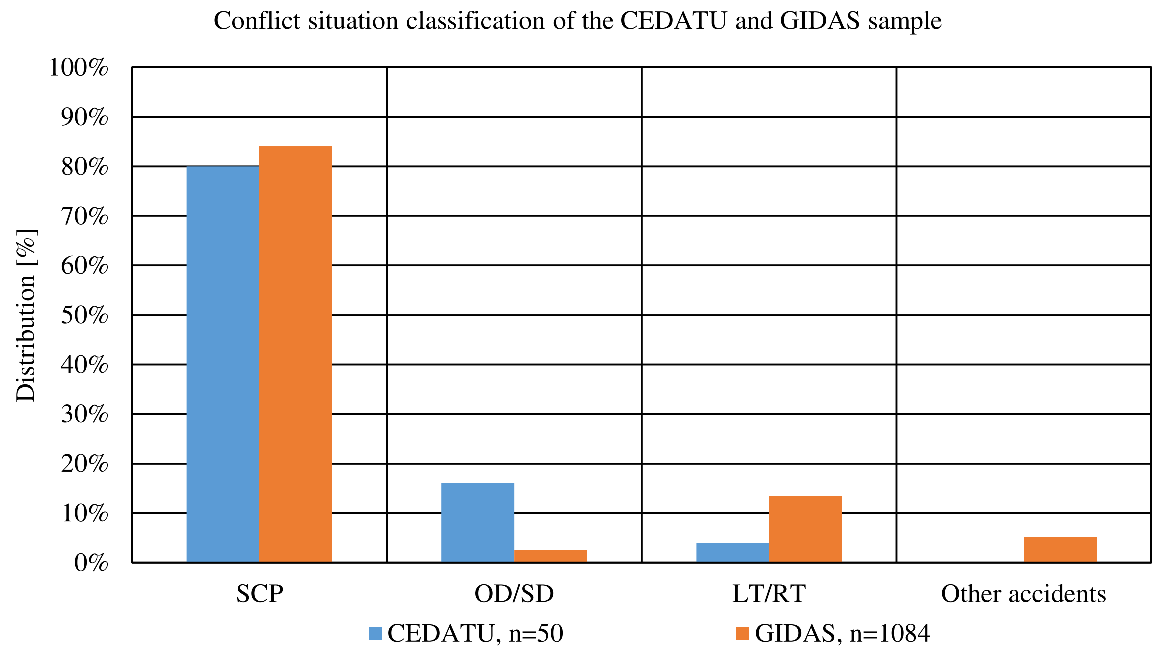
Source	CEDATU	GIDAS	V_PAD
Region	Austria	Hannover, Dresden	Sweden
Number of accidents for simulation	50	1084	68 SCP cases
cases with MAIS 4+ (AIS98)	50 %	7 %	3 %
cases with MAIS 3 (AIS98)	14 %	9 %	10 %
cases with MAIS 2 (AIS98)	24 %	33 %	40 %
cases with MAIS 1 (AIS98)	6 %	45 %	41 %
cases with unspec. MAIS 3+ (AIS98)	6 %	6 %	4 %
Analysed Scenarios	All	All	SCP
Mean initial speed [km/h]	50 (SD=22.9)	35.5 (SD=16.8)	31.5 (SD=17.1)
Mean collision speed [km/h]	47.2 (SD=20.4)	30.7 (SD=14.6)	23.6 (SD=16.3)
Median collision speed [km/h]	45	29.1	20
Simulation tool	X-Rate	rateEFFECT	VCART
Variations	Sensor 1-3; Brake 1-4	Sensor 1, Brake 1	Sensor 1-3; Brake 1-4

Only vehicle-to-pedestrian accidents which comply with the following filter criteria are considered in this study:

- the vehicle is a car or van, mass up to 3.5t,
- the vehicle is moving forward,
- the pedestrian was upright (not laying) prior to the impact,
- the pedestrian was struck by a single vehicle,
- only one pedestrian was involved in the accident,
- the vehicle was not skidding before the crash (but braking vehicles were included),

- Additional filter criterion for CEDATU and GIDAS: the pedestrian was impacted by the front of the vehicle,
- Additional Filter Criteria for V_PAD: the crossing path of the pedestrian was straight (SCP according to Figure 6 in the Appendix were considered).

The conflict situations (according to the classification introduced by Lindman et al. [17], which is explained in detail in Figure 6 in the Appendix) covered in the CEDATU and GIDAS sample, are shown in Figure 1: In the majority (80%) of the CEDATU cases, the pedestrian was crossing the road while the cars were driving straight (SCP). In 60% of the SCP accidents the pedestrian was entering the street straight from the left (far-side) and in 22,5% (9 cases) straight from the right side (near-side). In 20% of the CEDATU cases the pedestrian was either walking in the same direction (SD), oncoming direction (OD) of the, or the car was turning to the left (LT) prior to the impact. In the GIDAS dataset, 84% of the pedestrian were crossing the road while the cars were driving straight (SCP). I the remaining 9% of the GIDAS sample, the pedestrian was walking in the same direction (SD), oncoming direction (OD) of the car or the car was turning left (LT) or to the right (RT) prior impact. For 5%, another conflict situation occurred. In the V_PAD dataset, only conflict situations with a straight crossing pedestrian (SCP) were included. In 68% of the CEDATU and 69% of the GIDAS cases, the accident occurred on dry roads compared to V_PAD, where only 33.8% occurred on dry roads.



Source: CEDATU, GIDAS

Figure 1. Conflict situations covered in the CEDATU and GIDAS sample. For the V_PAD sample, only SCP crashes were considered.

Virtual pre-crash simulation

The pre-crash phases of reconstructed real-world accidents were rerun within a virtual forward simulation, where the vehicle follows the trajectory and the velocity profile of the reconstructed case until the system reacts. The baseline simulations were compared to treatment simulations, where the vehicles are virtually equipped with an ideal, conceptual P-AEB System having a generic sensor and various braking strategies.

The virtual forward pre-crash simulations in this study were made using three different simulation tools: X-RATE, rateEFFECT and VCaRT: In general, each of them operates on a time-step basis. At each time-step, the tool updates its information (speed, position, rotation, etc.) on dynamic objects by querying the dynamics simulation module. Based on that information, the sensor vision module determines which objects in the environment are visible. The sensor information is then forwarded to the function logic module which represents the P-AEB systems that are simulated by the individual tools. When the function logic module decides to intervene by e.g. braking, appropriate deceleration values are forwarded to the dynamics module for simulation of the next time step. The simulation terminates as soon as the stop criteria are fulfilled (i.e. first collision is detected or maximum simulation time reached).

X-RATE (Extended Effectiveness Rating of Advanced Assistance Systems) is developed by the Vehicle Safety Institute at TU Graz to simulate a variation of different sensor parameters and different active safety systems. It has already been used successfully for several research questions (e.g. pedestrian collision avoidance systems [19], collision mitigation for motorcycles at junctions [20], collision mitigation at intersections [21]) or in combination with traffic flow simulation [22]). X-RATE is developed in MATLAB and operates in conjunction with PC-Crash as driving dynamics simulation core.

rateEFFECT is a tool developed and used by Volkswagen Group to analyse the performance of advanced driver assistance or safety systems in traffic scenarios and to evaluate the effectiveness of active safety systems. The functionality is very similar to X-RATE as the vehicle dynamics and the scenery is based on PC Crash, too. Via a system editor it is possible to define own active systems with predefined or self-developed function blocks. The system configuration generally consists of sensors, algorithms, driver models and actuators. [23,24] The effectiveness assessment is an important procedure during the process of function development and is used for internal and external research questions, latest for the accident analysis done for the effectiveness evaluation of the General Safety Regulation for the European Commission [12–14].

VCaRT (Volvo Cars Research pre-crash simulation Tool) is a MATLAB tool to evaluate the potential of conceptual and ideal crash avoidance/mitigation ADAS. The tool main parts are simulation control, vehicle surrounding, virtual vehicle and collision control. The simulation control synchronizes the execution of the other parts, which can be configured depending on the test to be performed. Elements in the vehicle surrounding are 3-dimensional representations of the objects. The vehicle representation is based on a point-mass-model combined with actuator models that constrains the response on function logic requests. Examples of parameters that can be varied in the sensor model are field of view, sensor position and classification time.

Analysis of results

In order to analyse the potential safety effect of the P-AEB systems, the collision speed was used. It was defined as the speed of the vehicle at the first time step when the pedestrian and the vehicle geometries were intersecting. The mean and median collision velocities as well as the standard deviations (SD) were analysed from the different data sets separately. The mean of the relative reduction ($\overline{\Delta v_{c\_rel}}$) of the collision speed was calculated according to Equation (1) as 1 minus the mean value of the case-wise ratio of the collision speed in the treatment simulations ($v_{c-treatment_i}$) and the baseline simulation ($v_{c-baseline_i}$), with n being the number of analysed cases.

$$\overline{v_{c\_red\_rel}} = 1 - \frac{1}{n}\sum_{i=1}^{n}\frac{v_{c-treatment_i}}{v_{c-baseline_i}} \qquad \text{Equation (1)}$$

Conceptual P-AEB system

The generic sensor of the virtual P-AEB system was positioned 1.8 m behind the vehicle front. The range of the sensor model was set to 80 m. The opening angle of the sensor model was varied between 60° (Sensor 1), 90° (Sensor 2) and 120° (Sensor 3). The sensor vision was implemented by considering vision rays, also described in [25] and checks visibility of objects every 15 ms. The vision rays are emitted horizontally with a resolution of 0.1°, as shown in Figure 2. Intersections of the vision rays and the pedestrian are detected at each time step. If the pedestrian is fully within the sensor area, this is classified and the Time to Collision (TTC) is calculated.

The TTC is calculated by deriving a relative speed vector between the car and the pedestrian at each time step. The algorithm estimates how long it would take until a detected point, moving with the relative speed, contacts the ego-vehicle (car). The minimum time for all detected points is the estimated TTC for this time-step.

The P-AEB is triggered, when the pedestrian is classified (i.e. visible and 100% in the sensor area) for at least 150 ms (acquisition time) and the calculated TTC is $\leq$ 1 s. The car and pedestrian follow the original trajectory and the acceleration profiles remain unchanged until the AEB takes over.

After getting the AEB trigger signal, a 0.2 s actuator delay is assumed (=reaction time of the brake system).

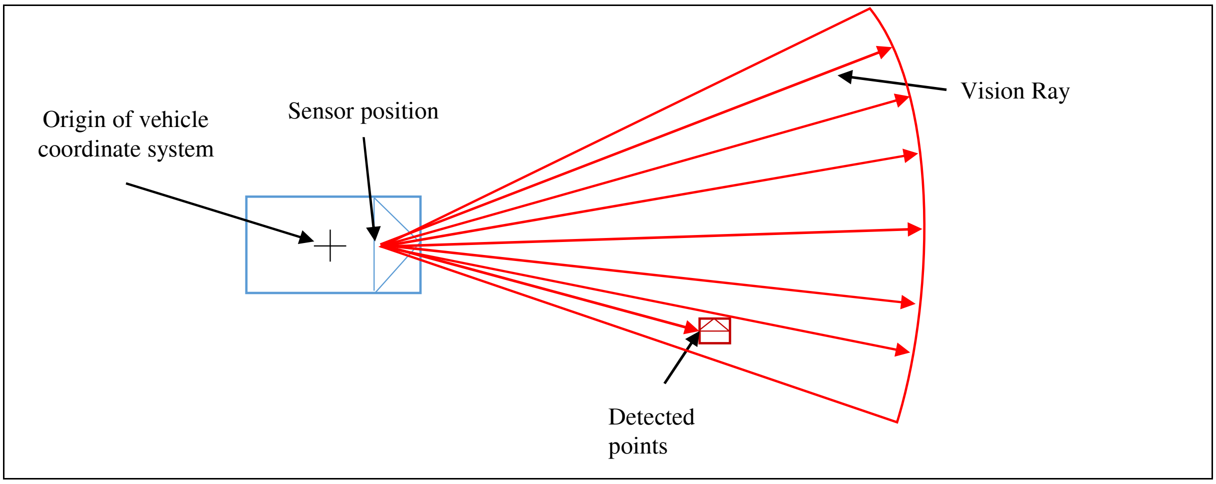


Figure 2. Top view of the sensor vision based on [25]

As brakes are activated, the maximum realisable acceleration is build up. The build-up time depends on the brake gradient of the system (see Equation (2). The results for the build-up times are shown in Table 9 in the appendix.

$$\textit{build-up time} = \frac{\textit{deceleration}}{\textit{brake gradient}} \qquad \text{Equation (2)}$$

The maximum deceleration depends on the friction coefficient which in turn depends on the road conditions. Different brake systems were evaluated (Table 2), which differed in terms of braking gradient and maximum realisable deceleration. In total four variations were investigated.

Table 2.
Definition of the braking systems for treatment simulations

	Braking system	Brake gradient	Max. realisable deceleration
Brake 1	Standard	24.5	0.8*g
Brake 2	Standard	24.5	1.1*g
Brake 3	Innovative	35	0.8*g
Brake 4	Innovative	35	1.1*g

The braking profiles of the different braking strategies are shown in Figure 3. After the actuator delay, the deceleration increases with the defined brake gradients to the maximally feasible deceleration.
Brake 1 and Sensor 1 as well as the applied strategy are in accordance with a previous studies [12–14].

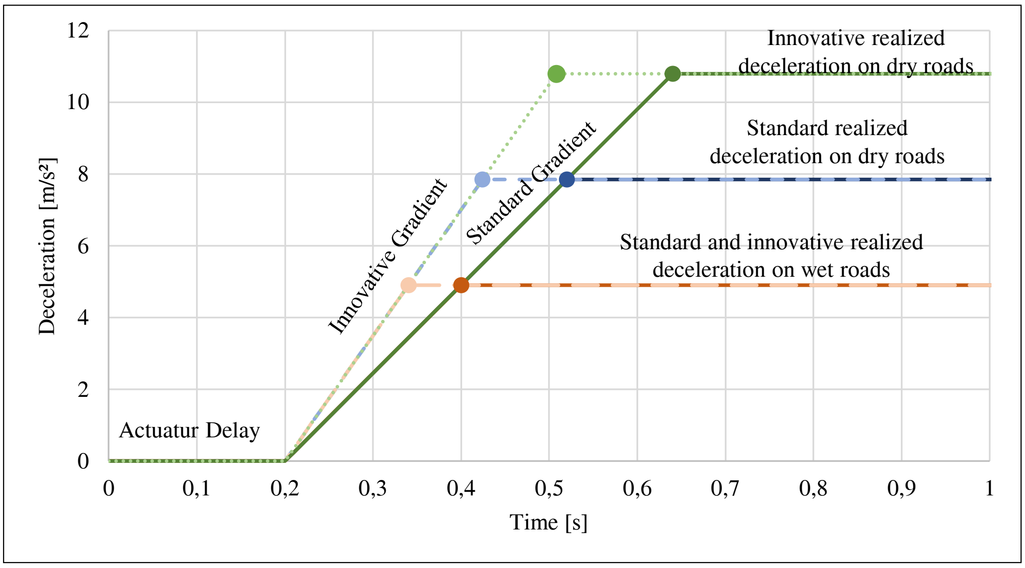


Figure 3. Braking Profile

RESULTS

In total, twelve treatment simulations of every baseline simulation were performed for the CEDATU and V_PAD sample. In GIDAS only one treatment simulation per baseline simulation (with Sensor 1 and Brake 1) was performed.

The results are presented by means of the data sample in this section. Collision speeds and the share of avoided cases of the different treatment simulations are compared to the baseline sample. For avoided accidents the collision speed was set to 0 km/h, resulting in a relative reduction of 100%. Mean and Median values were analysed per braking system for each sensor as well as overall braking systems.

CEDATU Cases

The mean collision speed of the original baseline CEDATU cases was 47.2 km/h (SD=20.4 km/h) and the median 45 km/h. The mean collision speed over all simulated P-AEB strategies was reduced by 55% to 24.9 km/h (SD=22 km/h). The individual results of the treatment simulations are shown in Table 3, depending on the sensor-opening angle and the braking system. The highest reduction of the collision speed $\overline{v_{c\_red}}$ (including avoided accidents as accidents with 0 km/h) was observed with Sensor 3 and Brake 4. The baseline collision speed of 47.2 km/h (SD=20.4 km/h) was reduced by 67.1% to 19.2 km/h (SD=22.7 km/h and the median from 45 km/h to 6.7 km/h. Sensor 3 and Brake 4 avoided 21 accidents (42%). The lowest change of the collision speed was observed with Sensor 1 and Brake 1. The reduction was 17.8 km/h (45.5%) and 9 accidents (18%) were avoided. A comparison of Sensor 1 and 2 shows that the difference of the mean collision speed due to the increased sensor angles was 0.1 km/h. A difference of the collision speed of about 0.3 km/h was observed between Sensor 1 and Sensor 3. Sensor 3 avoided one additional accident compared to Sensor 1 or 2. A comparison of Brake 1, 2 and 3 shows that a higher maximum deceleration results in a lower collision speed than a larger brake gradient.

With Brake 1 and Sensor 1 or 2, nine accidents were avoided (18%). When increasing the maximum deceleration to 1.1 g (Brake 2), five additional collisions were avoided (in total 28% avoided accidents). By increasing the brake gradient to 35 m/s³ (Brake 3), two additional accidents were avoided compared to brake 1. Combined with the higher maximum deceleration (Brake 4), a total number of 20 (40%) accidents were avoided.

Table 3.
Results of the CEDATU treatment simulations depending on the sensor opening angle and braking strategy including avoided accidents as accidents with 0 km/h

Sensor strategy	Braking strategy	Median v_c [km/h]	Mean $\overline{v_c}$ [km/h]	Mean reduction $\overline{v_{c\_red}}$ [km/h]	Mean rel. reduction $\overline{v_{c\_red\_rel}}$ [%]	Avoided cases
Baseline		45	47.2 (SD=20.4)	-	-	-
Sensor 1	Brake 1	27.6	29.4 (SD=22.5)	17.8	45.5%	9 (18%)
	Brake 2	19.5	23.8 (SD=22.6)	23.4	56.4%	14 (28%)
	Brake 3	25.1	27.6 (SD=22.5)	19.6	50.0%	11 (22%)
	Brake 4	8.7	19.6 (SD=22.6)	27.6	64.7%	20 (40%)
	Overall	24.2	25.1 (SD=22.9)	22.1	54.1%	
Sensor 2	Brake 1	27.6	29.3 (SD=22.6)	17.9	45.9%	9 (18%)
	Brake 2	19.4	23.7 (SD=22.6)	23.5	56.8%	14 (28%)
	Brake 3	25.0	27.5 (SD=22.6)	19.7	50.2%	11 (22%)
	Brake 4	8.7	19.5 (SD=22.6)	27.7	65.1%	20 (40%)
	Overall	23.0	25.0 (SD=22.9)	22.2	54.5%	
Sensor 3	Brake 1	27.6	29.1 (SD=22.7)	18.1	47.9%	10 (20%)
	Brake 2	19.4	23.5 (SD=22.7)	23.7	58.8%	15 (30%)
	Brake 3	25	27.3 (SD=22.8)	19.9	52.2%	12 (24%)
	Brake 4	6.7	19.2 (SD=22.7)	28.0	67.1%	21 (42%)
	Overall	23.0	24.8 (SD=23.0)	22.4	56.5%	

In Table 4 the results of the CEDATU sample were separated between cases where the pedestrians were coming from the left (far side) or right side (near side).

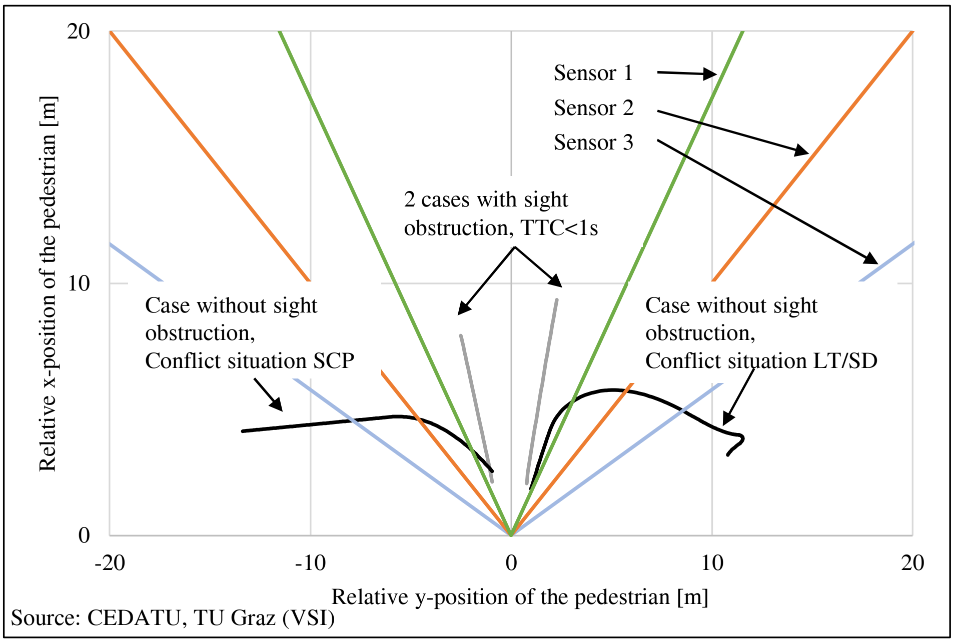
The mean collision speed of the 24 far side cases was 45.8 km/h (SD=16.9 km/h). The mean collision speed of the treatment simulations of all P-AEB systems was 23.7 km/h (SD=20.5 km/h), with a reduction of 55.7%. Due to the best braking strategy (Brake 4) the collision speed was reduced by 66.8% to 17.5 km/h (SD=19.8 km/h) compared to the least effective braking strategy (Brake 1), for which the mean collision speed was reduced to 28.2 km/h (47.2%). In the simulations with Brake 4, twelve accidents were avoided, while six accidents were avoided with Brake 1. For the far side scenario, no influence of the sensor angle was observed.

The sample comprises nine accidents from the nearside scenario with a baseline mean collision speed of 30 km/h (SD=13.1 km/h). The collision speed was reduced to 11.2 km/h (SD=12.3 km/h) within the simulations with Sensor 1 or Sensor 2, which is a reduction of 61.9%. The simulations with Sensor 3 achieved a collision speed of 10 km/h (SD=12.8 km/), this was a reduction of 73%. With Sensor 1 or 2, at least 3 accidents were avoided (33%). Sensor 3 and braking system 4 was the most effective system as 5 accidents were avoided (55%) and the lowest mean collision speed for treatment simulations (7.2 km/h, SD=11.8 km/h) was observed.

Table 4.
CEDATU treatment simulations for far side and nearside SCP traffic simulation scenarios including avoided accidents as accidents with 0 km/h

		Farside situations (n=24)			Nearside situations (n=9)		
Sensor strategy	Braking strategy	Mean $\overline{v_c}$ [km/h]	$\overline{v_{c\_red}}$ [km/h] ($\overline{v_{c\_red\_rel}}$)	Avoided cases	Mean $\overline{v_c}$ [km/h]	$\overline{v_{c\_red}}$ [km/h] ($\overline{v_{c\_red\_rel}}$)	Avoided cases
Baseline		45.8 (SD=16.9)	-	-	30.0 (SD=13.1)	-	-
Sensor 1	Brake 1	28.2 (SD=20.5)	17.5 (47.3%)	6 (25%)	13.0 (SD=12.7)	16.9 (56.4%)	3 (33%)
	Brake 2	22.4 (SD=20.2)	23.4 (58.6%)	8 (33%)	12.1 (SD=11.9)	17.9 (58.7%)	3 (33%)
	Brake 3	26.8 (SD=20.1)	18.9 (50.1%)	6 (25%)	11.4 (SD=12.4)	18.6 (62.6%)	3 (33%)
	Brake 4	17.5 (SD=19.8)	28.2(66.9%)	12 (50%)	8.4 (SD=11.6)	21.6 (69.9%)	4 (44.4%)
	Overall	23.7 (SD=20.5)	22.0 (55.7%)	-	11.2 (SD=12.3)	18.7 (61.9%)	--
Sensor 2	Brake 1	28.2 (SD=20.5)	17.5 (47.3%)	6 (25%)	13.0 (SD=12.7)	16.9 (56.4%)	3 (33%)
	Brake 2	22.4 (SD=20.2)	23.4 (58.6%)	8 (33%)	12.1 (SD=11.9)	17.9 (58.7%)	3 (33%)
	Brake 3	26.8 (SD=20.1)	18.9 (50.1%)	6 (25%)	11.4 (SD=12.4)	18.6 62.6%)	3 (33%)
	Brake 4	17.5 (SD=19.8)	28.2(66.9%)	12 (50%)	8.4 (SD=11.6)	21.6 (69.9%)	4 (44.4%)
	Overall	23.7 (SD=20.5)	22.0 (55.7%)	-	11.2 (SD=12.3)	18.7 (61.9%)	-
Sensor 3	Brake 1	28.2 (SD=20.5)	17.5 (47.3%)	6 (25%)	11.8 (SD=13.4)	18.1 (67.5%)	4 (44.4%)
	Brake 2	22.4 (SD=20.2)	23.4 (58.6%)	8 (33%)	10.9 (SD=12.5)	19.1 (69.8%)	4 (44.4%)
	Brake 3	26.8 (SD=20.1)	18.9 (50.1%)	6 (25%)	10.2 (SD=12.9)	19.8 (73.7%)	4 (44.4%)
	Brake 4	17.5 (SD=19.8)	28.2(66.9%)	12 (50%)	7.2 (SD=11.8)	22.7 (81.0%)	5 (55.5%)
	Overall	23.7 (SD=20.5)	22.0 (55.7%)	-	10.0 (SD=12.8)	19.9 (73.0%)	-

An influence of the opening angle was observed in two simulated accident cases without sight obstructions at junctions (conflict situation LT/SD and SCP). The relative trajectory of the pedestrian to the vehicle is shown in Figure 4 with black lines. For the first accident (SCP), only the P-AEB with Sensor 3 was able to avoid the accident. In the second case (LT/SD), the AEB was triggered with Sensor 2 and 3 earlier. The System was able to reduce the collision speed by about 23.4% from 25 km/h to 19.4 km/h with the best system (Sensor 3 and Brake 4). In Figure 4, the relative position of the pedestrian to the vehicle is shown for 2 other CEDATU cases as grey line. These two cases with sight obstructions were detected for all sensor angles at the same time.
In another 5 accidents with sight obstructions, the pedestrian was classified at the same time and no influence of the opening angle was observed.



Source: CEDATU, TU Graz (VSI)

Figure 4. Trajectories of the pedestrian relative to the vehicle of CEDATU simulations for four selected cases

GIDAS Cases

The mean collision speed of the original GIDAS cases was 30.7 km/h (SD=14.6). Due to treatment simulations with Sensor 1 and Brake 1 (Table 5), the collision speed was reduced by 17.1 km/h to 13.6 km/h (SD=14.7), which equals a relative reduction ($\overline{v_{c\_red\_rel}}$) of 57.7%. This system avoided 39.6% of 1078 cases.

Table 5.

Results of the GIDAS treatment simulations depending on the sensor opening angle and braking strategies including avoided accidents as accidents with 0 km/h

Sensor strategy	Braking strategy	Median v_c [km/h]	Mean $\overline{v_c}$ [km/h]	Mean reduction $\overline{v_{c\_red}}$ [km/h]	Mean rel. reduction $\overline{v_{c\_red\_rel}}$ [%]	Avoided cases
Baseline		29.1	30.7 (SD=14.6)	-	-	-
Sensor 1	Brake 1	11.0	13.6 (SD=14.7)	17.1	57.7%	429 (39.6%)

V_PAD Cases

The mean collision speed of the original V_PAD cases was 23.6 km/h (SD=16.3 km/h) and the median 20 km/h. The mean collision speed for all simulated P-AEB strategies was reduced by 70.2% to 7 km/h (SD=22 km/h).
The treatment simulation results are shown in Table 6, depending on the sensor opening angle and the braking system. The highest change of collision speed $\overline{v_{c\_red}}$ (including avoided accidents with 0 km/h) was achieved with Sensor 3 and Brake 4. The baseline collision speed of 23.6 km/h (SD=16.3 km/h) was reduced to 5.8 km/h (SD=12.4 km/h). This represents a reduction of 17.8 km/h ($\overline{v_{c\_red\_rel}}$ =86.6%). The lowest reduction of the collision speed ($\overline{v_{c\_red\_rel}}$ =79%) was achieved with Sensor 1 and Brake 1. The effect of the different sensors was very small. The mean collision speeds differed by only 0.1-0.2 km/h for all brakes. The results of Sensor 2 and 3 were equal for all brakes. The mean collision speed of Sensor 1 over all braking systems was 7.1 km/h

(SD=13.2 km/h). All braking systems with Sensor 2 and Sensor 3 were able to reduce the collision speed to 7 km/h (SD=13.3 km/h).

A comparison of the braking systems shows that Brake 4 leads to the lowest collision speed for all three simulated sensors. With Brake 2 and 3, differences in standard deviation and number of avoided accidents were observed.

In the simulations with Sensor 1 and Brake 1 at least 45 (66.2%) accidents were avoided, while the number of avoided cases with Sensor 2 and 3 was at least 47 (69.1%). The best system (Sensor 3, Brake 4) avoided 54 accidents (79.4%).

Table 6.
Results of the V_PAD treatment simulations depending on the sensor opening angle and braking strategy including avoided accidents as accidents with 0 km/h

Sensor strategy	Braking strategy	Median v_c [km/h]	Mean $\overline{v_c}$ [km/h]	Mean reduction $\overline{v_{c\_red}}$ [km/h]	Mean rel. reduction $\overline{v_{c\_red\_rel}}$ [%]	Avoided cases
Baseline		20	23.6 (SD=16.3)	-		-
Sensor 1	Brake 1	0	8.2 (SD=13.9)	15.4	79.0%	45 (66.2%)
	Brake 2	0	7.2 (SD=13.3)	16.4	81.1%	48 (70.6%)
	Brake 3	0	7.2 (SD=13.1)	16.4	81.4%	49 (72.1%)
	Brake 4	0	6.0 (SD=12.4)	17.7	83.7%	52 (76.5%)
	Overall	0	7.1 (SD=13.2)	16.5	81.3%	-
Sensor 2	Brake 1	0	8.1 (SD=14.0)	15.6	81.9%	47 (69.1%)
	Brake 2	0	7.0 (SD=13.3)	16.6	84.0%	50 (73.5%)
	Brake 3	0	7.0 (SD=13.2)	16.6	84.3%	51 (75.0%)
	Brake 4	0	5.8 (SD=12.4)	17.8	86.6%	54 (79.4%)
	Overall	0	7.0 (SD=13.3)	16.6	84.2%	-
Sensor 3	Brake 1	0	8.1 (SD=14.0)	15.6	81.9%	47 (69.1%)
	Brake 2	0	7.0 (SD=13.3)	16.6	84.0%	50 (73.5%)
	Brake 3	0	7.0 (SD=13.2)	16.6	84.3%	51 (75.0%)
	Brake 4	0	5.8 (SD=12.4)	17.8	86.6%	54 (79.4%)
	Overall	0	7.0 (SD=13.3)	16.6	84.2%	-

In Table 7 the results of the V_PAD sample were separated in far side and near side scenarios. The mean collision speed of the 32 far side cases was 26.8 km/h (SD=17.8 km/h). The collision speed was reduced to 9.7 km/h (SD=15.3 km/h) with simulations of Sensor 1. The mean relative reduction ($\overline{v_{c\_red\_rel}}$) was 74%. The simulations with Sensor 2 and 3 achieved a reduction of 80.3 % to a collision speed of 9.4 km/h (SD=15.4 km/h). With Sensor 1, at least 19 accidents (59.4%) were avoided. The most effective System (Sensor 3 and Brake 4) avoided 23 (71.9%) of the 32 far side scenarios and reduced the collision speed about 18.6 km/h (82.6%) to 9.4 km/h (SD=15.4 km/h)

The V_PAD sample comprises 36 nearside scenarios with a baseline collision speed of 20.9 km/h (SD=14 km/h). The collision speed was reduced for all 3 sensors by about 87.7% to 4.8 km/h (SD=10.6 km/h). Brake 1 avoided 26 (72.2%), Brake 2 28 (77.7%) and Brake 3 29 (80.5%) accidents. The best system with Brake 4 avoided 31 of the 36 near side cases (86.1%). No influence of the sensor opening angle for the nearside scenario was observed.

Table 7.
V_PAD treatment simulations for farside and nearside SCP traffic simulation scenarios including avoided accidents as accidents with 0 km/h

		Farside scenario (n=32)			Nearside scenario (n=36)		
Sensor strategy	Braking strategy	Mean $\overline{v_c}$ [km/h]	$\overline{v_{c\_red}}$ [km/h] ($\overline{v_{c\_red\_rel}}$)	Avoided cases	Mean $\overline{v_c}$ [km/h]	$\overline{v_{c\_red}}$ [km/h] ($\overline{v_{c\_red\_rel}}$)	Avoided cases
Baseline		26.8 (SD=17.8)	-	-	20.9 (SD=14.0)	-	-
Sensor 1	Brake 1	10.9 (SD=15.9)	15.8 (71.7%)	19 (59.4%)	5.8 (SD=11.3)	15.1 (85.5%)	26 (72.2%)
	Brake 2	9.9 (SD=15.5)	16.8 (73.4%)	20 (62.5%)	4.8 (SD=10.3)	16.1 (87.9%)	28 (77.7%)
	Brake 3	9.5 (SD=15.0)	17.3 (74.7%)	20 (62.5%)	5.1 (SD=10.8)	15.7 (87.3%)	29 (80.5%)
	Brake 4	8.5 (SD=14.5)	18.3 (76.4%)	21 (65.6%)	3.7 (SD=9.7)	17.1 (90.2%)	31 (86.1%)
	Overall	9.7 (SD=15.3)	17.0 (74.0%)	-	4.8 (SD=10.6)	16.0 (87.7%)	-
Sensor 2	Brake 1	10.6 (SD=16.1	16.1 (77.9%)	21 (65.5%)	5.8 (SD=11.3)	15.1 (85.5%)	26 (72.2%)
	Brake 2	9.6 (SD=15.7)	17.1 (79.7%)	22 (68.8%)	4.8 (SD=10.3)	16.1 (87.9%)	28 (77.7%)
	Brake 3	9.2 (SD=15.1)	17.6 (80.9%)	22 (68.8%)	5.1 (SD=10.8)	15.7 (87.3%)	29 (80.5%)
	Brake 4	8.2 (SD=14.6)	18.6 (82.6%)	23 (71.9%)	3.7 (SD=9.7)	17.1 (90.2%)	31 (86.1%)
	Overall	9.4 (SD=15.4)	17.3 (80.3%)	-	4.8 (SD=10.6)	16.0 (87.7%)	-
Sensor 3	Brake 1	10.6 (SD=16.1	16.1 (77.9%)	21 (65.5%)	5.8 (SD=11.3)	15.1 (85.5%)	26 (72.2%)
	Brake 2	9.6 (SD=15.7)	17.1 (79.7%)	22 (68.8%)	4.8 (SD=10.3)	16.1 (87.9%)	28 (77.7%)
	Brake 3	9.2 (SD=15.1)	17.6 (80.9%)	22 (68.8%)	5.1 (SD=10.8)	15.7 (87.3%)	29 (80.5%)
	Brake 4	8.2 (SD=14.6)	18.6 (82.6%)	23 (71.9%)	3.7 (SD=9.7)	17.1 (90.2%)	31 (86.1%)
	Overall	9.4 (SD=15.4)	17.3 (80.3%)	-	4.8 (SD=10.6)	16.0 (87.7%)	-

Summary of most and the least effective system

In Table 8, the mean reduction of the least effective system (Sensor 1, Brake 1) and the most effective System (Sensor 3, Brake 4) including avoided accidents as accidents with 0 km/h collision speed is shown. The results show a similar reduction of the collision speed for Sensor 1 and Brake 1 for all three databases. In the GIDAS sample, the speed was reduced by 17.1 km/h (57.7%) compared to 17.8 km/h (45.5%) in the CEDATU cases and 15.4 km/h (79%) in the V_PAD cases. With the most effective system (Sensor 3, Brake 4), a higher reduction of the collision speed was observed compared to the least effective System. In CEDATU, a reduction of 28 km/h (67.1%) was observed and in V_PAD, 17.8 km/h (86.6%).

Table 8.
Mean reduction of the collision speed through treatment simulations including avoided accidents as accidents with 0 km/h

	Sensor 1, Brake 1		Sensor 3, Brake 4	
Database	Mean reduction $\overline{v_{c\_red}}$ [km/h]	Mean rel. reduction $\overline{v_{c\_red\_rel}}$ [%]	Mean reduction $\overline{v_{c\_red}}$ [km/h]	Mean rel. reduction $\overline{v_{c\_red\_rel}}$ [%]
CEDATU	17.8	45.5%	28	67.1%
GIDAS	17.1	57.7%	-	-
V_PAD	15.4	79.0%	17.8	86.6%

DISCUSSION

Effect of different data sources

Accident scenarios in different countries can highly differ [26] for various reasons (e.g. different speed limits, country specific regulations, etc.). Thus, it is valuable to include different regions for such kind of investigation. For the present study, three databases were available.

The three different data samples differed in terms of the collision velocities of the accidents. The mean speed in the CEDATU sample was highest with 47.2 km/h, followed by GIDAS with 30.7 km/h and V_PAD with 23.6 km/h. The greater severity of the CEDATU accidents is also obvious from the analysis of the injury severities: In the CEDATU sample, 50% of the pedestrians suffered an injury of severity greater than AIS 4 +. In the GIDAS sample only 7% and the V_PAD sample only 3% of the pedestrians sustained AIS 4+ injuries.

Even if the relative speed reduction is similar in simulations based on the three different data sources, the mean speeds for remaining crashes is lower in V_PAD. The V_PAD sample is based on insurance claim reports, and is thus including a wide range of crash situations. Compared to VRU cases in the police reported sample in STRADA, only 50% of crashes reported to the insurance company were covered by police reports [27]. This is a probable reason why the mean collision speed in this data sample is lower than in the other two data samples. Also, the baseline sample from V_PAD only included SCP crashes that are associated with lower collision speeds than e.g. situations in longitudinal traffic. CEDATU and GIDAS include more severe accident cases and therefore, results based on CEDATU and GIDAS are reflecting higher collision speeds. Differences in initial speed are caused by the original focus of CEDATU on accidents resulting in fatalities (cases before 2008) and different share of conflict situations between the CEDATU and GIDAS datasets.

For all three data sources, information of crashes were collected retrospectively. The collision speeds and trajectories of the baseline simulations are calculated based on accident sketches. However, in GIDAS an accident team is investigating the accident on the spot whereby in CEDATU and V_PAD the data are investigated based on various kinds of reports. In order to compensate for uncertainties in the pre-crash data, robustness analysis of parameters should be performed (e.g. variation of pedestrian- and car speed). This is usually done for baselines from V_PAD, but was not performed in the current study.

Although it was tried to perform analysis as similar as possible, the applied simulation tools were not harmonised. Those differences are discussed within the P.E.A.R.S. initiative [11], which is working on the definition of a harmonised assessment process for effectiveness evaluations.

The results show a similar reduction of the collision speed for all three data sources with the least effective system (Sensor 1 and Brake 1).

Speed range for passive safety measures

To calculate the overall effectiveness, the avoided cases are assigned a collision speed of 0 km/h. Else the effectiveness evaluation would rate systems poorer as they are, because only severe cases remain.

When defining requirements for the passive safety measures, though, it makes no sense to consider avoided cases. Therefore, those were excluded for the definition of requirements to future passive safety measures that is discussed in the following section.

It is remarkable that even for the severe CEDATU sample the least effective P-AEB system (Sensor 1, Brake 1) is able to reduce the mean collision speed to less than 40 km/h, which is the impact speed in current passive safety systems. 63.4% of the unavoided cases would be covered by current pedestrian safety testing. In the V_PAD simulations with the least effective system, 87% of the simulated were below 40 km/h.

The speed distribution (shaded area) and the cumulative speed distribution (lines) of the cases are shown in Figure 5. The baseline speeds include all cases, the treatment simulation only unavoided cases. The analysis show that if it is intended to cover the same ratio of accidents with passive safety measures as today (with vehicles without P-AEB system), the speed considered for the evaluation of passive safety measures can be reduced by at least 34%. With the impact speed at 40 km/h [ref procedure], it would be possible to address a larger proportion of accidents than today. Looking at the results based on the V_PAD sample (although considering only SCP situations) more than 90% of the remaining accidents had speeds below this.

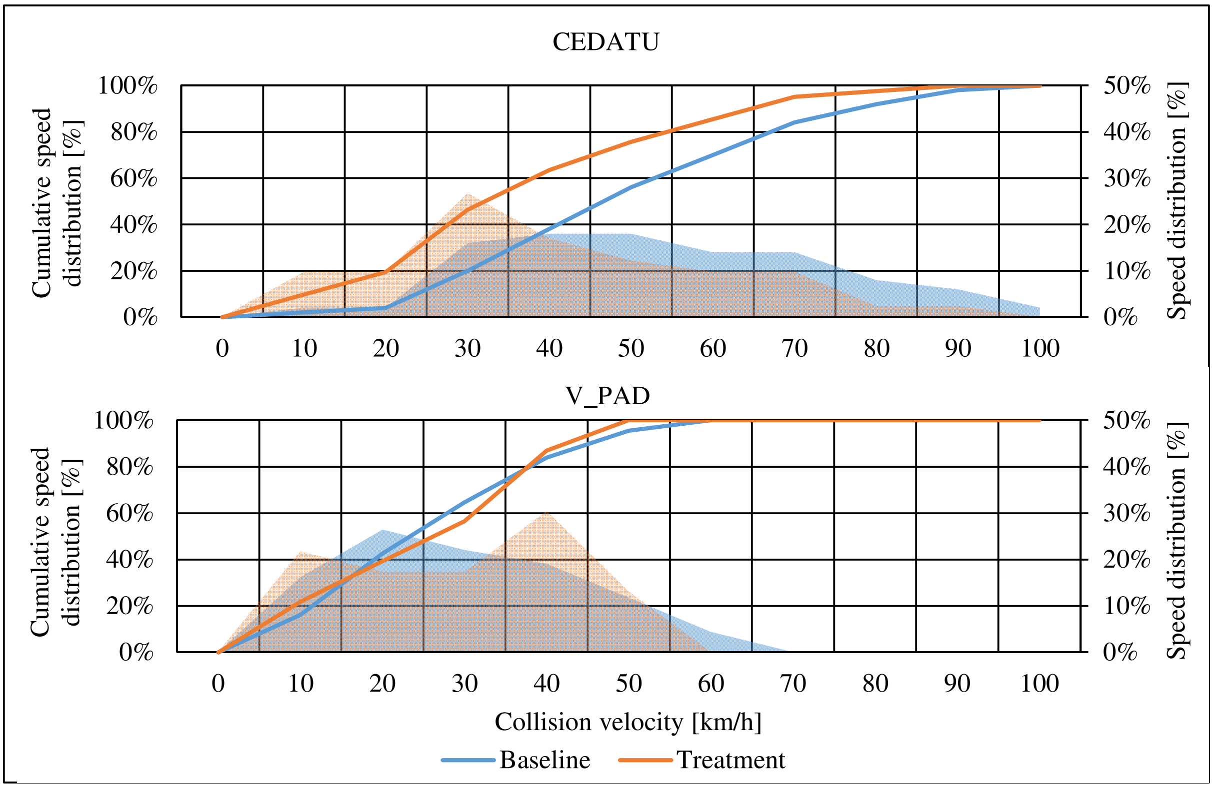


Figure 5. Distribution of the cumulative collision speed for crashes in baseline and unavoided crashes in treatment condition (baseline cases in the treatment not considered)

Effect of opening angle

A similar effect of the sensor opening angle was noticed in treatment simulations of the V_PAD and CEDATU cases. Increasing the sensor angle did affect the results only marginally. Within CEDATU, a sensor opening angle of 120° additionally avoided one accident more (+2%) compared to 60° and 90°. For V_PAD, a sensor opening angle of 90° and 120° avoided 2 additional accidents (+2.9%) compared to 60°.

Effect of braking characteristics

A higher brake gradient (Brake 3 versus Brake 1) leads to two additional (+4%) avoided cases in CEDATU and four additional (+5.8%) in the V_PAD sample. Increasing the maximum realisable deceleration (Brake 1 vs 2 and 3) has a greater effect on the CEDATU cases than on the V_PAD sample.

The effect of the different braking systems depends to a great extent on the sample composition. In the CEDATU sample, 68% of the cases were on dry road, 69% in GIDAS and 33.8% in V_PAD. A comparison of Brake 2 and 3 in V_PAD showed no differences in mean collision speed, while 5.6 km/h in CEDATU.

For real sensors, proper classification and collision detection of moving objects such as pedestrians is a particular challenge. With the ideal generic sensors, in the performed simulations, the pedestrian was classified only when it was 100% in the sensor field of view. Collision detection was based on deriving a relative speed vector between the car and the pedestrian and exact detected positions, while real sensor output is noisy and contains measurement error. The algorithm of the real safety system therefore operates under the assumption that the data is noisy, which leads to different implementations than with an ideal sensor. Furthermore, environmental influences (rain, fog) also negatively affect the visibility of objects, which has not been accounted for in the ideal sensor. Overall, the effects from ideal P-AEB systems that were evaluated in this study can differ from real P-AEB systems.

CONCLUSIONS

Virtual precrash simulations of different ideal and conceptual P-AEB systems using real-world pedestrian cases from three different accident databases as baseline, showed that the lower the mean baseline collision speed in the data sample, the more accidents were avoided. The maximum deceleration was the most influential P_AEB system parameter on the share of avoided cases and on the collision speed of the remaining cases. With the best system and the least severe data sample, 20% of the accidents/crashes still remained. A drastic reduction of collision speed (min 34%) was observed in all three data samples and this even with the most conservative P-AEB system parameters. This clearly highlights the need for a combined vehicle safety assessment instead of a separate evaluation of active and passive pedestrian safety measures.

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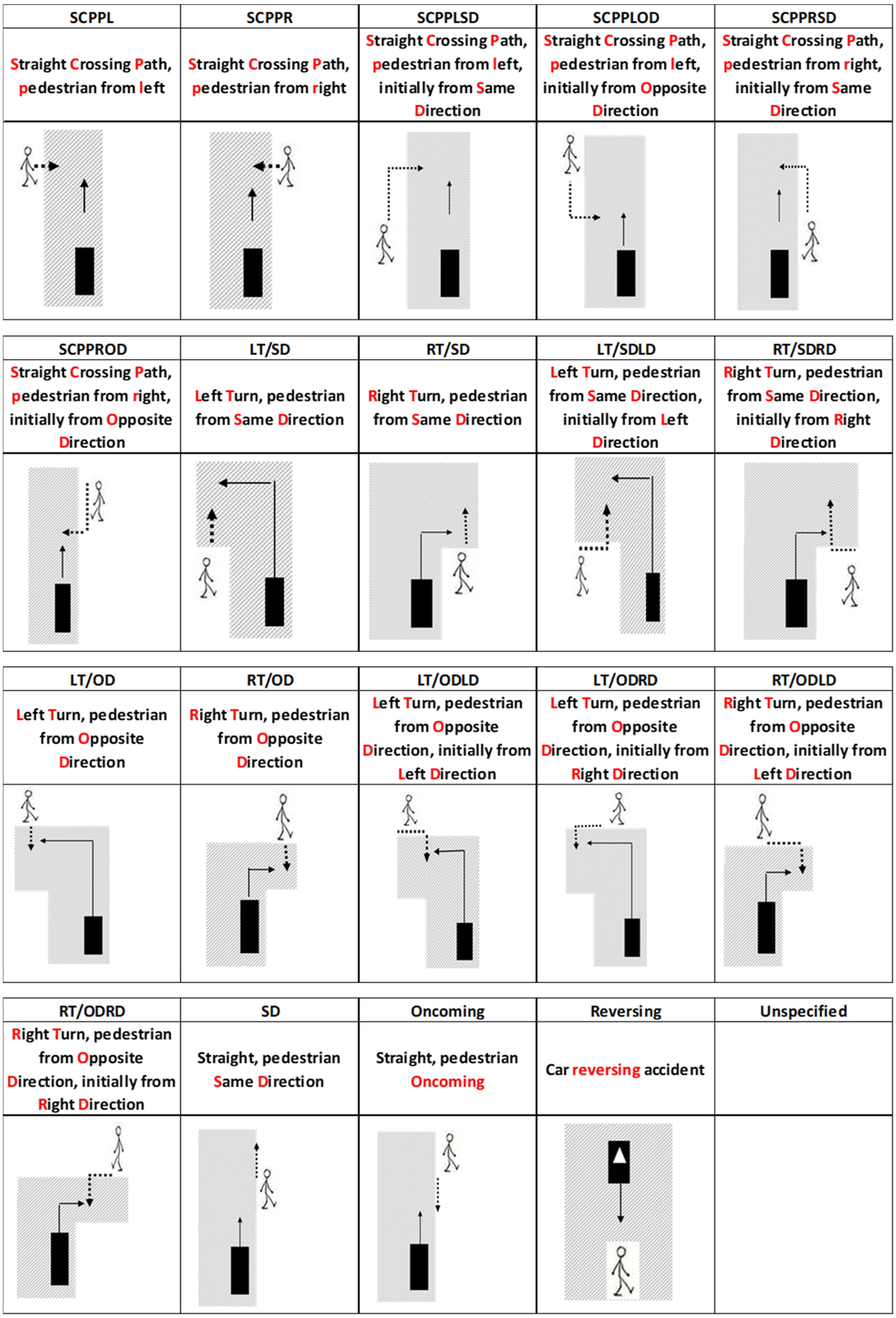
APPENDIX

Table 9.
Calculated Build - Up Times

Build-up times	Brake gradient	
Realized Deceleration	24.5 m/s³	35 m/s³
0.5*g = 4.91 m/s²	0.2 s	0.14 s
0.8*g = 7.85 m/s²	0.32 s	0.22 s
1.1*g = 10.79 m/s²	0.44 s	0.31 s



SCPPL	SCPPR	SCPPLSD	SCPPLOD	SCPPRSD
Straight Crossing Path, pedestrian from left	Straight Crossing Path, pedestrian from right	Straight Crossing Path, pedestrian from left, initially from Same Direction	Straight Crossing Path, pedestrian from left, initially from Opposite Direction	Straight Crossing Path, pedestrian from right, initially from Same Direction
SCPPROD	**LT/SD**	**RT/SD**	**LT/SDLD**	**RT/SDRD**
Straight Crossing Path, pedestrian from right, initially from Opposite Direction	Left Turn, pedestrian from Same Direction	Right Turn, pedestrian from Same Direction	Left Turn, pedestrian from Same Direction, initially from Left Direction	Right Turn, pedestrian from Same Direction, initially from Right Direction
LT/OD	**RT/OD**	**LT/ODLD**	**LT/ODRD**	**RT/ODLD**
Left Turn, pedestrian from Opposite Direction	Right Turn, pedestrian from Opposite Direction	Left Turn, pedestrian from Opposite Direction, initially from Left Direction	Left Turn, pedestrian from Opposite Direction, initially from Right Direction	Right Turn, pedestrian from Opposite Direction, initially from Left Direction
RT/ODRD	**SD**	**Oncoming**	**Reversing**	**Unspecified**
Right Turn, pedestrian from Opposite Direction, initially from Right Direction	Straight, pedestrian Same Direction	Straight, pedestrian Oncoming	Car reversing accident	

Figure 6: Definition of conflict situations according to Lindman et al. [17]