BENEFITS ASSESSMENT OF AUTONOMOUS EMERGENCY BRAKING PEDESTRIAN SYSTEMS BASED ON REAL WORLD ACCIDENTS RECONSTRUCTION

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ABSTRACT

Despite the success in reducing Spanish traffic fatalities by 65 percent in the past decade (2004 - 2013), pedestrian fatalities only have diminished by 45% (decreased by 35% in urban areas).

This paper describes the main findings of a coordinated study performed by INSIA-UPM aimed to assess the potential influence of two active safety systems, a brake assist system (BAS) and an autonomous emergency braking system (AEB), in vehicle-pedestrian collisions through reconstruction of real-world accidents occurred in the city of Madrid (Spain).

A total number of 50 vehicle-pedestrian collisions have been in-depth investigated following a common methodology, including on the spot data collection, analysis and reconstruction to estimate the collision speed and the pedestrian kinematics. Every single case has been virtual simulated twice using PC-Crash® software: the first is a reconstruction of the real accident and the second is a simulation in which the operation of active safety systems is emulated.

The performance of the BAS system acts together with the antilock braking system (ABS). The AEB system emulated in this paper through computer simulations is based on the DaimlerChrysler's PROTECTOR system.

The benefit is assessed in terms of both collision speed and Injury Severity Probability (ISP) by comparing the reduction of their values from the real conditions to the virtual simulations. The pedestrian ISP was estimated, depending on the collision speed and the pedestrian head impact point, using a specific application to calculate its value based on the results of head form impact laboratory tests.

The findings show that in several cases the collision could be avoided by implementing the active safety systems (12% if the vehicle was fitted with BAS+ABS system; 42% with PROTECTOR system); and it would reduce their consequences in terms of the estimated ISP. It was also found that in few cases a low reduction of the collision speed would increase the head injury severity (10%).

Further research should include injury information and/or estimation (HIC). Other limitations are the sample size (only one city and frontal collisions) and no unhurt accidents have been included.

The injury severity assessment within this study only considers head impacts to the front surface of the vehicle, injuries provoked by subsequent impacts were not taken into account. Hence it can be an interesting subject for further research.

This is new because: it is a prospective assessment of active safety systems and autonomous emergency braking systems; it is based on accurate reconstructions, highly detailed parameters; the behavior of the system is simulated according to design parameters.

Multi-disciplinary approaches such as this study make the identification of critical parameters easier and simplify the development of practical solutions by quantifying their potential impact on future actions to improve pedestrian safety. The active safety braking pedestrian systems have a potential benefit in real conditions. It also has limitations so we cannot rely just on it. It has to act together with other passive features and the driver has to keep aware. This methodology can serve to test the benefit of forthcoming active safety technologies.

INTRODUCTION

Pedestrians are the most vulnerable road users and when involved in traffic accidents often suffer severe and fatal injuries. In year 2013 a total of 378 pedestrians were killed in the Spanish roads (22.5% of the overall traffic fatalities), 224 fatalities ocurred in urban areas (49.8% of the urban traffic fatalities). Compared with the year 2004 figures, the pedestrian fatalities percentage of total fatalities has increased (in 2004, 14.4% of national traffic fatalities, 38.1% of urban traffic fatalities).

This high vulnerability has its response in the manufacturers and the Public Administrations, which adopt different measures to protect these road users, e.g. driver and pedestrian education, urban planning, vehicles design and equipment...

The technological advances for vehicles adopted to enhance road users' protection have been primarily focused on secondary safety; however there are a number of recent developments aimed to avoid the collisions. Many accidents are caused by late braking and/or braking with insufficient force. In this way, the European Parliament and the Council have enacted Regulation (EC) 78/2009 (The European Parliament and the Council of the European Union, 2009 [11]) "on the type-approval of motor vehicles with regard to the protection of pedestrians and other vulnerable road users..." binding the manufacturers to equip the new vehicles placed on the European market with a type-approved brake assist system (BAS). According to the text of the Regulation, a brake assist system is a function of the braking system that deduces an emergency braking event from a characteristic of the driver's brake demand and, under such conditions assists the driver to deliver the maximum achievable braking rate; or is sufficient to cause full cycling of the Anti-lock Braking System (ABS).

The brake assist system was originally introduced to compensate the insufficient brake rates due to unexpected driver reactions discovered in rear-end collisions. It was found that despite the antilock braking system, the braking distance in critical situations was not significantly reduced. The reason was that drivers were not pushing the brake pedal strong and quick enough to its full stroke. The advantages of BAS as an active safety system were soon evidenced to avoid collisions and reduce the impact speed when the collision was inevitable. Thus the European Commission decided to make mandatory the fitting of BAS in new vehicles, representing one of the first active safety requirements for type-approval of motor vehicles with regard of the pedestrian protection (Badea-Romero et al, 2013 [1]).

Additionally primary safety systems have been developed for vehicles in order to autonomously detect a pedestrian and to avoid or mitigate the impact. The global functioning of these systems is based on analyzing the forward path of the vehicle in real time in order to try to identify a pedestrian on the road. If it is determined that the pedestrian trajectory is across the forward path of the vehicle, as a countermeasure to avoid an imminent crash, these systems employ emergency braking and some may potentially employ emergency steering (Hamdane et al, 2014 [4]). The systems they have developed can be grouped under the title AEB: Autonomous (the system acts independently of the driver to avoid or mitigate the accident); Emergency (the system will intervene only in a critical situation); and Braking (the system tries to avoid the accident by applying the brakes). AEB systems improve safety in two ways: firstly, they help to avoid accidents by identifying critical situations early and warning the driver; and secondly they reduce the severity of crashes which cannot be avoided by lowering the speed of collision ([14]).

The evaluation of the benefit of two active safety systems, a brake assist system (BAS) and an autonomous emergency braking system (the DaimlerChrysler's PROTECTOR system), for pedestrians involved in accidents is tackled in this paper which describes an in-depth accident investigation performed by INSIA-UPM. Data of 50 frontal vehicle-pedestrian collisions occurred in the city of Madrid between 2002 and 2006 were collected. Every single case has been virtual simulated twice using PC-Crash® software: the first is a reconstruction of the real accident and the second is a simulation in which the operation of the two active safety systems, BAS and PROTECTOR systems, is emulated modifying the collision parameters and its potential consequences.

To harmonise the process, a simulation procedure with simplified hypotheses about the driver's reactions, the brake assist system and the autonomous emergency braking pedestrian system operation was previously adopted. Collision speeds and pedestrian kinematics have been obtained from the reconstructions, which

allowed estimating the Injury Severity Probability (ISP) as the parameter considered for assessing the benefit of the active safety systems in terms of injury mitigation.

METHODOLOGY

The methods presented in this section were developed within the framework of a research project (INSIA et al., 2008 [5]). The methodology was established to encompass into one optimal procedure to investigate on the spot every single accident, perform reconstructions and simulations, and analyse the obtained data and the results.

Accident investigation and reconstruction

To investigate and reconstruct accidents occurred in Madrid, a multidisciplinary team was created with the support of local police forces, emergency services and hospitals.

The sampling was based in three main criteria: first, according to the road characteristics, the selected accidents should occur in urban areas; the second criterion is about the vehicle type, considering only accidents in which the striking vehicle was a passenger car (86%), a SUV (2%) or a people carrier (12%); the third is related to the accident configuration, only where the pedestrian was struck by the front of a passenger car. No restrictions about pedestrian characteristics such us gender, age, height or weight were imposed.

On the spot accident investigation and data collection was the first step of the process. The investigation teams in collaboration with the police forces attended the scene to collect all the available information about the scenario, geometry of the roads, visibility, visual evidence such as skid marks and traces, and also vehicle damages, dents and marks. Information about the injuries was obtained from paramedics and hospital data and used in the analysis phase for determining the injury mechanisms.

Once the investigation and data compilation phases were finished, the available information was analyzed, revised and prepared to be used in the reconstruction. Fully detailed scene plans were drown to be used in the reconstruction process.

Next the corresponding vehicle was selected in each case and loaded from the vehicle database available in the computer program; its characteristics were set up according to the real vehicle. The frontal shapes of real vehicles were accurately measured for this purpose.

Based on anthropometric studies (Spanish Ministry of Health, 2008 [10] and Benjumea, 2001 [2]), multi-body pedestrian models have been defined, representative of the up-to-date Spanish population for both male and female, and for a wide range of ages.

Finally, the virtual simulations of the accidents were performed using a reconstruction software. As it has been recently shown (Untaroiu et al., 2010 [12]) the initial conditions have a strong influence on the reconstruction kinematics. Many parameters such as approaching speed, path, position, pedestrian motion, driver maneuvers and sequences are slightly modified and tested in different combinations in an iterative process that leads to a reliable reconstruction, matching both the impact points with the visual evidence such as dents or marks and with the injury locations and mechanisms, and the vehicle and pedestrian rest positions.

Some simplifying hypotheses were established so all the simulations were performed from a common approach. These basic simplifications were: 1) the reaction time of the driver was considered to be one second for all cases; 2) the lag for a conventional brake system was 0.25 s; 3) the Possible Perception Point (PPP) of the driver was the instant in which the pedestrian stepped onto the pavement and no obstacle covered the driver's field of vision; 4) three intensity levels were established for the pre-collision brake force: no brakes when the evidence show that the driver had no time to react or was completely unaware of the pedestrian presence on the vehicle path, a default medium intensity brake for most accidents and a full brake when evidence such as skid marks leaded to it.

Simulation of BAS+ABS operation

The BAS operation can be described in three steps: a) detection of the pedal signal; b) interpretation and decision; and c) actuation.

At the first step a sensor detects a signal from the brake pedal. At the second phase the input signal is processed by the electronic central unit which decides if it corresponds to an emergency braking situation, triggering the system or keeping it in standby when normal braking. Next, if the control unit estimates that the signal corresponds to an emergency braking, an electric valve is opened and the pressure of the system increases to its maximum operating level activating the antilock system that prevents the vehicle from skidding.

The BAS operation features specified for its approval were taken into account when performing the virtual simulations. The parameters used to emulate the BAS in the virtual simulations are presented in table 1.

Table1. BAS and PROTECTOR systems variables used in the virtual simulations.

Variable Name	Notation	Unit	Source
Pre-collision braking distance	S_k	m	Reconstruction
Approaching speed	V_0	km/h	Reconstruction
Braking deceleration with BAS+ABS	a_{BAS}	m/s^2	BAS-simulation
Braking deceleration with PROTECTOR	a_{PROT}	m/s^2	PROT-simulation
Braking deceleration	a_k	m/s^2	Reconstruction
Reaction time	t_0	s	Average values
Pre-collision braking time	t_k	s	Reconstruction
Lag of the brake system with BAS+ABS	t_{BAS}	s	SAVE-U ([6])
Collision speed	V_k	km/h	Reconstruction
Collision speed with BAS+ABS	V_{kBAS}	km/h	Reconstruction
Collision speed with PROTECTOR	V_{kPROT}	km/h	Reconstruction
Brake distance with BAS	S_{BAS}	m	BAS-simulation
Collision speed with BAS	V_{BAS}	m	BAS-simulation
Brake distance with PROTECTOR	S_{PROT}	m	PROT-simulation
Collision speed with PROTECTOR	V_{PROT}	m	PROT-simulation

Starting from the initial driving speed (V_0) obtained from the real accident reconstruction; a second virtual simulation was performed considering the BAS. The hypotheses adopted for the pre-impact phase were: when the BAS starts to operate, the ABS has to be activated and its operation frequency set up at the correct value to prevent from skidding, regardless if the original vehicle was fitted or not with such system. The PPP remains the same as also does the reaction time of the driver (t_0) but the lag of the brake system is reduced from 0.25s in normal conditions to 0.1s when the BAS is activated according to the results presented by Meinecke et al. (2003 [6]) within the SAVE-U project.

After the reaction and the lag sequences, the braking phase was established at the maximum deceleration (a_{BAS}) allowed by the computer program according to the friction conditions, which was considered equal to the deceleration that can be achieved with full cycling of the ABS (a_{ABS}). Then new values of the braking distance and the impact velocity were obtained and the difference was evaluated. If the braking distance to the collision point with the BAS (S_{BAS}) was less than the pre-collision braking distance (S_k) obtained from the reconstruction, then the collision could have been avoided due to the BAS; otherwise new simulations of the collision and post-collision phases had to be performed modifying the values of both the impact velocity and brake deceleration (V_{BAS} and a_{BAS} respectively). The modifications of the relative position between the vehicle and the pedestrian and the pitch angle of the vehicle at the collision point were also considered.

Simulation of the DaimlerChrysler's PROTECTOR system

The DaimlerChrysler's PROTECTOR system (SAVE-U consortium, 2005 [9]) has been tested in the EC-Project "SAVE-U. Sensors and system Architecture for VulnerablE road Users protection (Project IST - 2001 - 34040)".

Two strategies for the protection of vulnerable road users (VRU) have been implemented in the DaimlerChrysler vehicle: acoustical driver warning and automatic braking. In case of a high risk of a collision, automatic braking tries to either avert the crash at all or to mitigate the impact if the collision is unavoidable.

The deployment strategy of these protection measures consists of three phases:

- Phase 1: Early Detection. The sensor platform detects and tracks all VRUs in front of the vehicle (within the sensor coverage area), but none of protection measures are activated yet.
- Phase 2: Acoustical Driver Warning. A VRU is detected to enter the vehicle's path, but there is no risk of an immediate collision yet. The driver is alerted by an acoustical signal about this potentially dangerous situation.
- Phase 3: Automatic Braking. A high risk of a collision has been identified. The vehicle is decelerated in order to avert the collision or, in case a collision is unavoidable, mitigate the impact.

The decision about the activation of a protection measure is made from the position and heading direction of the pedestrian, and the current vehicle path. For that purpose, the detection area is divided into three zones, see figure 1:

- The red zone, 1.5m to each side, approximately represents the vehicle path. VRUs within this area are considered of being in risk of collision.
- VRUs in the yellow zone, from 1.5m to 3m to each side, are considered only if they are heading towards the vehicle path.
- VRUs in the green zone are not considered for the activation of one of the protection measures.

The automatic brake system operation features specified for the DaimlerChrysler's PROTECTOR system were taken into account when performing the virtual simulations. The parameters used to emulate this system in the virtual simulations are presented in table 1.

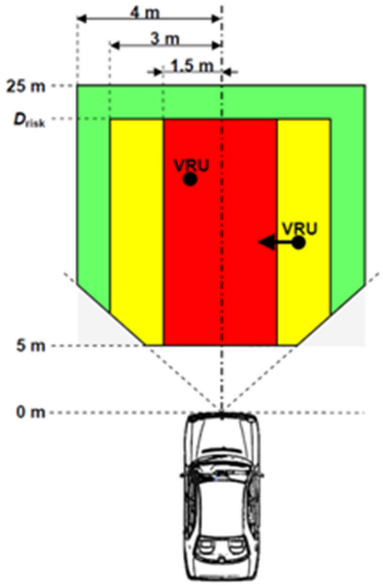

Figure1. DaimlerChrysler's PROTECTOR system. Subdivision of the detection area into 3 risk zones.

Starting from the approaching speed (V_0) obtained from the real accident reconstruction; a second virtual simulation was performed considering the PROTECTOR system. The hypotheses adopted for the pre-impact phase were: when the pedestrian goes into the red zone an automatic brake system starts to operate, the ABS has to be activated and its operation frequency set up at the correct value to prevent from skidding, regardless if the original vehicle was fitted or not with such system. The PPP (Possible Perception Point) remains the same as also does the reaction time of the driver (t_0).

After the reaction and lag sequences, the braking phase was established at the maximum deceleration (a_{PROT}) allowed by the computer program according to the friction conditions, which was considered equal to the deceleration that can be achieved with full cycling of the ABS. Then new values of the braking distance and the impact velocity were obtained and the difference was evaluated. If the braking distance to the collision point with the PROTECTOR system was less than the pre-collision braking distance (S_k) obtained from the reconstruction, then the collision could have been avoided due to the PROTECTOR system; otherwise new simulations of the collision and post-collision phases had to be performed modifying the values of both the impact velocity and brake deceleration (V_{PROT} and a_{PROT} respectively). The modifications of the relative position between the vehicle and the pedestrian and the pitch angle of the vehicle at the collision point were also considered.

Estimation of the Injury Severity Probability (ISP)

Head injuries are the most severe and with threat to life that pedestrians suffer when struck by a vehicle (Yao et al., 2008 [13]). The severity of the injuries depend on many parameters such as the collision speed, head impact point, collision configuration, vehicle shape, anthropometric measures of the pedestrian and rigidity of the component hit by the head.

The intensity of head impact is often assessed by the head injury criterion (HIC) (Mizuno and Ishikawa, 2001 [7]). The HIC can be correlated to the risk of severe injury, which gives a much clear idea of the how serious the head impact might be.

The methodology used in this research to estimate the head injury severity is described in figure 2 (Badea-Romero et al., 2013 [1]). First, the location of the head impact point is obtained from the computer simulation and represented by a row and a column corresponding to the wrap around distance (WAD) and the distance across the frontal respectively.

Then data from several laboratory tests performed at Applus+ IDIADA are used to estimate the correspondent HIC.

To estimate the injury severity, the value of the HIC obtained from the test is then derived into the probability of suffering a severe (AIS3+) head injury (ISPHIC,H,3). Thus the intensity of the head impact given by the HIC is translated into the injury severity that it can potentially cause. This is not a novel procedure, it has been previously presented by Fröming et al. (2006) [3].

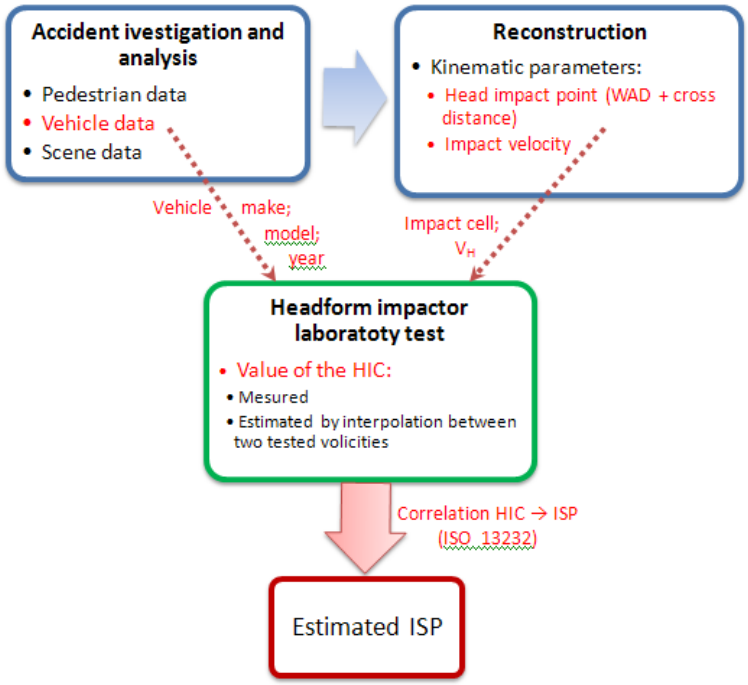

Figure2. Methodology to estimate the Injury Severity Probability (ISP) [1].

RESULTS AND DISCUSSION

All the 50 reconstructions of the real accidents have been obtained with reliable results matching the impact points and rest positions for both vehicle and pedestrian with the visual evidence collected on the spot.

By modifying the parameters that affect the braking sequences according to the active safety systems characteristics, a second set of virtual simulations for all the cases has been obtained. Both BAS+ABS and PROTECTOR system simulation outputs were compared by pairs.

It was found that in the 88% of the accidents, the vehicle started to brake during the pre-collision phase. No evidence of braking maneuvers was found for the other 12% of the cases, this hypothesis was confirmed by the reconstructions. I was proved that the driver was probably unaware of the pedestrian on his path, or the pedestrian was detected too late leaving no time to react.

Related to the ISP estimation, the pedestrian head impact point was located out of the car frontal in the 20% of the accidents so the ISP value could not be calculated. The Injury Severity Probability (ISP) estimated versus collision speed (Vk) is shown in figure 3.

Figure 4 shows the distribution of the cases according to the reduction in percentage between real and the BAS+ABS/PROTECTOR systems simulated collision speeds (V_{kBAS}/V_{kPROT} reduction in %); and figure 5 the distribution of the cases according to the reduction in percentage between real and the BAS+ABS/PROTECTOR systems simulated ISP (ISP_{kBAS}/ISP_{kPROT} reduction in %).

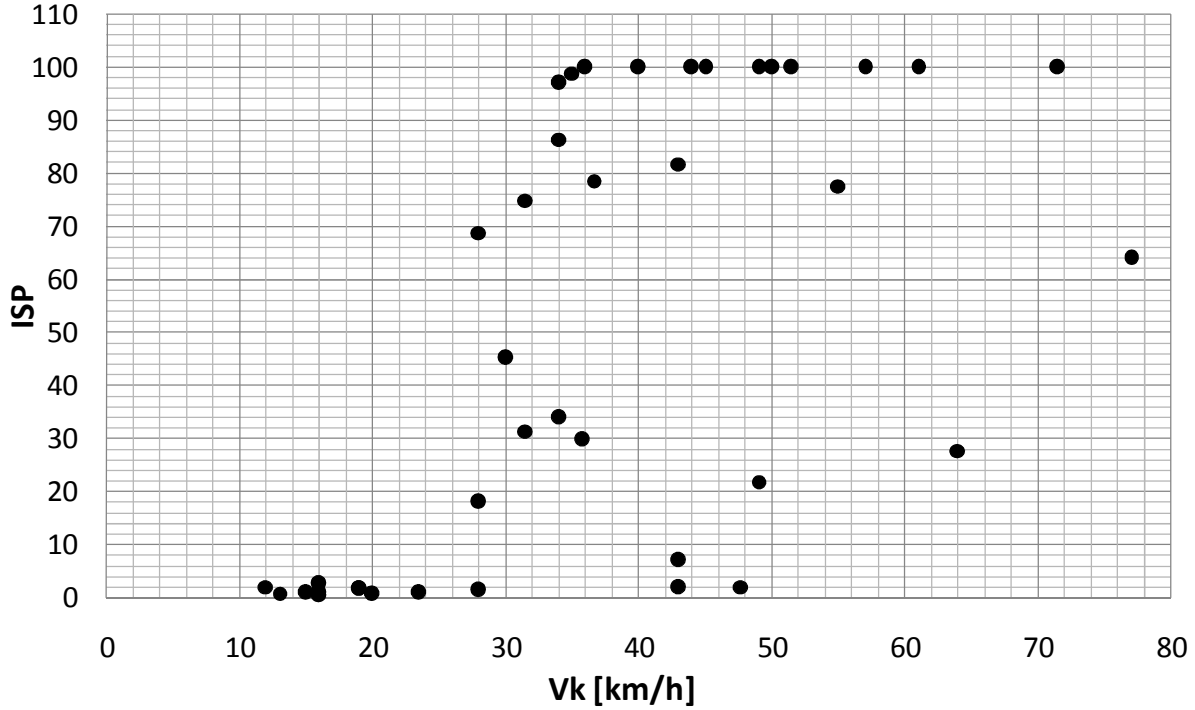

Figure3. Injury Severity Probability (ISP) versus collision speed (V_k).

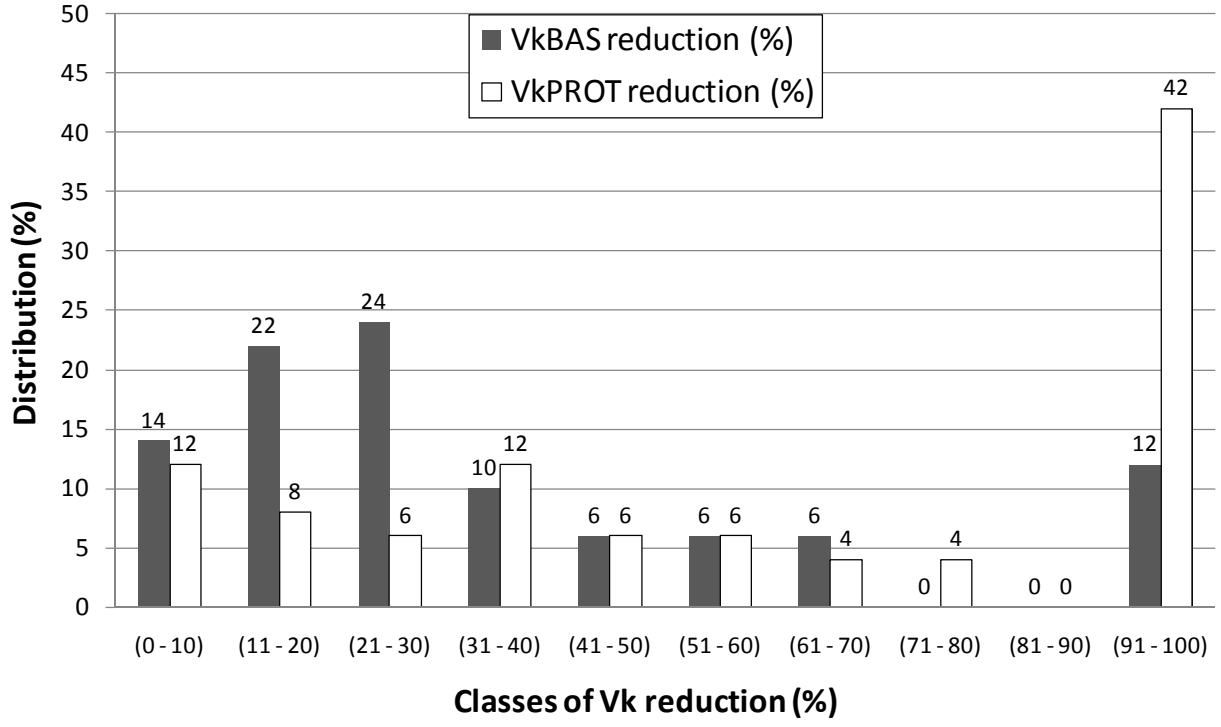

Figure4. Distribution of the cases by the percentage of collision speed (V_k) reduction.

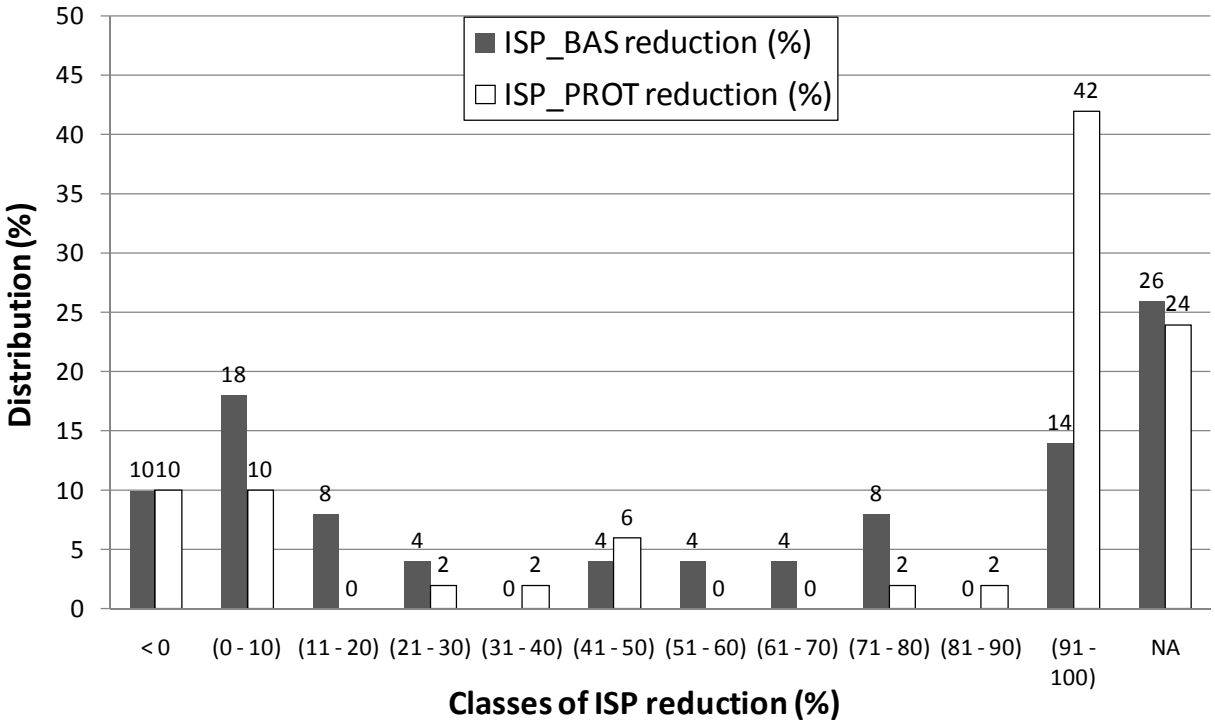

Figure5. Distribution of the cases by the percentage of Injury Severity Probability (ISP) reduction.

The collision could have been potentially avoided in 12% of the cases if the vehicle was fitted with BAS+ABS system ($V_{kBAS} = 0$) and in these accidents the ISP_{BAS} reduction is 100%. In 55% of the cases of the studied sample, the speed reduction achieved is less than 5 km/h. In 26% of the cases the ISP_{BAS} reduction value could not be calculated (NA) due to the pedestrian head impact point was located out of the car frontal (in the real accident and/or in the BAS+ABS system simulated). The data show that 18% of the cases in the sample present a percentage ISP_{BAS} reduction less than 10%, and in a 10% that reduction is negative (there is an increase in the value of ISP; these cases commented below).

In 42% of the cases with the PROTECTOR system simulated the percentage of the speed reduction achieved is more than 90% ($V_{kPROT} = 0$, the collision has been avoided due to the PROTECTOR system) and in these accidents the ISP_{PROT} reduction is 100%. In 70% of the cases of the studied sample, the speed reduction achieved with the PROTECTOR system is greater than 10 km/h, and in 44% of the cases the percentage of the ISP_{PROT} reduction achieved is greater than 80%. In 24% of the cases the ISP_{PROT} reduction value could not be calculated (NA) due to the pedestrian head impact point was located out of the car frontal (in the real accident and/or in the PROTECTOR system simulated). The data show that only 10% of the cases in the sample present a percentage ISP_{PROT} reduction less than 10%, and in a 10% that reduction is negative (there is an increase in the value of ISP; these cases commented below).

Reductions of ISP up to 50% correspond to low levels of collision speed reduction. This fact evidences that improvements of pedestrian protection in frontal collisions depend not only on speed but on other parameters (in our study, these parameters are those from which the ISP is calculated: characteristics of the vehicle and head impact point).

In 10% of the cases (both BAS+ABS system and PROTECTOR system simulated) the percentage of the ISP reduction is negative; it was found that the head impact location changed to a stiffer area of the vehicle causing a more severe head impact

Since vehicle-pedestrian collisions are complex phenomena in which many parameters are involved, some simplification hypotheses were made in order to make the reconstruction process easier and quicker. These simplifications are related to parameters that can hardly be estimated such as the driver behavior.

The injury severity assessment within this study only considers head impacts to the front surface of the vehicle, injuries provoked by subsequent impacts were not taken into account. Hence it can be an interesting subject for further research.

The accident sampling is specific for this study and their characteristics are limited by the criteria that the Local Police Forces use for attending within their coverage area. So the 50 cases cannot be considered a representative sample for the whole pedestrian accidents that occur in the Spanish cities and the findings of this investigation might be different for other samples.

CONCLUSIONS

Multi-disciplinary approaches such as this study make the identification of critical parameters easier and simplify the development of practical solutions by quantifying their potential impact on future actions to improve pedestrian safety.

Using this methodology, a database containing 50 pedestrian accidents was created, including in detail information of the vehicle, person (anthropomorphic variables, injury codification); scene and pedestrian kinematics. Reconstructions of these accidents were performed using advanced techniques to accurately estimate multiple parameters from the collision, the pre- and post-impact phases.

The gathered information has been used for the evaluation of the effectiveness of two active safety systems, a brake assist system (BAS+ABS) and an autonomous emergency braking system (AEB). The performance of these systems has been simulated in the reconstructions, so it was possible to analyze their capacity for severity reduction in pedestrian accidents or even its avoidance.

Both analyzed systems (BAS + ABS and PROTECTOR) proved to be efficient for reducing severity of pedestrian accidents in most of the studied cases. In the case of the BAS+ABS system the findings show that even though most of the collisions could not have been avoided by implementing these systems, their consequences would have been reduced in terms of the estimated ISP. The PROTECTOR system proved to be efficient for reducing collision speed of pedestrian accidents in most of the studied cases so the effect in terms of the estimated ISP reduction is greater than the case of the BAS+ABS system simulated.

In some cases a low reduction of the collision speed due to the simulated systems would increase the estimated ISP. The interaction between collision speed, vehicle frontal design and pedestrian parameters –height, weight, speed – is more relevant for the severity of the pedestrian head impact than the speed by itself, because it determines the head trajectory, acceleration and impact point. Thus, these primary safety systems should be combined with other secondary safety devices, such as the pop-up bonnet or the windscreen airbag.

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