Prospective Evaluation of the Effectiveness of Autonomous Emergency Braking Systems in Increasing Pedestrian Road Safety in France.

Jacques Saadé, Henri Chajmowicz, Sophie Cuny[1]

Abstract Autonomous Emergency Braking systems with pedestrian detection (AEB Pedestrian) equip a growing proportion of new vehicles, but are still scarce on the automotive market, so their impact on road safety can still mostly be assessed by prospective studies. In the present study, a complete set of injury risk curves, built from representative AEB-Pedestrian relevant French accident data, were used, allowing AEB effectiveness assessment in terms of lives saved and mitigated injuries. These injury risk curves were used in combination with re-simulated impact speed distributions that were derived from a car kinematic model to which AEB sensors with realistic detection and actuator actions strategies were fitted. Metrics synthesising AEB effectiveness were built and used in a Taguchi-matrices based Design of Experiments setup, which allowed to highlight critical AEB design parameters, by means of a variance analysis.

This sensitivity analysis – performed over three different AEB setups - showed the influence of the decision algorithm and braking design parameters over the influence of detection parameters. Results nevertheless show encouraging effectiveness values on all levels of injury, depending on the field of view parameters alone, once reference values of the decision algorithm and braking design parameters have been set.

Keywords Autonomous Emergency Braking, car-to-pedestrian accidents, effectiveness, Injury Risk Curve, sensitivity analysis

I. INTRODUCTION

Pedestrian road safety remains a key challenge worldwide. In 2016, pedestrians accounted for 23% of the 1.35 million road fatalities recorded worldwide [1]. In Europe, pedestrian fatalities have dropped by 36% between 2007 and 2016 [2]. However, there were still more than 5 500 pedestrians fatally injured in the EU in 2016, 47% of them were over 65 years old [3]. In 2017 in France, pedestrian road fatalities accounted for 13% of the overall road fatalities [4]. With 484 pedestrian fatalities, this is an almost exact match to the 2010 tally.

To increase pedestrian safety, one solution is to fit cars with Advanced Driver Assistance Systems (ADAS). Autonomous Emergency Braking for pedestrians (AEB-Pedestrian) is one of these systems that can either avoid or mitigate car-pedestrian crashes, by automatically applying the vehicle brakes. Some systems may first issue a warning and only apply the brakes if the driver is unresponsive to the warning.

The scientific literature contains several studies addressing AEB-Pedestrian effectiveness [5][6][7][8][9], which have been summarised in [10]. As the market penetration of AEB technology is still low, studies mostly consist of prospective analyses of the potential benefits, making use of re-simulations - with virtual vehicle models including AEB technology - of relevant instances of car-pedestrian collisions selected from detailed real-life accident databases.

One study [7] assessed the influence of one specific definition of AEB on impact velocities and locations of the impact of the pedestrian's head. Accident sample representativeness was not sought, a common feature with [6]. Some studies [5][6][8][9] used injury risk curves to evaluate the effectiveness of AEB systems. Two of them [8][9] used representative samples from the German In-Depth Accident Study (GIDAS) database and evaluated AEB effectiveness in reducing fatal [8][9] and fatal or severe [8] pedestrian injuries. Effectiveness was evaluated for different values of the AEB sensors angle of view [9]. Different combinations of parameters were also tested [8] and the effects of parameters such as field of view or maximum braking intensity were assessed, although no systematic approach was used to assess the effects of individual design parameters. In [5], injury risk curves were

[1] J. Saadé is Research Engineer and S. Cuny is Data Analyst in Accident Science at the European Centre for Safety Studies and Risk Analysis (CEESAR), Nanterre, France. H. Chajmowicz is Active Safety and Autonomous Vehicle Researcher at LAB (Laboratory of Accidentology, Biomechanics and Human Behaviour / PSA – Renault), Nanterre, France.

used for fatal, severe and slight injuries to comprehensively assess three generations of AEB systems.

In the present study, a complete set of injury risk curves allowing AEB effectiveness assessment in terms of lives saved and mitigated injuries was built from French accident data. These fatal, severe and slight injury risk curves were used in combination with accident re-simulations using a car kinematic model to which AEB sensors with realistic detection and actuator actions strategies were fitted. Metrics synthesising AEB effectiveness were built and used in a Taguchi-matrices based Design of Experiments setup, which allowed highlighting critical AEB design parameters, by means of a variance analysis.

II. METHODS

Data

AEB-Pedestrian was evaluated using AEB-Pedestrian relevant accidents selected from the French accident database, VOIESUR [11]. This database was built in the context of the VOIESUR project that was set up in 2012 and involved four major actors of road safety research in France (LAB, CEREMA, IFSTTAR and CEESAR). The database gathered all the fatal accidents that had occurred in France in 2011 and 5% of all accidents resulting in an injury, selected at random. About 8,500 accidents were coded with information related to the infrastructure, the vehicle, the occupants and the injury. Experts in accident science added information related to vehicle impact speed, human functional failure, responsibility level, etc. This database is weighted to be representative of the accidental situation of France for year 2011, as described in the national census BAAC [12]. The weight depends on accident severity and on type of police force reporting the accident.

The AEB-Pedestrian target population used here consists of accidents in which a pedestrian (any age) was hit by the front part of a passenger car and impact speed was available. However, some cases were excluded from the selection: car in loss of control situation prior to impacting the pedestrian (Electronic Stability Control relevant cases), side swipe collisions were also left out because they would have required specific injury risk curves. Cars colliding with an obstacle prior to impacting the pedestrian, pedestrians lying on the road prior to impact or attempting suicide were not considered as relevant to AEB-Pedestrian. The raw data sample contains 164 fatally injured, 47 severely injured and 60 slightly injured pedestrians. A common bias is that vehicle impact speed is more often available for fatal accidents or accidents resulting in severe injuries, so a correction factor was applied to make up for the underrepresentation of slight injury accidents in the final sample containing cases with available impact speeds. The final weighted sample consists of 197 fatally injured, 1863 severely injured and 3103 slightly injured pedestrians. Injury severity is defined according to police definitions and not according to the AIS level as data are provided by police accident report : fatalities occur within 30 days of the accident, a severely injured pedestrian stays in hospital more than 24h and a slightly injured pedestrian stays in hospital less than 24h or not at all.

Injury Risk Curves

Injury risk curves are needed for the three levels of injury, as injury mitigation has to be taken into account within the evaluation process. Pedestrian injury risk curves for AEB-Pedestrian evaluation were built from a polytomous complementary log-log (CLOGLOG) regression model using the squared impact speed as an independent variable [13]. Probabilities of fatal injuries ($P(K)$) and probabilities of fatal or severe injuries ($P(KSI)$) were found to be given by the following equations:

$$P(K) = 1 - e^{\left(-e^{\left(-4{,}6451+0{,}00079*impactspeed^2\right)}\right)} \tag{1}$$

$$P(KSI) = 1 - e^{\left(-e^{\left(-1{,}5174+0{,}00079*impactspeed^2\right)}\right)} \tag{2}$$

where *impactspeed* is in km/h. A severe injury risk curve was derived by subtracting equation (1) from equation (2), and a slight injury risk curve by subtracting equation (2) from constant 1. The confidence intervals were estimated with the percentile confidence interval methodology [14].

Accident Reconstruction

Since VOIESUR database was used, the accident reconstruction was based on the available information in the police reports: photos of the vehicles and of the location after impact, documented two-dimensional (2D) infrastructure map with accident details such like the impact location, pedestrian projection distance, brake marks if any, etc. Witness interview details present in the reports were taken into account on one hand to confirm the police-given information, and on the other hand to complement eventually missing details in the maps. Thus, the last few meters of pre-crash vehicle trajectories were modelled, going as far back in time as the available data would allow, and trajectory types were restricted to portions of circles or straight lines. Pre-crash phase car acceleration or deceleration were assumed constant. Evaluating pedestrian pre-crash speeds was made through estimates based on age and attitude, e.g., walking, running. Evaluating impact speeds was made from estimates based on pedestrian projection distances [15][16][17]. Eventually, impact speeds and angles, cruising speeds and possible accelerations/decelerations prior to collision, trajectory radiuses of curvature, and whether the car was turning right, left or going straight, were reconstructed for all relevant accidents. Visibility obstacles (fixed and mobile environmental masks which may occlude the pedestrian from driver's or sensor vision such like buildings, trees or other moving vehicles) length and width in 2D were also coded.

Functional Simulation of AEB System

With the purpose of simulating the response of AEB-Pedestrian equipped vehicles in real-life accident situations and comparing simulated and actual outcomes, a simulation tool was developed in Matlab (*Mathworks*; Natick, Mass., USA). This tool makes use of the injury curves given by Equations (1) and (2) to transform simulation results expressed in terms of impact speeds into injury probabilities. Its inputs are:

1. Accident scenarios described by vehicle and pedestrian trajectories during a user-defined Time to Collision (TTC) value. Scenarios can include obstacles, fixed or moving.
2. Sensor characteristics such as range, vision angle, longitudinal and lateral position on the vehicle, detection delay.
3. Braking characteristics (transmission delay, maximal braking value, full braking delay). Maximal braking values mainly depend on road conditions (e.g. ice, rain).
4. Injury Risk Functions characteristic values

The outputs of this tool are:

1. Vehicle trajectories with AEB. These are determined using a point-mass, bi-dimensional vehicle model that computes the kinematic response to the AEB-controller input. This results from the chosen AEB braking logic described in this section.
2. TTC at pedestrian detection by the AEB system.
3. Distribution of impact speeds (original and with AEB). Track is kept of two different types of impact speed zero cases: the vehicle may cross the pedestrian's path without impact or stop prior to crossing the pedestrian's path.
4. Distribution of injured pedestrians (original and with AEB).

For braking to start, the chosen AEB logic requires that all of the following conditions are satisfied.

a. The pedestrian has entirely remained in the sensor's Field-of-View (FoV) for a user-defined detection and tracking time.
b. The pedestrian lateral distance, relative to the vehicle's direction of travel, has been lower than a maximal distance throughout the whole detection time.
c. The model-computed TTC is lower than a maximal value.
d. The vehicle Distance to Collision (DTC) is lower than a maximal value.

Once the *decision* to brake is made, braking does not start immediately, but after a (user-defined) information transmission delay. And when this is passed, the user-defined maximal braking value (maximal deceleration in m/s^2) is not reached immediately but after a linear increase over a (user-defined) full braking delay. The complete braking timeline is illustrated in Figure 1 and is similar to what was used in [8] – the main difference being that, in the context of the present paper, original drivers' pre-crash braking manoeuvres (if any) were combined – not replaced - with AEB responses, so as to maximise simulation realism.

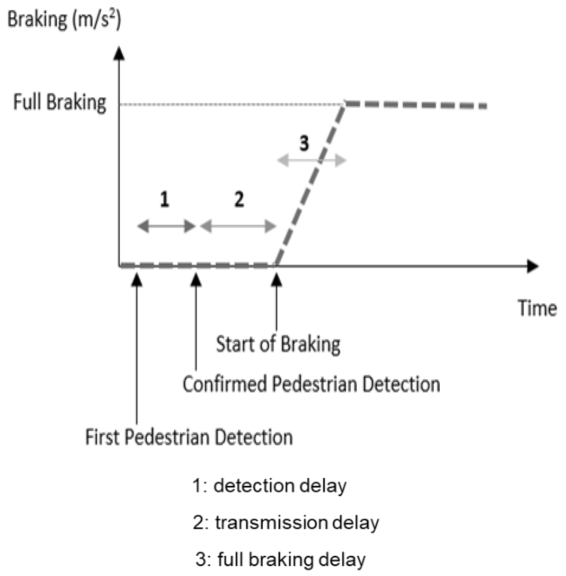


Fig. 1. Braking Profile.

Effectiveness Calculation

Assessing AEB-Pedestrian effectiveness consists in comparing outcomes from the original population of car-pedestrian accidents to the outcomes of their simulation with AEB in operation. Amongst all possible injury severity level dependent metrics, the following efficiency (E_{inj}) metric was used:

$$E_{inj} = 100 * \frac{N_{injini} - N_{injAEB}}{N_{injini}} \tag{3}$$

where N_{injini} is the original number of pedestrians at a given injury severity level and N_{injAEB} is the number of pedestrians remaining at that injury severity level after AEB simulation. For each individual accident, an injury probability is computed by making use of the injury risk curves and the new (with AEB) individual impact velocity. This probability is then multiplied by the pedestrian's statistical weight and the sum of these products gives the number of killed or injured resulting from the new impact speed. Only in the simulated accident population might avoided accidents (resulting in a *0 km/h* impact speed) occur. Avoided accidents have injury probability zero, regardless of injury level.

Assessed Configurations Four system setups were assessed in this study, differing only by the number, angle and range of their sensors. They are referred to as *narrow angle*, *reference*, *bi-sensor* and *high-end* systems in the sequel. For the *bi-sensor* and *high-end* systems, two sensor setups were supposed to collaborate for detecting pedestrians. A pedestrian was considered detected if remaining entirely inside one of the sensors' field of view throughout the relevant detection delay. All system parameters values are illustrated in table I.

TABLE I

SYSTEM PARAMETERS VALUES

System parameter	Narrow angle	Reference	Bi-sensor	High-end
Sensor1 range	40 m	20 m	30 m	40 m
Sensor1 vision angle	18°	60°	35°	18°
Sensor1 detection delay	0.2 sec	0.2 sec	0.2 sec	0.2 sec
Sensor2 range	--	--	30 m	15 m
Sensor2 vision angle	--	--	35°	90°
Sensor2 detection delay	--	--	0.2 sec	0.2 sec
Maximal TTC	1 sec	1 sec	1 sec	1 sec
Braking transmission delay	0.05 sec	0.05 sec	0.05 sec	0.05 sec
Braking slope	0.3 sec	0.3 sec	0.3 sec	0.3 sec
Maximal braking value	-9 m/s^2	-9 m/s^2	-9 m/s^2	-9 m/s^2
Pedestrian lateral distance	2.9 m	2.9 m	2.9 m	2.9 m
DTC	15 m	15 m	15 m	15 m

Sensitivity Analysis

Setting experiments to assess response sensitivity to a set of factors is known as factorial design of experiments (DoE). These can be *full* (using all possible combinations of factors) or *fractional*. Taguchi constructed sets of orthogonal arrays that stipulate the way to build minimal size fractional DoE. An overview of these methods can be found in [18].

Factors Sensitivity analyses were undertaken on three sensor configurations: one single sensor, one coaxial bi-sensor (one Long Range / Narrow Angle sensor and one Short Range / Wide Angle sensor sharing the same lateral position on the vehicle) and one frontal bi-sensor (two Short Range / Wide Angle sensors sharing the same longitudinal position on the vehicle). Factors are listed in Tables II through IV.

TABLE II

SINGLE SENSOR ANALYSIS SETUP

Feature	Factor	Unit	Values
Sensor	Longitudinal Position	m	0, -1, -1.3
"	Lateral Position	m	-0.7, 0, 0.7
"	Detection Delay	s	0.2
"	Range	m	5, 10, 20
"	Angle	°	20, 45, 90
"	Braking Transmission Delay	s	0.05
"	Maximal Braking Value	m/s^2	9
"	Full Braking Delay	s	0.3
"	Maximal Lateral Distance	m	3
"	Maximal Distance to Collision (DTC)	m	15
"	Maximal Time to Collision (TTC)	s	1

TABLE III
COAXIAL BI-SENSOR ANALYSIS SETUP

Feature	Factor	Unit	Values
Long Range Sensor	Longitudinal Position	m	0, -1, -1.3
"	Detection Delay	s	0.1, 0.2, 0.3
"	Range	m	50, 75, 100
"	Angle	s	20, 30, 40
Short Range Sensor	Detection Delay	s	0.1, 0.2, 0.3
"	Range	m	10, 30, 50
"	Angle	°	40, 60, 90
Common Features	Braking Transmission Delay	s	0.1, 0.15, 0.2
"	Maximal Braking Value	m/s^2	4, 7, 9.8
"	Full Braking Delay	s	0.1, 0.2, 0.3
"	Maximal Lateral Distance		1, 2, 5
"	Maximal Distance to Collision (DTC)	m	10, 20, 30
"	Maximal Time to Collision (TTC)	s	0.5, 1, 1.5

TABLE IV
FRONTAL BI-SENSOR ANALYSIS SETUP

Feature	Factor	Unit	Values
Short Range Sensors	Distance from Vehicle Longitudinal Axis	m	0.3, 0.5, 0.7
"	Detection Delay	s	0.1, 0.2, 0.3
"	Range	m	10, 20, 30
"	Angle	°	20, 40, 90
Common Features	Braking Transmission Delay	s	0.1, 0.15, 0.2
"	Maximal Braking Value	m/s^2	4, 7, 9.8
"	Full Braking Delay	s	0.1, 0.2, 0.3
"	Maximal Lateral Distance	m	1, 2, 5
"	Maximal Distance to Collision (DTC)	m	10, 20, 30
"	Maximal Time to Collision (TTC)	s	0.5, 1, 1.5

Equation (4) gives the minimum number of experiments (N) required by the Taguchi method if N_f is the number of factors with L_i possible levels:

$$N = 1 + \sum_{i=1}^{N_f} (L_i - 1) \tag{4}$$

L36 – a matrix of 36 experiments, Equation (4) giving a minimum of 27 – was chosen for all analyses.

Responses Response metrics address different aspects of AEB performance. The first three are number of avoided fatally injured (A_F), number of avoided severely injured (A_{SI}) and number of avoided slightly injured (A_{SLI}). Use was made of the maximal social cost estimates (C_F, C_{SI}, C_{SLI}) from European project Safety Cube [19] to set up a Global Metric (M_G), reflecting the fact that although injuries are less *expensive* to society than fatalities, they are far more frequent.

$$M_G = C_F * A_F + A_{SI} * C_{SI} + A_{SLI} * C_{SLI} \tag{5}$$

Factor Contributions Response variations over the entire DoE were quantified by variance indicator *SCT* (equation (6)). Individual factor's contributions were quantified through global contribution indicators (equation (9)) ranking contributions to the global variance:

$$SCT = \sum_{i=1}^{n} (Y_i - \bar{Y})^2 \tag{6}$$

$$e_{A_i} = \bar{Y}_{A_i} - \bar{Y} \tag{7}$$

$$SC_A = \frac{n}{m} * \sum_{i=1}^{m} {e_{A_i}}^2 \tag{8}$$

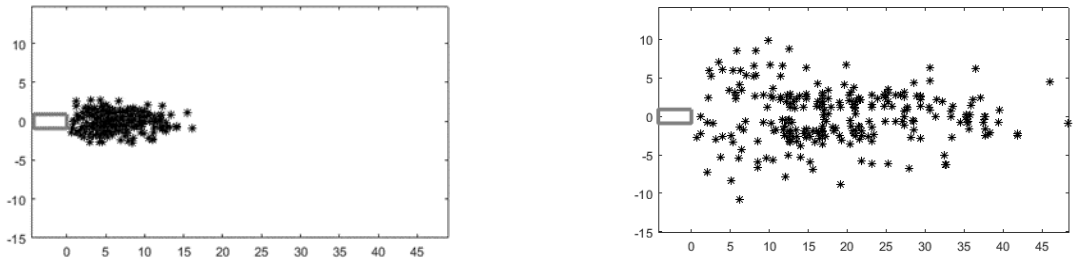
$$CTR_A = \frac{SC_A}{SCT} \tag{9}$$

where $\bar{Y}$ is the average response of the DoE, Y_i is the response for line i of DoE, n is the number of experiments in the DoE, $\bar{Y}_{A_i}$ is the average DoE response when factor A is at level i out of m possibilities.

III. RESULTS

Pedestrian Positions Relative to the Car

The simulation tool provides pedestrian positions relative to the car at various TTC values (Fig. 2).



(a) (b)

Fig. 2. Pedestrian positions at (a) TTC = 0.5 sec and (b) TTC = 1.5 sec.

Sensitivity Analysis

Table V shows the results of the coaxial bi-sensor analysis in decreasing order of factor contributions (in %) to the global metric.

TABLE V
COAXIAL BI-SENSOR ANALYSIS RESULTS

	Global	Fatally injured	Severely Injured	Slightly Injured
Maximal Braking Value	38,38	42,82	37,88	24,73
Maximal Lateral Distance	31,7	29,1	31,98	29,07
Maximal TTC	9,76	6,82	9,99	14,24
Short Range Sensor Angle	6,25	2,09	6,83	15,52
Full Braking Delay	3,61	4,03	3,59	2,21
Braking Transmission Delay	2,36	2,31	2,37	2,07
Maximal DTC	2,3	8,07	1,7	1,63
Long Range Sensor Angle	1,64	0,71	1,68	4,16
Long Range Sensor Detection Delay	0,59	0,38	0,63	0,78
Short Range Sensor Range	0,21	0,19	0,22	0,58
Long Range Sensor Longitudinal Position	0,19	0,1	0,22	0,38
Long Range Sensor Range	0,12	0,07	0,12	0,71
Short Range Sensor Detection Delay	0,03	0,06	0,02	0,03
Residual	2,86	3,25	2,77	3,89

The maximal braking value appears to be the most influential factor, in nearly all metrics, with contributions ranging from over 24% (slightly injured) to around 43% (fatally injured) and effectiveness increasing as maximal braking values increase. Two very influential factors are worth mentioning: the maximal Lateral Distance (pedestrians occurring beyond this distance limit are not detected) and the maximal Time to Collision (no car braking action if the remaining TTC is over this limit). Lateral Distance is the most influential on slightly injured whereas maximal TTC contribution increases from 6.8% to 14% as the level of injury decreases. For both factors, higher values result in higher AEB effectiveness. Maximal DTC only ranks seventh for the global metric but is one of the most effective factors in reducing fatalities. Higher settings of this factor favour AEB effectiveness. Finally, the short-range sensor's angle emerges as influential on slightly injured.

The front bi-sensor sensitivity analysis results in a very different picture. Table VI illustrates this fact by showing all factors in decreasing order of contributions (in %) to the global metric.

TABLE VI

FRONTAL BI-SENSOR ANALYSIS RESULTS

	Global	Fatally injured	Severely Injured	Slightly Injured
Sensor Angle	32,29	37,91	30,3	22,38
Maximal Lateral Distance	24,19	14,35	26,01	28,35
Maximal Braking Value	21,15	8,25	24,23	30,02
Sensor Range	5,62	19,17	3,43	0,89
Maximal TTC	4,32	3,28	4,43	4,23
Full Braking Delay	2,84	3,83	2,62	1,09
Braking Transmission Delay	0,9	0,55	0,9	1,6
Sensor Detection Delay	0,64	0,85	0,6	0,7
Lateral Sensor Distance	0,46	1,33	0,31	0,08
Maximal DTC	0,01	0,33	0,01	0,43
Residual	7,58	10,15	7,16	10,23

Sensor angle, maximal lateral distance and maximal braking value all play an important part and their predominance depends on metric. Sensor angle is most influential on fatally and severely injured, lateral distance and braking value on slightly injured. Sensor range appears as the second most influential on fatalities and maximal TTC does not appear to be effective. High residual values suggest that factor interactions (not considered here) could have an influence on this ranking. Table VII illustrates the single sensor analysis and shows balanced contributions of angle (over 52%) and range (over 40%) in slightly injured. Other metrics offer a more contrasted view as increased range emerges as most and almost sole beneficial factor on fatally and severely injured.

TABLE VII

SINGLE SENSOR ANALYSIS RESULTS

	Global	Fatally injured	Severely Injured	Slightly Injured
Longitudinal Sensor Position	0,02	0,14	0,02	0,55
Lateral Sensor Position	0,43	0,06	0,49	1,54
Sensor Range	75,38	91,59	72,9	40,01
Sensor Angle	20,6	6,75	22,47	52,76
Residual	3,57	1,46	4,12	5,14

Effectiveness Analysis

Fig. 3 shows the FoV of different systems in dashed lines and circle portions at TTC=1s. Pedestrians who were hidden from the systems' or driver's FoV by an obstacle were represented by square boxes.

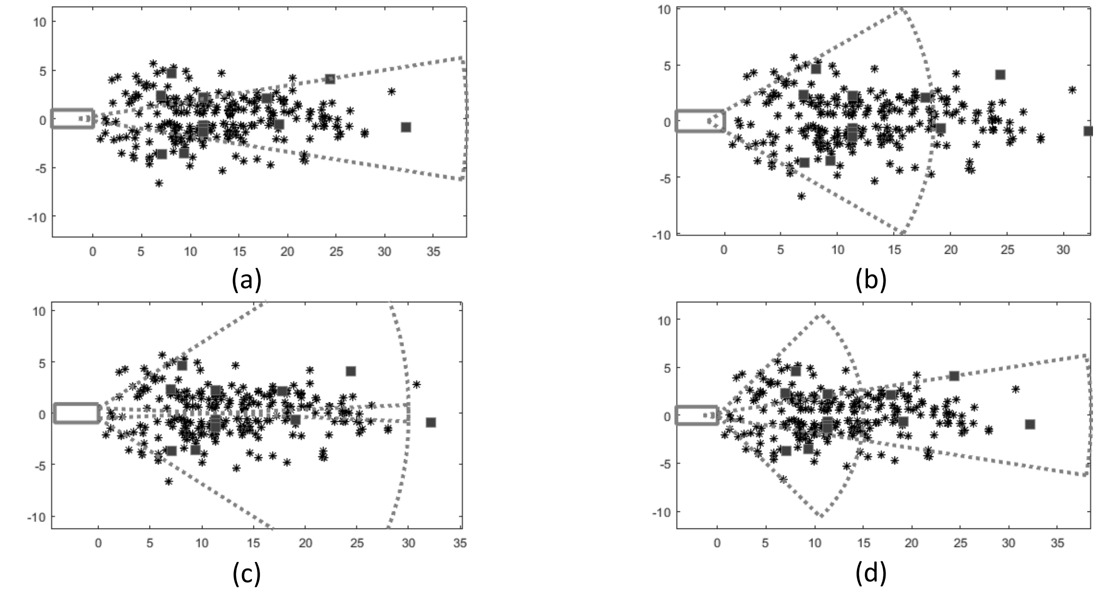


Fig. 3. Pedestrian positions relative to the car at TTC = 1 sec and FoV for (a) *narrow angle*, (b) *reference*, (c) *bi-sensor*, and (d) *high-end* systems

The simulated mean impact speed dropped from 28.4 km/h to 18.3 km/h, 8.7 km/h, 9.5 km/h, and 8.4 km/h for the *narrow angle*, *reference*, *bi-sensor* and *high-end* systems respectively (Figure 4).

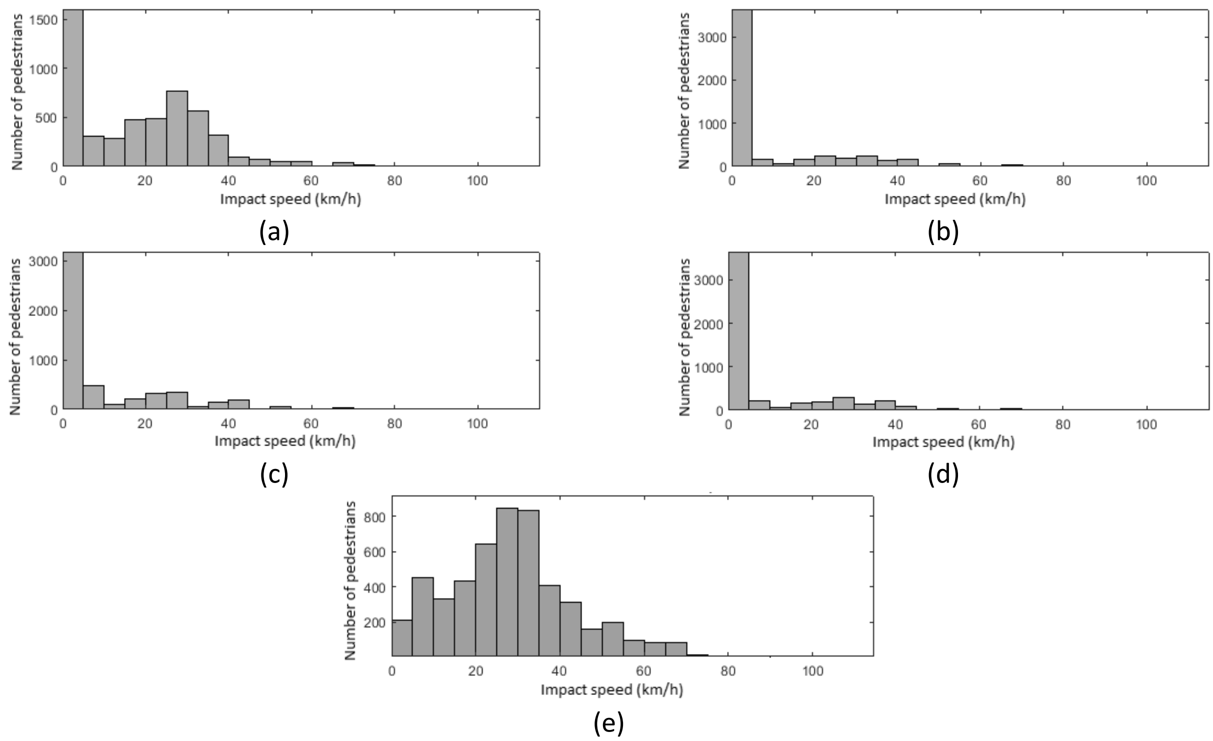


Fig 4. Weighted original (e) and simulated impact speed distributions and mean value for the (a) *narrow angle*, (b) *reference*, (c) *bi-sensor*, and (d) *high-end* systems

These speeds enabled AEB-Pedestrian effectiveness calculations. Table VIII gives the effectiveness of the four AEB pedestrian systems while Figure 5 shows the number of still injured pedestrians.

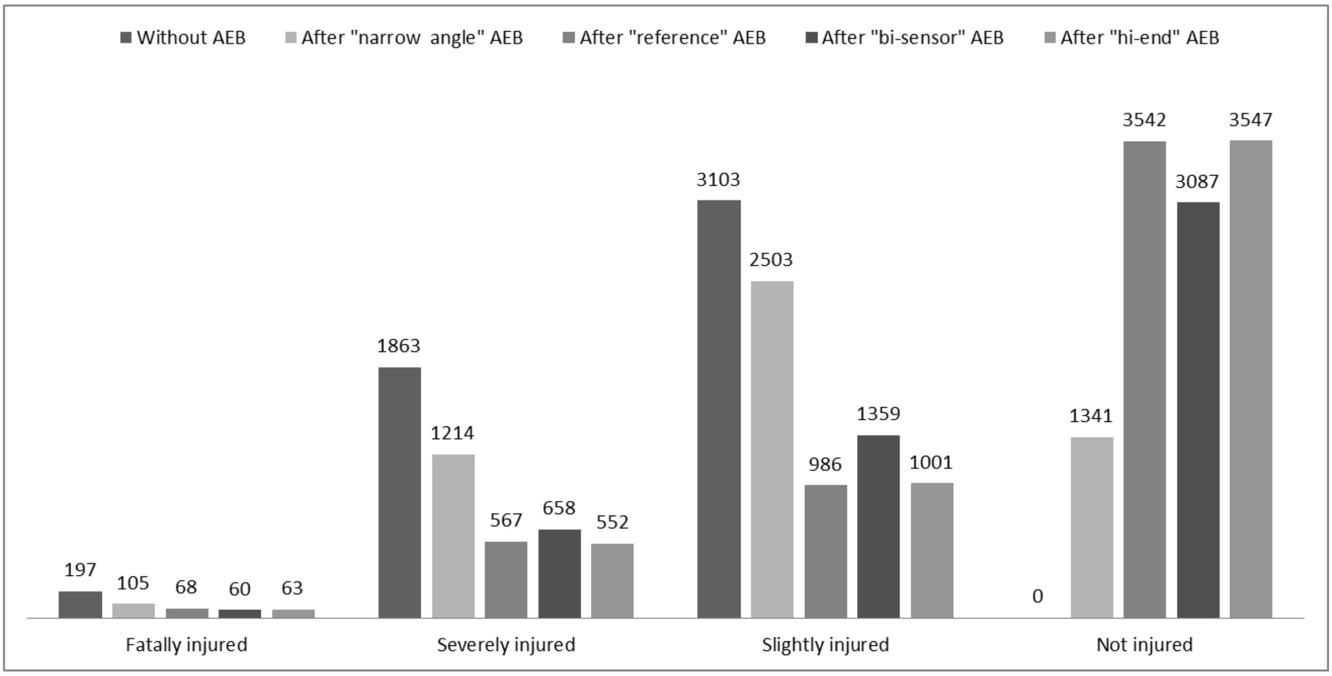


Fig. 5. Weighted distributions of injured pedestrians before AEB simulation and after application of the four different systems.

TABLE VIII
EFFECTIVENESS OF THE ILLUSTRATED SYSTEMS

Injury level	Narrow angle	Reference	Bi-sensor	High-end
Fatal	46%	65%	70%	68%
Severe	35%	70%	65%	70%
Slight	19%	68%	56%	68%

IV. DISCUSSION

The scientific literature contains several studies addressing AEB-Pedestrian effectiveness [9], of which references [10] through [14] stand out. To the best of the authors of the present study's knowledge, references [10][13-14] are the only ones that could be compared with the presented results, since reference [12] did not use injury risk curves, only assessed one AEB technology and did not seek to use a representative baseline accident sample. This representativeness issue is also present in [11]. One novel aspect of this study is the fact that a comparison between single sensor and bi-sensor AEB setups was achieved in terms of effectiveness in reducing the number of injured pedestrians. The present work also showcases a first of its kind sensitivity analysis of different sensor settings.

The sensitivity analysis results presented in this paper help rank the most influential factors by type of pedestrian injury situation. This type of analysis cannot be found in any of the mentioned studies, as their authors focused on evaluating and comparing a few realistic or existing combinations of factors. However, the beneficial influence of maximal braking force, maximal TTC, maximal lateral distance or sensor angle is highlighted in all studies. Maximal braking force is influential in all metrics. This is a reminder that AEB will not work as a miracle solution in all configurations and has to be supplemented, e.g., by Autonomous Emergency Steering (AES) for optimal effectiveness. The variability on this factor mainly lies in varying road conditions – lower values occurring on wet or icy roads – even though manufacturers can regulate maximal braking values for better driver comfort and safety. Results were also shown to be heavily dependent on sensor architecture, e.g., number, typology, position. Maximal TTC appears influential in one of the bi-sensor analyses and its contribution increases as the level of injury decreases. This fact is explained by fatalities occurring when a pedestrian becomes fully visible from the car at very short notice. Setting high values for this factor and also maximal Lateral Distance would result in more false positive situations - causing driver discomfort or an increase in other types of accident, e.g., rear-ending through unnecessary braking. This again causes manufacturers to restrain variability ranges on these factors.

The effectiveness results obtained in this study are comparable to those found in the literature, even though different accident samples and injury risk curves were used and the systems that were compared have parameters that do not match. However, for example, when for comparing the *Max brake* system from [13] (82% effectiveness on fatally injured and 76% on fatally and severely injured) to the *High-end* system from this study, the 14% better efficiency is widely accounted for with higher system variable values like TTC and pedestrian lateral distance. When focusing on different sensor designs and setting the remaining parameters to optimistic nominal values, the number of sensors seems to have less influence on the effectiveness than the FoV design. When comparing the four systems illustrated in this study, the *narrow angle* system turned out to be, as expected, the least efficient system especially for slightly and severely injured where its effectiveness is really low when compared to the other systems. This is supported by figure 3 (a), which shows that many pedestrians that are at a low longitudinal distance from the vehicle at TTC = 1 sec (low vehicle speed cases) are not detected at TTC = 1 sec. Conversely, many pedestrians that are at a high longitudinal distance from the vehicle at TTC = 1 sec (high vehicle speed cases) are detected due to the high range of the FoV of this system. The results also show that optimised single sensor settings, e.g., *reference* system, gives very comparable results in terms of effectiveness when compared to multiple sensor settings combining short range and long-range sensors. The fact that the *high-end* system uses a sensor with wide-view angle does not improve its effectiveness on severely and slightly injured. The *bi-sensor* system is also less effective on slightly injured than the *reference* system. This could be related to pedestrians occurring close to the middle of the car front-end and thus being too close for complete detection by either of the two sensors of the *bi-sensor* setup.

The authors would like to remind that this study did not take AEB possible side-effects into account. Examples of these include more rear-endings caused by unexpected AEB braking (especially false activations) and driver over-confidence in systems that are not 100% effective in critical situations.

V. CONCLUSIONS

This study estimates the effectiveness of AEB pedestrian systems based on real-life accidental situations selected from a representative French accident database. It shows that AEB pedestrian systems have a good potential of injury reduction as their effectiveness ranges from 46% to 70% for fatally injured, from 35% to 70% for severely injured, and from 19% to 68% for slightly injured. However, it is important to mention that this prospective analysis utilises a “nominal” AEB model supposing a perfect functioning of the system in all situations (sensors that work in all lighting conditions, braking force that doesn’t depend on road conditions, etc). A list of potential issues that may reduce AEB effectiveness are given in [20]. Thus, the effectiveness values given in this study should be interpreted as a maximal potential for AEB pedestrian systems in reducing pedestrian injuries.

The safety benefits of using multiple sensor combinations instead of one single optimised sensor could not be ascertained. Long range / low angle of view sensors are widely used in the industry because of their cost-effectiveness, since they can be used for a variety of Advanced Driver Assistance Systems, i.e., Lane Keeping or Adaptive Cruise Control. The present work shows that this kind of sensor enables a moderate reduction in the number of fatal pedestrian injuries while its effectiveness in avoiding or mitigating non-fatal injuries remains low.

The sensitivity analysis results helped rank the most influential factors by type of pedestrian injury situation. Some of them depend almost solely on road conditions, some others have an influence on driver comfort and must be carefully tuned. This is a reminder that AEB alone cannot avoid all accidents in all configurations and that it has to be supplemented by other active or passive safety systems for optimal effectiveness.

VI. REFERENCES

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