# EVALUATION OF THE EFFECTIVENESS OF PEDESTRIAN PROTECTION SYSTEMS THROUGH IN-DEPTH ACCIDENT INVESTIGATION, RECONSTRUCTION AND SIMULATION

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## ABSTRACT

Around 15% of traffic accident casualties in Europe are pedestrians. To date, most of the studies carried out only provide statistical information on the problem and few in-depth studies provide countermeasures which might correct it.

There are many studies concerning pedestrian protection, which can be grouped into 'pedestrian modelling', 'biomechanical limits for pedestrians' and 'statistical analysis for pedestrian accidents'. Despite these studies, there is no predictive analysis of the benefits of pedestrian protection systems based on their intrinsic capabilities applied to a real accident sample.

This paper describes a methodology for the evaluation of pedestrian protection systems based on the analysis of a wide sample of urban pedestrian accidents. All of them are analysed in-depth and reconstructed with PC-Crash®. The effects of the frontal structure of the vehicles and several active systems, such as BAS and Pedestrian Detection Systems are evaluated.

The paper includes the description of the methodology followed for a sample of approximately 140 pedestrian urban accidents in three cities of Spain (Madrid, Barcelona and Zaragoza) and the corresponding reconstructions generated with PC-Crash®. Then, a methodology to simulate the passive and active improvements (including pedestrian friendly structure, BAS and Pedestrian Detection Systems) is defined and applied to all sample accidents. The results of these new simulations are used to evaluate the benefits of these systems. The main conclusions are discussed, accounting for the limitations of the study, which basically lie in the modelling of the Pedestrian Detection Systems.

The methodology proposed in this paper can be applied to other vehicle safety devices to evaluate their effectiveness, based on the analysis of real accidents. All the results presented here come from a project partly funded by the Spanish Ministry of Industry.

## In-depth Analysis of a Sample of Pedestrian Accidents

The following general methodology was used for the pedestrian accident analysis:

- Accident Scenario Information
    - Accident description
    - Sketch
    - General photographs
    - Pedestrian Data
- Analysis and information process
    - Damage to the vehicle
    - Pedestrian injuries
        - Injury description
        - Injury mechanism
- Virtual reconstruction of the accident
    - Vehicle parameters and profile definition
    - Pedestrian model
    - Simulation with PC-Crash®
        - Tyre-road adherence
        - Impact velocity

- Previous phase to the pedestrian accident

### Definition of the Simulation Methodology with PC-CRASH® and Parameter Adjustment

Once the initial phase of information compilation from the accident scenario is complete, and after having carried out the complete analysis of that information, a series of input data is obtained for simulation with PC-Crash®.

The first step in the reconstruction of the pedestrian accident is the definition of a complete, scaled sketch of the accident scenario (street geometry and configuration, vehicles involved in their initial, intermediate and final positions, manoeuvres, pedestrian trajectory, obstacles, distances, comments, etc). In the complete project, all sketches and accident analyses can be found for each case.

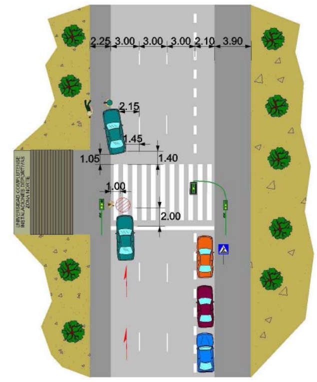


**Figure 1. Sketch of the accident scenario.**

The next step and according to the real situation, vehicle properties and parameters (make & model, manufacturing year, version, engine, weight, etc.) are chosen from the PC-Crash® data base. Some of these parameters can be modified according to the real case.

Related to this topic, the real geometry of the frontal profile of the vehicles involved has been measured in the available cases, as it is shown in the following figure. This geometry has been used during the virtual reconstructions.

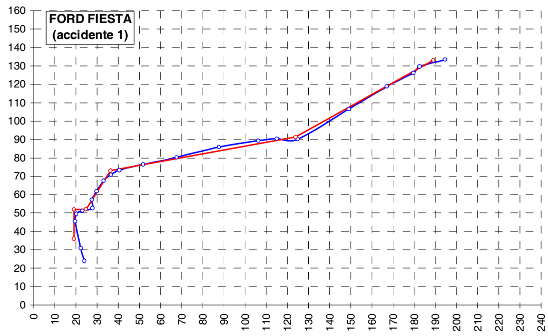



**Figure 2. Real geometry of the frontal profile of the vehicles.**

Once the vehicle and its parameters have been adjusted properly, the pedestrian model is defined by using a multi-body model created for this project, where height, weight, age and gender are taken into consideration.

Next, the adherence conditions are defined by adjusting the pedestrian-vehicle and pedestrian-ground friction coefficients, adding the dynamic adherence of the tyres.

Finally, the pedestrian accident is simulated. All the information about the parameters involved, driver manoeuvres before the accident, reactions, events, initial speed, etc. are included and adjusted for the simulation. In order to simplify and standardize the simulations, some basic criteria were established:

- Driver reaction time is always 1 second.
- The time reaction for a conventional brake system is 0.25 second.
- The possible perception point (PPP) is the point where the pedestrian invades the lane where the vehicle was driving.
- Just before the accident and according to the case, the vehicle can drive with constant speed (without reaction), brake with medium intensity (pre-established value) or brake with maximum intensity (skid marks were seen on the accident place).

### Analysis of the Sample of Studied Accidents

A data base for 139 pedestrian accidents from three representative cities in Spain (Madrid, Barcelona and Zaragoza) was created. It includes information on the vehicle, person (anthropomorphic variables, injury codification), scenario and pedestrian accident kinematics. This data base constitutes one of the most complete data bases for pedestrian protection studies in Europe. In general, the studied cases are frontal accidents involving touring cars inside urban areas.

The following characteristics have been analyzed:

- Time when the pedestrian accident happened
- Characteristics and geometry of the vehicle involved in the accident
- Pedestrian parameters:
    - Gender
    - Age
    - Height and weight (when available).
    - Walking velocity.
    - Relative to vehicle orientation before the accident.
- Injuries produced during the accident
    - Severity of pedestrian injuries

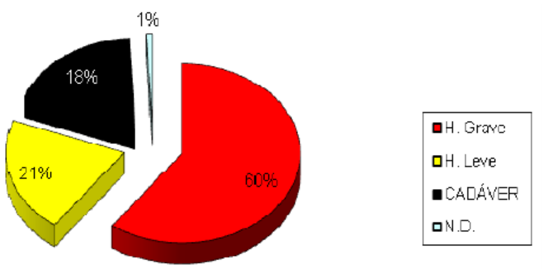



**Figure 3. Severity of pedestrian injuries.**

- Location and kind of injury

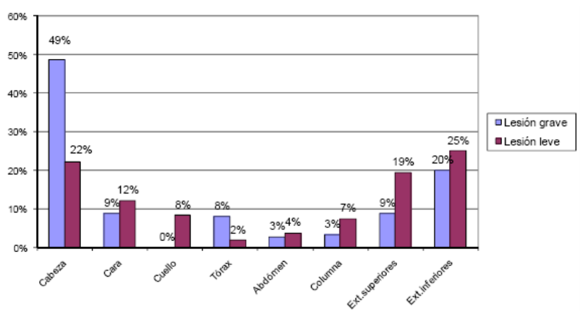



**Figure 4. Body location and severity of injury.**

- Distribution of the main injury mechanisms
- Driver manoeuvres before the accident

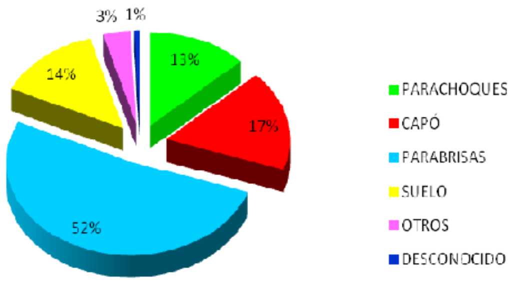



**Figure 5. Principal Injury Mechanism Distribution.**

According to the analyzed pedestrian sample accidents, the majority of them occurred in broad daylight. 93% of the vehicles involved in these accidents were passenger cars and most of them small cars. In almost half of the cases (49%) the vehicle was equipped with ABS, but only 8% of the total incorporated BAS. In 71% of the cases, the driver of the vehicle involved in the pedestrian accident tried to do a braking manoeuvre before the accident. 34% of the pedestrians were older than 60 years old, and 21% were younger than 20. 60% of the persons were seriously injured and 18% accounted as fatalities.

The majority of serious injuries occur in the head (49%) and lower extremities (20%).The most frequent injury mechanism is the vehicle (82%), for which the most important element is the windscreen (52%), followed by the bonnet (17%) and the bumper (13%). In 14% of the cases the most important injury for the pedestrian was produced when impacting against the ground.

**Primary Safety Technologies Effectiveness Evaluation Methodology**

**PC-CRASH® Simulation Methodology for the Chosen Systems** - Parameter adjustment and the simulation methodology for the primary safety systems subject to study (ABS+BAS System and Pedestrian DETECTION + Automatic Brake system) are detailed in the entire project. Nevertheless, some of the most important aspects are emphasized in this paper.

**Simulation Parameters** - The parameters under simulation, bearing in mind the different performance of both braking systems (ABS+BAS and pedestrian DETECTION + Automatic brake systems) are:

**ABS+BAS System**:

- Pedestrian reaction time*:* pre established at 1 second.
- Brake System with BAS reaction time: pre-established at 0.1 second.

- ABS Action Frequency: in general 10 Hz.
- Adherence coefficient: general value.
- Tyre adherence curve (one of the four predefined models): implies the definition of the µmax, µd, Fmax, Fd values.
- Maximum deceleration possible depending on the chosen adherence model and the ABS performance.

**Pedestrian DETECTION + Automatic Brake System**:

- Detection range with risk sector division, remarking especially automatic system actuation area.

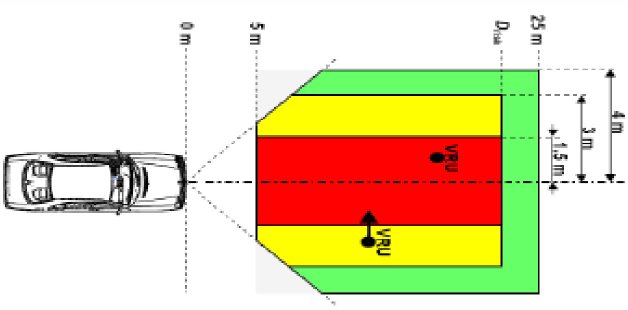



**Figure 6. Division of the risk areas for the pedestrian DETECTION + Automatic Brake system.**

- All parameters from the BAS+ABS system mentioned above, apply for the Automatic brake system

In both cases, simulations provide a series of parameters which can be used for the evaluation of the vehicle's dynamic performance in each case. Some of these parameters are:

- Braking distance ($S_f$), by measuring directly in the simulation.
- Medium deceleration ($a_K$) from the resultant graphics.
- Brake time (tf), directly from the simulation.

**Simulation Algorithms**

**Simulation with ABS+BAS** - Having previously defined the adherence model and tyre performance, ABS is activated in the vehicle options, the system reaction time is reduced from 0.25 seconds to 0.1 seconds and the brake force is amplified to the maximum (pedal position).

**Simulation with BAS and Pedestrian Detection Systems** - With the same configuration used before, the driver reaction time is eliminated and the entry moment for the BAS function is chosen based on the scope ratio established for the detection system.

**Pedestrian Injury Risk Evaluation**

**Development of a Software Tool for Head Injury Risk Evaluation -** A software tool for determining head injury risk values was developed in this project. After all possible impact points in the frontal part of a standard vehicle have been mapped; a bench test rig simulating the front part of a standard vehicle was built and validated by means of correlating the results with those of Euro NCAP tests.

By these means, a software tool for the determination of head injury risk values in different areas of the frontal part of the vehicle was developed in this project. As an example, some of the results for a speed of 30 km/h are shown in the next figure:

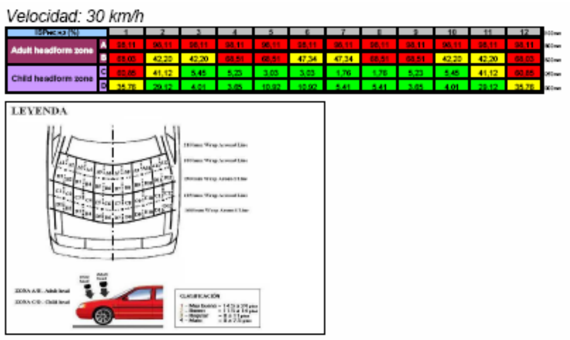



**Figure 7. Head Injury Risk Value Evaluation by means of the developed software tool.**

**Methodology for Software Tool Application in PC-CRASH® Simulations -** The software tool for determining head injury risk values developed in this project is applied to the simulations done with PC-Crash®, following the next algorithm:

As a result of the simulations, the value of the run over speed ($V_k$ or $V_{at}$) is known; this is one of the input data in the application. Next, the head impact point with the vehicle has to be determined. This step lies in the application of the impact area matrix to the frontal part of the vehicle and the location of the pedestrian head contact cell.

Simulation is stopped when the pedestrian head impacts against the vehicle, instant in which two images are taken (cross-section and elevation). In the cross-section of the vehicle used during the simulation, a wrap-around measurement is done and the contact line in the matrix is determined, as shown in **Figure 8**. The head impact column is also determined using the elevated view, as shown in **Figure 9**.

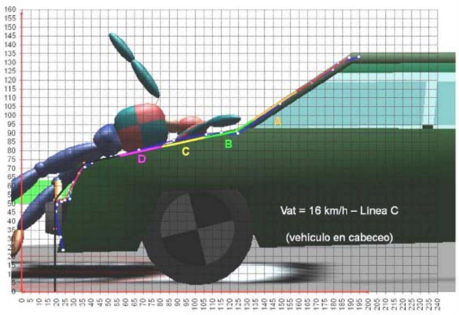



**Figure 8. Head impact line determination.**

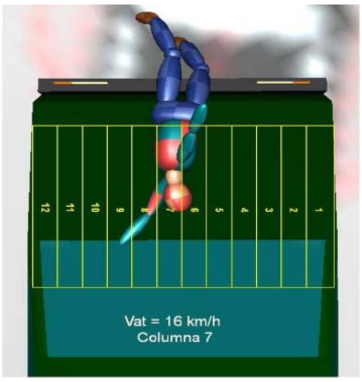
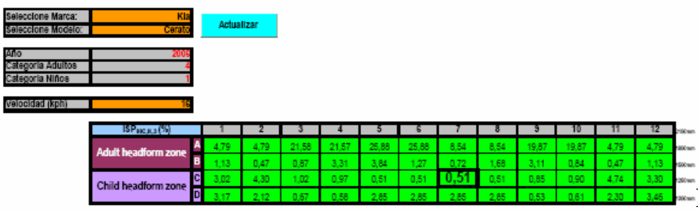



**Figure 9. Head impact column determination.**

The next step consists of choosing the vehicle make and model from the application data base and calculates the ISP (head injury risk index) value for the respective cell. In those cases in which the vehicle make and model were not included in the software application database, another similar model (with similar frontal cross-section) was chosen.




| ISP (%) | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adult headform zone | A | 4,79 | 4,79 | 21,58 | 21,57 | 25,88 | 25,88 | 8,54 | 8,54 | 19,87 | 19,87 | 4,79 | 4,79 |
| | B | 1,13 | 0,47 | 0,87 | 3,31 | 3,84 | 1,27 | 0,72 | 1,68 | 3,11 | 0,84 | 0,47 | 1,13 |
| Child headform zone | C | 3,02 | 4,30 | 1,02 | 0,97 | 0,51 | 0,51 | 0,51 | 0,51 | 0,85 | 0,90 | 4,74 | 3,30 |
| | D | 3,17 | 2,12 | 0,67 | 0,58 | 2,85 | 2,85 | 2,85 | 2,85 | 0,53 | 0,61 | 2,30 | 3,46 |

**Figure 10. Head injury risk index ISP calculation (C7 cell, $V_{at}$ = 16 km/h, ISP = 0.51).**

## RESULTS AND EVALUATION OF SYSTEM EFFECTIVENESS

In this section the results of the new simulations are used to evaluate the benefits of the systems. The main conclusions are discussed, taking into account the limitations of the study, which basically lie in the modelling of Pedestrian Detection Systems.

Their efficiency, capacity for reducing run over speed, avoiding the accident or reducing the severity of the injuries produced are some of the aspects analysed in this section.

Many investigations discuss, from a general point of view, the reduction of distance and brake time by using BAS systems, concluding that the number of accidents can be reduced; but until now the benefits of the system as a primary safety tool for avoiding pedestrian accidents have not been looked at.

Even more interesting are the results obtained for the Pedestrian Detection Systems. In this case, the results obtained based on real accidents represent, a priori, an evaluation of the potential benefits of this kind of system. This information could be very appreciated for evaluating the cost/benefit ratio in case of implementation.

### Efficacy and Influence on Run over Speed

According to the simulations, 48% of the pedestrian accidents analysed could have been avoided with a system of pedestrian detection and automatic brake. The brake system ABS+BAS would have helped the driver to avoid the accident in 11% of the cases. 44% of the accidents could not have been avoided with any of the analysed systems. See **Figure 11***:*

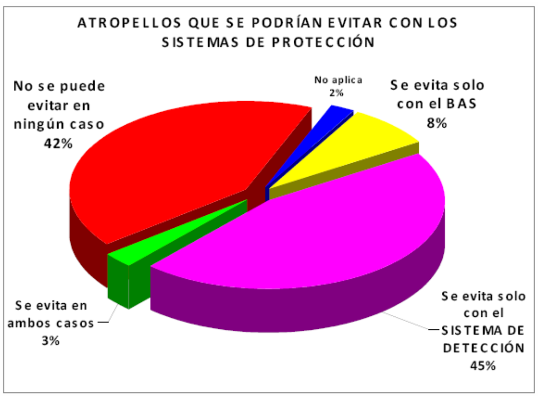



**Figure 11. Pedestrian accidents that could be avoided by means of the use of the protection systems.**

In the next figure, pedestrian accident reduction tendency with each of the two systems is shown.

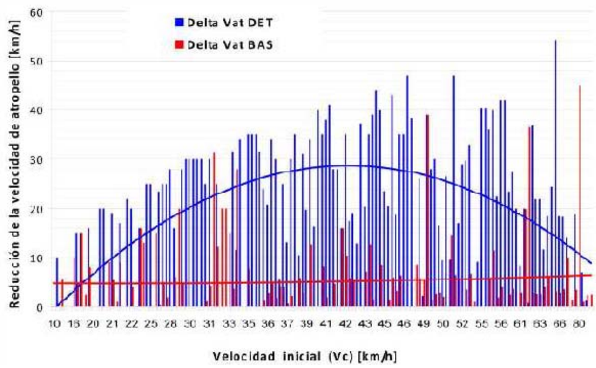



**Figure 12. Reduction of the run over speed.**

The blue curve represents the speed reduction obtained with the pedestrian DETECTION + automatic brake system and it reaches its peak value at about 42 km/h. In contrast, with the BAS system, the speed reduction remains practically constant (red line) at about 5-7 km/h.

In only 21% of the cases, the BAS system would have reduced vehicle speed in the moment of the accident to less than half of its initial driving speed. On the other hand, with the DETECTION+ Automatic Braking System this reduction would have happened in 74% of the cases.

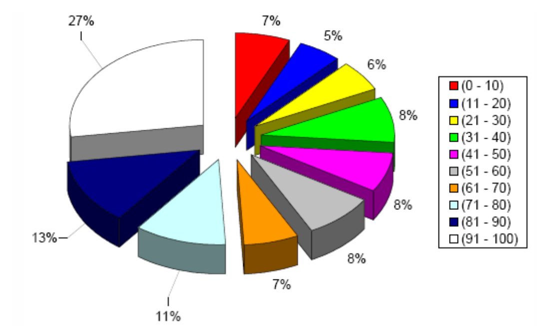



**Figure 13. Percentage reduction of the pedestrian accident speed with the BAS system.**

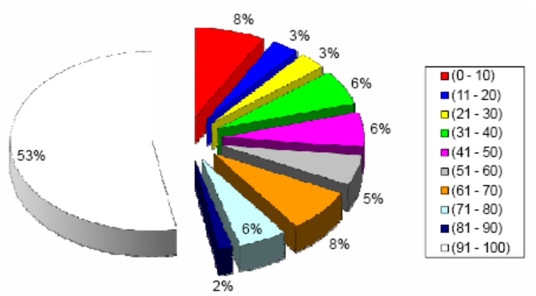
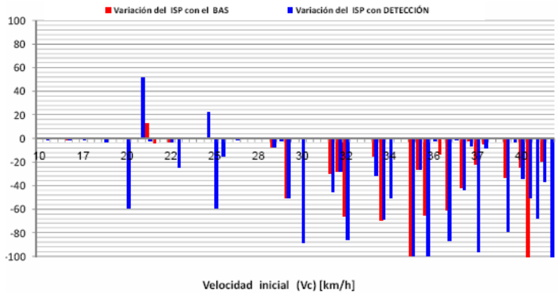


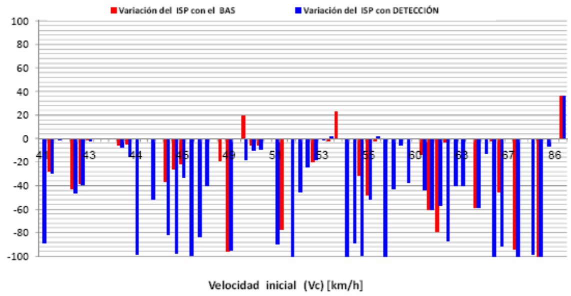

**Figure 14. Percentage reduction of the pedestrian accident speed with the DETECTION + Automatic Brake system.**

## Influence of the Systems in Head Injury Risk

In the following figures the ISP (index that represents the probability of a serious head injury) based on driving speed is shown for both systems: BAS system and DETECTION + Automatic brake system.




(a)




(b)

**Figure 15. Absolute variation of the ISP. (a) Vc = 0 – 41 km/h (b) Vc = 41 – 87 km/h.**

In the following figure, the reduction (in percentage) of the ISP with the vehicle equipped with ABS+BAS in comparison to the ISP value in real life accidents is shown. It is observed that the ISP would be reduced by more than 80% in 18% of the cases.

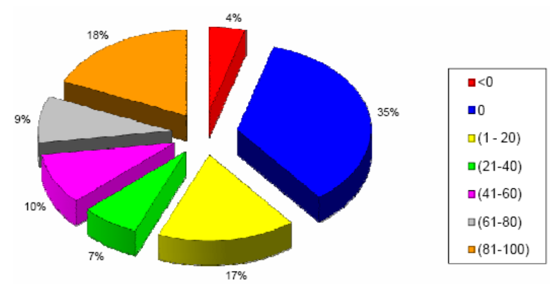



**Figure 16. Relative reduction of the ISP with ABS+BAS.**

As shown in the next figure, by equipping the vehicle with a DETECTION + Automatic Brake System the ISP is reduced by the same amount in 66% of cases.

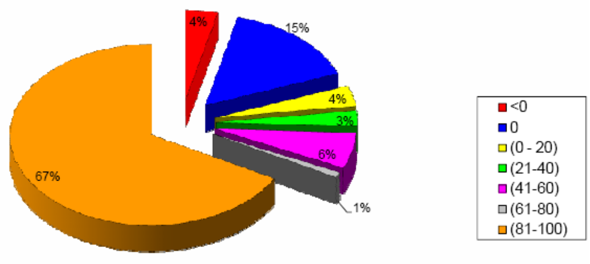
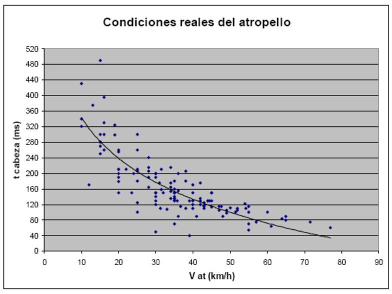



**Figure 17. Relative reduction of the ISP with DETECTION + automatic brake.**

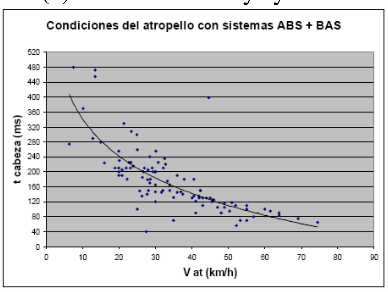
**Influence on Parameters from Secondary Safety Devices**

An important factor related to the actuating time of pedestrian protection devices installed in the frontal part of some vehicles, is the impact time of the pedestrian head on the vehicle from the moment in which the pedestrian lower extremities came in contact with the frontal part of the vehicle.

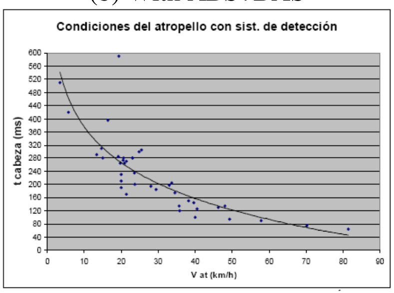
The impact time of the pedestrian head on the vehicle, according to the pedestrian accident speed, is shown in the following three graphics: (a) *without security systems (b) with ABS+BAS (c) with DETECTION + automatic brake system.*




(a) Without security systems




(b) With ABS+BAS




(c) With DETECTION + automatic brake system

**Figure 18. Head impact time.**

It is observed that the dot clusters for both systems (b) and (c) is displaced to the left and upwards compared to the real accident conditions (a). This fact is due to the lower pedestrian accident speed achieved with these systems and the increase of the pedestrian impact time with the vehicle

These times are used as a reference for pedestrian secondary protection systems which are activated once the pedestrian has impacted against the frontal bumper, such as, for example, an active bonnet and pedestrian protection external airbags installed in the bonnet and on the lower part of the windscreen.

## CONCLUSIONS

This project is the result of collaboration between Spanish Research Institutes such as SERNAUTO (coordinator), Applus+IDIADA (participant), Centro Zaragoza (participant) and INSIA (subcontractor), and Local Traffic Authorities (Madrid, Zaragoza and Barcelona councils) who will have at their disposal a common methodology for pedestrian accident investigation.

A database for 139 pedestrian accidents was created, in which information of the vehicle, person (anthropomorphic variables, injury codification); scenery and pedestrian accident kinematics were included. This database constitutes one of the most complete databases for the study of pedestrian protection in Europe.

According to the analyzed pedestrian sample accidents, the majority of them occurred in broad daylight. 93% of the vehicles involved in these accidents were passenger cars with the majority of them being small cars. In almost half of the cases (49%) the vehicle was equipped with ABS, but only 8% of the total incorporated BAS. In 71% of the cases the driver of the vehicle involved in the pedestrian accident tried to do a braking manoeuvre before the accident. 34% of the pedestrians were older than 60 years old, and 21% were younger than 20 years old. 60% of the persons were seriously injured and 18% were fatalities.

The majority of serious injuries occur in the head (49%) and lower extremities (20%).The most frequent injury mechanism is the vehicle (82%), for which the most important element is the windscreen (52%), followed by the bonnet (17%) and the bumper (13%). In 14% of the cases the most important injury for the pedestrian was produced when impacting against the ground.

The compiled information has been used for the evaluation of the effectiveness of two primary security systems: BAS (brake assistance system) and the Pedestrian Detection Systems. The performance of these two systems has been simulated during reconstructions done with PCCrash©, analyzing their capacity for reducing severity of run over accidents or for avoiding them.

A new software tool was developed for calculating head injury risk values based on the runover speed and the head impact point over the frontal part of the vehicle.

Both analyzed systems (BAS and Pedestrian Detection Systems) proved efficient for reducing severity of pedestrian accidents in the majority of cases. BAS is being progressively incorporated in the current fleet. Nevertheless, Pedestrian Detection Systems are still being investigated as a prototype.

Pedestrian Detection Systems would avoid run over cases by at least half and greatly reduce falling speed in the rest of the cases, which reduces the head injury risk. The brake assistance system (BAS) presents lower effectiveness in the prevention of pedestrian accidents compared to Pedestrian Detection Systems.

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