Pedestrian Fatal Head Injury Risk as a Function of the Wrap Around Distance (WAD) and the Front Geometry of the Vehicle

R. Suárez del Fueyo, M. Junge, F. J. López-Valdés

Abstract The aim of this study is to determine the risk of fatal head injury for adult pedestrians struck by a passenger car. The research focuses on the wrap around distance (WAD) and vehicle front geometry, including the effects of pedestrian height, impact speed and other parameters that directly influence the head impact against the vehicle. Data from GIDAS (German In-Depth Accident Study) were analysed. Imputation was used to increase the sample size and the statistical power. The probability distribution of the WAD was developed and projected onto the car contour. A WAD between 190 and 205 cm would imply a head impact against the windscreen for a medium sedan, but against the A-Pillar if the impact occurs on the front side zone. The front of the most frequent passenger vehicles was measured and classified in order to account for the injury causation potential. Respective injury risk curves for the different zones on the car front of medium and large sedans were obtained. As a result, four risk curves were developed relating the WAD and the probability of sustaining a fatal head injury during a pedestrian–passenger car accident. This probability is higher on the front side of the vehicle, reaching values of 70% for WADs between 190 and 200 cm. In pedestrian accidents where a medium sedan is involved and the person hits the centre of the vehicle front, for a WAD of 180 cm the probability of sustaining a fatal head injury is 30%.When a larger vehicle is involved, the risk could reach 47% for WADs of 190 cm.

Keywords fatal head injuries, pedestrian, vehicle front geometry, wrap around distance (WAD).

I. INTRODUCTION

Every year more than 270,000 pedestrians die from vehicle collisions, making up 22% of world-wide traffic deaths [1]. In 2013, 557 pedestrians died in Germany, which accounted for 16.7% of all the victims [2]. The same percentage rises in Spain up to 22.5% of the traffic deaths [3]. Vehicle-to-pedestrian accidents constitute a problem that equally concerns citizens, governments and car manufacturers all around the world.

The most severe injuries caused by pedestrian accidents are associated with legs and head, with head injuries being a serious threat to life [4]. Although the injuries to the head can be a consequence from either an impact against the vehicle or an impact against the ground, it is contact with the vehicle that seems to be responsible for the most severe and fatal head injuries [5]. Previous analysis of GIDAS data showed that vehicle impacts caused twice as many injuries as ground impacts [6]. Severity of head injuries depends on the vehicle speed and the location of the impact on the car front. Injury risk increases in strengthened structural zones, like the A pillar, the windscreen frame and the wiper zone. The examination of the vehicle during the accident on-scene reconstruction provides evidences of head impacts against the car.

Forty years ago Ashton et al. [7] defined a parameter that represents contact locations of the pedestrian body with the vehicle, known as Wrap Around Distance (WAD). The WAD to the head is the distance from the ground to the head contact point on the car along the vehicle front geometry, measured in a two-dimensional space. During the reconstruction process, the WAD to the head is measured as follows [8].

1. At the vehicle centreline.
2. Placing the end of a flexible tape measure on the floor vertically below the front face of the bumper.
3. Wrapping the tape over the bumper, bonnet, windscreen and roof, ensuring that it is maintained in a vertical longitudinal (X, Z) plane and that its end is still in contact with the ground.

This means that the measurement of the WAD does not consider a possible transverse movement of the pedestrian between consecutive impacts against the car front. With increasing pedestrian height, the WAD increases, being normally greater than the height when a passenger car is involved in the accident [5].

Ivarsson et al. [9] affirmed that the body height of the pedestrian and the shape of the involved vehicle explain 40% of the variation of WAD. The other 60% is explained by impact speed, acceleration at braking, initial pedestrian stance and the bumper lead and vehicle front end shapes. The authors indicated that it was not

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possible to predict the WAD as a function of impact speed, height of the pedestrian and shape of the car. However, Wood et al. [10] provided a model to estimate vehicle impact speed using the WAD, applicable for velocities under 40 km/h.

The main goal of this study is to develop a risk curve relating the WAD and the probability of sustaining a fatal head injury when a pedestrian–passenger car crash occurs.

The WAD gives an approximation of where on the car front the pedestrian head is impacting. As previously explained, depending on the position on the car front, the severity of the injuries sustained can change. If the relationship between injury risk, WAD and car contour is understood, the head injury potential for the different parts on the vehicle front could be predicted. In this study, the value of the WAD will depend on the height of the pedestrian and his initial stance, impact velocity, the shape of the car and braking conditions. All of these factors are considered together by developing the WAD distribution of the population from real crash data.

The risk curves, obtained from accident parameters, can be used to predict and quantify the effectiveness of the new AEB (Autonomous Emergency Braking) systems by calculating the reduction of injury severity.

II. METHOD

The GIDAS database, with almost 3,400 pedestrian accidents coded, was used in this study in order to accomplish a robust statistical analysis. Cases were restricted to vehicle–pedestrian events where a passenger car was involved and the victim was older than 14 years. When necessary, an imputation method was used to increase the number of cases and to improve the quality of the data. Two different WAD distributions for the same body height were developed and projected onto the car contour. The front of the most frequent passenger vehicles was measured and classified in order to account for the injury causation potential. Respective injury risk curves for the different zones on the car front were obtained. Also two different car sizes were considered. As a result, WAD distributions and the potential risk of the vehicle front were combined in the same head injury risk curve.

Database

Data from GIDAS were used in this project. The GIDAS database is the result of a cooperative project between FAT (Forschungvereinigung Automobiltechnik, or Automotive Industry Research Association) and BASt (Bundesanstalt für Straßenwesen, or the Federal Road Research Institute) with the objective of augmenting the information about the crash circumstances available in police reports. . About 2,000 on-scene reconstructions in the areas of Hanover and Dresden are performed by specialists every year since 1999 . Accident data, characteristics and parameters are coded in almost 3,000 different variables per case.

In-depth data analysis

A total of 3,384 pedestrian GIDAS events occurring since 2000 were reviewed initially to be included in this study. Thirty two per cent of the cases from the original sample were a pedestrian-vehicle collision with a resultant MAIS3+. From these, 644 included a head impact against any type of vehicle (passenger cars, SUVs, vans, bicycles, etc.), which means 19% from the original 3,384 cases. Within this last group, there were 28 fatal pedestrian crashes, and half of these involved a head impact against the vehicle.

Four filters were applied to the sample:

1. Only pedestrian–passenger car accidents were considered since “Wrap Projection” (referring to pedestrian kinematics after the first impact [11]) normally occurs when the person is hit by the car below his centre of gravity. Initial impact with the bumper is followed by the bending of the torso over the front of the vehicle, with a high probability of hitting the head against the bonnet or the windscreen [12]. Impacts against other types of vehicle, such as SUVs or LTVs, could result in forward projection of the pedestrian without head contact against the car [13].

2. Only pedestrians aged 14 years and older were considered in this study. In the case of children, the impact against the bonnet or the windscreen does not necessarily occur and they may be thrown forward by the impacting vehicle [14].

3. Only accident cases where the WAD to the head impact is coded have been included. After these filters, the sample was reduced to 320 pedestrian events.

4. Only cases where the WAD to head is between 160 cm and 260 cm were considered: Euro NCAP uses the adult head impactor to assess points on the car front, including a WAD from 170+ cm (from 150 cm on for those cases where the bonnet rear reference line is situated more to the front) [7].

After the filtering process, 231 accidents were included in the study.

Imputation by regression to predict WAD in accidents without head impact coded in GIDAS

The analysis of GIDAS data showed that in many of the cases where there was an impact with the pelvis, thorax or shoulder, an impact with the head also occurred. Looking at accidents with a MAIS4+, it was observed that in 42% of the cases where an impact with pelvis is coded and 41% where a thorax impact is coded, there was a head impact afterwards. This percentage increases to 58% if there is a shoulder impact. This phenomenon is explained by pedestrian post-impact kinematics in wrap projections.

There was also evidence of head impacts that could have existed in some cases without being coded in GIDAS. The possible contact point of the head on the vehicle was predicted for those cases where the pelvis, thorax or shoulder hit against the car front and no head impact had been coded in the original GIDAS data set.

A method based on regression was developed to predict the WAD of cases with shoulder, thorax or pelvic impact that did not have a head impact coded and thereby increase the number of cases included in the study.

Imputation to obtain the height of the pedestrian in cases where it is missing

From the 231 original data with a head impact coded, the body height of the pedestrian was unknown in 58 cases. A second imputation method was carried out to estimate the body height in the cases where they were missing. The method is known as Hot Deck (HD) Imputation. This procedure involves replacing missing values of one or more variables with an observed response from a "similar" unit. HD is commonly used by government statistics agencies and survey organisations to provide rectangular data sets, but it has also been applied in epidemiologic and medical settings [15-16].

The variable missing is the pedestrian's body height. The WAD to the head was used as reference variable for the imputation because of its close relationship with the height. In order to assure the proper operation of the method, the sample was separated by gender. Then, if in an accident with an adult male where a head impact against the car occurred and WAD to the head is coded but height is unknown, this blank in the data set would be predicted with the height of another male whose WAD to the head had been the same. If there is not the same WAD coded, the method will pick up the height of the closest case. If there is more than one WAD with the same value, the method will code the height choosing randomly between the cases with the same WAD.

Measurements of the most frequent vehicles involved

Ten models of passenger cars involved in most of the crashes coded in GIDAS were measured to give an account of the WAD to significant parts on the car front. The measurements were taken following the same procedure as for measuring the WAD during the accident reconstruction.

As already stated [17], injury patterns of pedestrian body, and especially of head, depend on the stiffness of the contact point. Some zones on the front part of the car are associated with more severe injuries, such as the A pillar, wiper zone or windscreen frame. For this reason, two different areas on the vehicle front were considered in this study: the centre and the side front (Fig. 1).

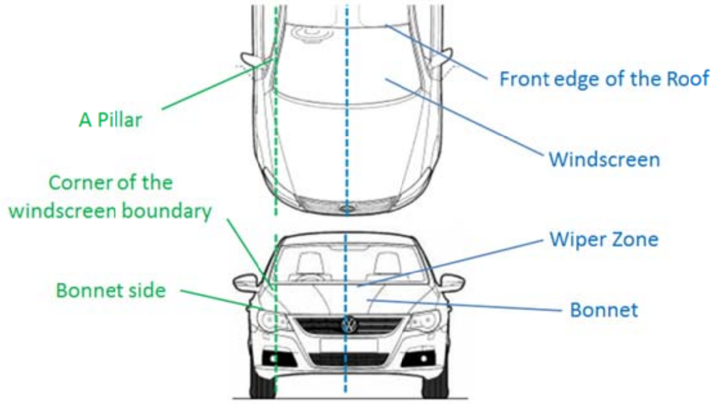


Fig. 1. Potential zones of injury on the car front (*center in blue, side in green*).

Passenger cars were also classified in two groups (medium and large sedans) due to the significant differences on the front geometry that could highly alter impact location.

Head Injury risk scaling and estimation

The coefficient NISSx, derived from the NISS (New Injury Severity Score) by rescaling, was used to account for the severity of head injuries sustained. NISSx is obtained by the addition of the exponentials of the AIS (Abbreviated Injury Scale) of the three most severe injuries, regardless of body region. In the manner of ISSx [18], the exponentials used are scaled to fit the ISS range of values between 0 and 75, and the coefficient, expressed on a metric scale, becomes mathematically decomposable into body regions.

Fatalities can be approximated by injuries with an injury severity of twice the multiple injured severity of NISS>15, or what is the same, a NISSx value of 10 or greater. This scaling is explained further in Niebuhr et al. (2015) [19].

In order to associate an injury potential to the different parts of the car front, the 231 initial accident cases were double-checked, recoding manually the location of the head impact zone according to Fig. 1. Then, each NISSx value sustained to the head was associated to the zone where the impact occurred. As a result, seven new variables were obtained with the form: NISSx_zone (NISSx_bonnet, NISSx_windscreen, NISSx_Apillar, etc.).

To provide a better understanding, NISSx coefficient was associated to a percentage value, meaning the risk of sustaining a fatal head injury. Since 75 is the maximum NISS value, indicating that the injury sustained caused the death, a NISSx of 75 was considered as 100% of risk. In equivalence to a NISSx value greater than 10 [19], a percentage larger than 13.3% could indicate fatal consequences.

III. RESULTS

Imputation by regression to predict WAD in accidents without head impact coded in GIDAS

As stated, imputation was implemented to predict the WAD of cases with shoulder, thorax or pelvic impact but with no head impact coded in GIDAS. The objective was to increase the number of cases included in the study.

The imputation consisted of a regression model, which relates cases where a head impact and other contact with pelvis, thorax or shoulder occurred, also taking into consideration pedestrian height. In order to establish a relationship between these parameters, coefficients HH, PH, TH and SH[1] shown in equations (1), (2), (3) and (4) below, were developed. They relate the WAD to each body region to the stature of the pedestrian. The height from the ground to the bonnet leading edge (BLE) is subtracted from the WAD, in view of the fact that the vertical distance from the ground to the point where the first impact occurs does not change with increasing speed.

$$HH = \frac{WAD^{head} - BLE}{Height^{pedestrian}} \quad (1)$$

$$PH = \frac{WAD^{pelvis} - BLE}{Height^{pedestrian}} \quad (2)$$

$$TH = \frac{WAD^{thorax} - BLE}{Height^{pedestrian}} \quad (3)$$

$$SH = \frac{WAD^{shoulder} - BLE}{Height^{pedestrian}} \quad (4)$$

The BLE is defined as the front upper outer structure of the car, including bonnet and wings, the upper side members of the headlight surround and any other attachments [7-8]. The height and shape of the BLE are important parameters that influence the kinematic motion of the head and determine its impact point against the vehicle. Contact forces increase with increasing height of the BLE. This parameter is difficult to distinguish in

[1] Relative Heights of the Head, Pelvis, Thorax and Shoulder.

newer cars, whose front profile is softer and more rounded than in older cars. This is one of the reasons why it is not coded in GIDAS [12].

In 2005 Snedecker et al. [20] suggested average measurements and standard deviations for the geometric parameters on car fronts. Since values for the vehicle bumper height (BH) are known for each case analysed, a mathematical relationship between BLE and BH, equation (5), was established and experimentally checked with the vehicle measurements executed during the study (see Table 1).

$$BLE = 1.5\,BH \quad (5)$$

As a first step, three different 2D regressions, one for each body region, were calculated to relate WAD to the head (or head impact point) to WAD to the pelvis/thorax/shoulders. In the first regression (Fig. 2), relating HH and PH coefficients, accidents where a head impact and a pelvis impact occurred were examined. Some points distant from the tendency line were eliminated because it was found that for many of those cases an uncommon accident occurred (like a pedestrian hitting the car on the side). It was found that the relationship between HH and PH is linear, and HH accounts for 50.2% (r^2 =0.502) of the variation of PH. The effect of the increasing impact velocity, measured in m/s, is also represented in the graph.

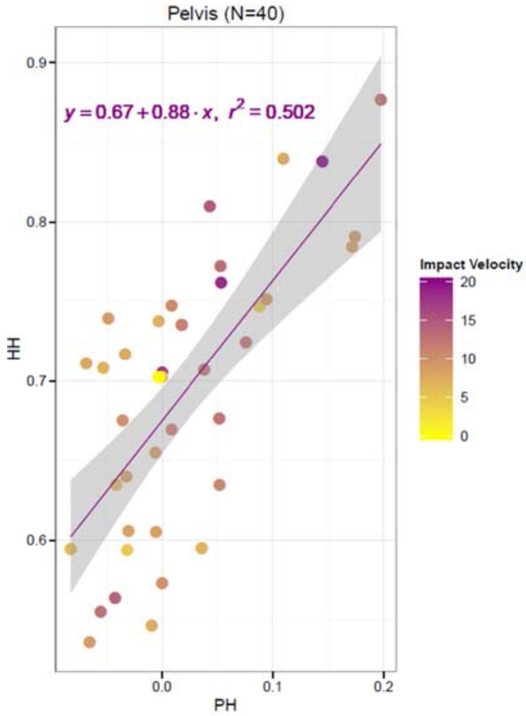


Fig. 2. Accidents with head and pelvis impact (HH and PH coefficients). Equation and R-squared value.

Regressions for the thorax region (HH and TH) and shoulders (HH and SH) are available in the appendix (Fig. A1 and Fig. A2 respectively). The coefficient of determination increases to 0.585 for thorax–head impacts. It seems to be a lower proportion of cases with thorax impacts compared to pelvis and shoulders. This has already been explained for collisions with modern passenger cars where the elbow-bonnet impact protects the thorax [21]. The coefficient HH accounts for more than 70% of the variation of SH (r^2=0.722), which is reasonable if impacts with shoulders and head occurred simultaneously. The uncertainty in measurements of the WAD to both respective regions during the reconstruction would have been lower since both impact marks on the car would have been very close to each other.

Collisions with multiple impacts were also considered for the imputation. A multidimensional regression was conducted. It relates accident cases with head, thorax and pelvis impact against the front of the car by a regression plane between parameters HH, TH and PH (Fig. 3).

In the 3D regression, the same process as before was used to assure the quality of the data and it was implemented with 13 accident cases. By simultaneously considering the WAD to the pelvis and the WAD to the thorax 74% (r^2=0.7484) of the WAD to the head could be justified.

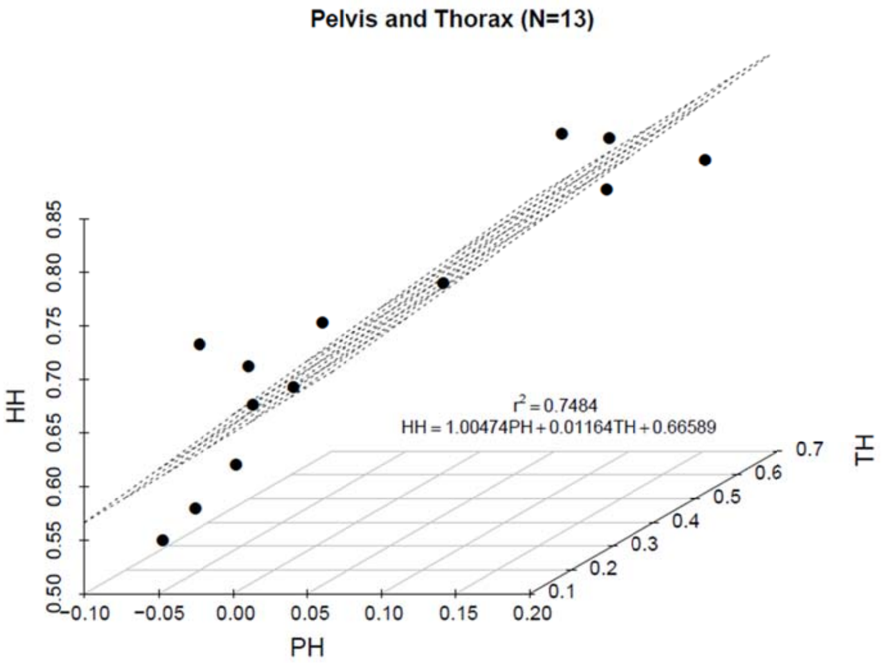


Fig. 3. Accidents with head, thorax and pelvis impact (HH, TH and PH coefficients). Equation and R-squared value.

By applying the equations obtained from the regression to cases where pelvis, thorax and shoulder but no head impact was coded, the number of cases increased by 180. The same process applied to cases with head impact to carry out the regressions was considered to eliminate inappropriate data after the imputation, ensuring the quality of the results obtained.

After the imputation, the number of cases for inclusion was increased to 411. Most of the new data were obtained from the pelvis–head impacts and the 3D regression (pelvis and thorax impacts). After calculating a HH coefficient for each case, plausible values for the WAD to the head were obtained. Figure 4 shows how the distribution of the WAD to the head looked before and after applying the regression model.

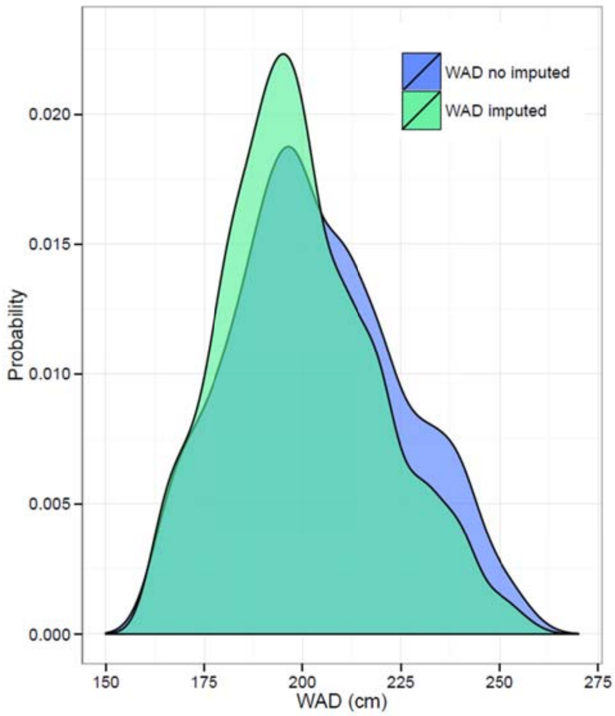


Fig. 4. Distribution of the WAD before (N=231) and after the imputation (N=411).

Imputation to obtain the height of the pedestrian in cases where it is missing

By applying HD Imputation, values for pedestrian height were predicted for 58 cases where this data was missing in GIDAS. After this second imputation method, the sample of 411 pedestrian–vehicle collisions was finally completed with information about the WAD, injuries sustained, crash conditions, vehicle and anthropometric data.

Measurements of the most frequent vehicles involved

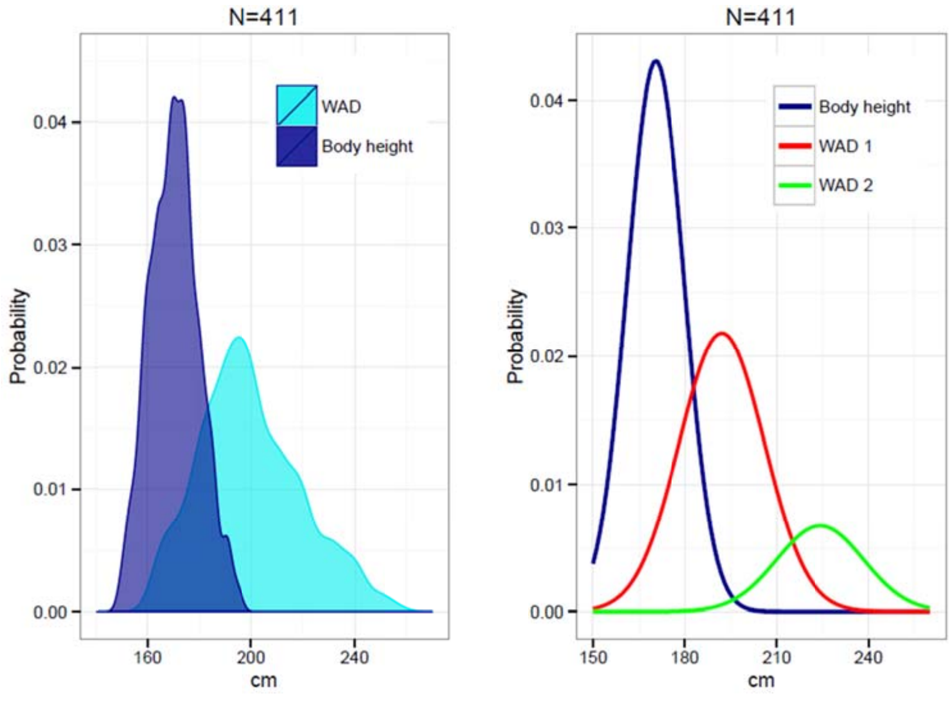
Table 1 shows the average measurements from the ground of the vehicle contour for the two different zones and groups previously described. As already stated, the measurements were taken following the same procedure as for measuring the WAD during the accident reconstruction.

TABLE I
Average measurements of the zones of vehicle front *(cm)* where a head impact occurs

Vehicle Part	Medium Sedan	Large Sedan
Bonnet	83	89
Bonnet Side	83	89
Wiper Zone	163	185
Corner of the windscreen boundary	161	184
Windscreen	179	199
A Pillar	174	193
Front edge of the Roof	254	276
Roof	265	303

Body height of the pedestrian and WAD: approximation to normal distributions

Figure 5(a) shows the body height distribution of the population for the accident cases analysed and the WAD distribution associated with those accidents after both imputation methods. The stature of the population has been approximated by a normal distribution (Fig. A3, see Appendix).



(a) (b)

Fig. 5. (a) WAD and body height distributions; (b) approximation of WAD and body height by normal curves.

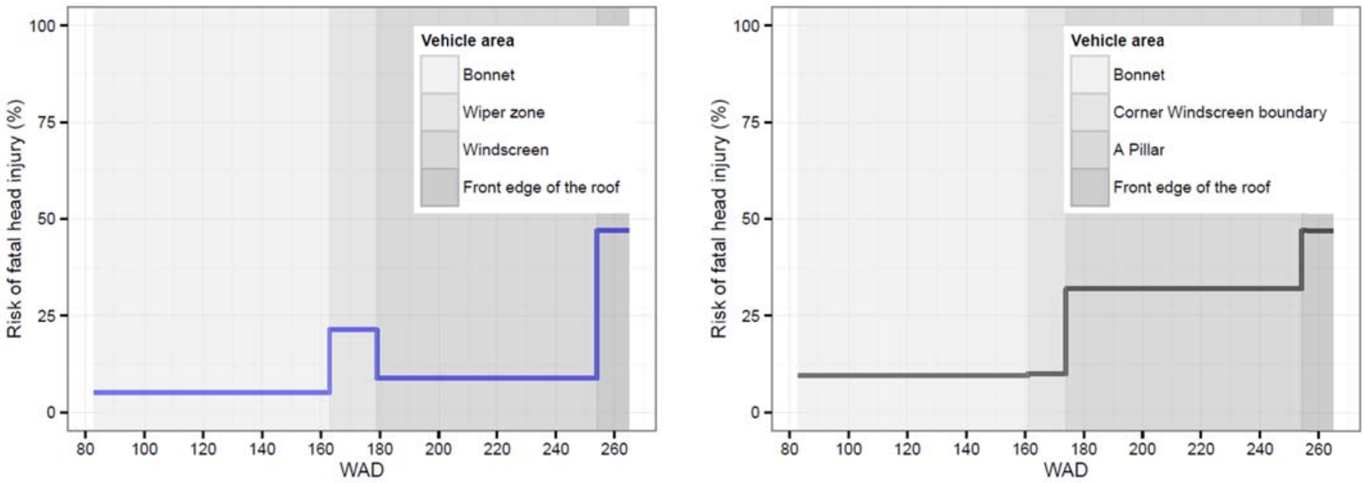
The distribution of the WAD could also be approximated by the superimposition of two normal distributions (Fig. A4, see Appendix) with known statistical parameters. These two curves represent two different probability curves for the same data set. This means that the distribution of the data is represented by the solid red in 76% (λ =0.76) and by the solid green in 24% (λ =0.24). WAD data in the intersection area of the two curves belong simultaneously to both probability distributions. Concentration of data is observable for distances between 190 cm and 205 cm. Figure 5(b) shows how both parameters, body height and WAD, were approximated by normal curves.

Body height of the pedestrian and WAD: how they relate

Correlation between the stature of the pedestrian and WAD was also analysed. Taking all the data where the WAD is less than 180, in order to consider only cases which belong 100% to the greatest WAD distribution (solid red in Fig. 5(b)) and calculating its Pearson correlation coefficient with the variable of the height, a value of 0.9584 was obtained. When only considering WADs longer than 240 in order to consider cases which belong 100% to the smaller probability distribution (solid green in Fig. 5(b)), the Pearson correlation coefficient to the height was 0.7298.

Potential of sustaining fatal head injury for the general car front

A risk of fatal head injury for pedestrians hitting the central or side front part of a medium and large sedan was determined. As stated before, a NISSx was associated to each part of the vehicle front for the 231 cases obtained by applying the filters and where the WAD is coded. Finally, the mean NISSx_zone value was determined and expressed as a percentage, considering that the 100% value of risk indicates head injury causing death. As a result, an average risk of fatal head injury was obtained for each zone considered.
Figure 6(a) and (b) show respectively the risk function obtained for the centre and side front part of a medium sedan (see Fig. 1). The X-axis shows the average measurements of the car front contour shown in Table 1 or, in other words, WAD. The Y-axis represents the percentage risk of sustaining a fatal head injury. The same graphs for a larger sedan are available in the Appendix.



(a) (b)

Fig. 6. Risk of fatal head injury on being hit by the centre (a) and the side (b) front of a medium sedan.

The Front edge of the roof and the A pillar represent, respectively, 47% and 32% of risk of sustaining a fatal head injury. Bonnet and windscreen are the less dangerous parts, accounting for risk values under 10%.

Probability of sustaining a fatal head injury during a pedestrian–passenger car collision

Figure 7(a) and (b) show the resultant curves from combining the WAD distribution for the population (Fig. 5(b)) and the risk of fatal head injury along the vehicle contour (Fig. 6). In terms of conditional and joint probability: by multiplying the probability of WAD by the probability of fatal head injury conditioned by WAD, the intersection (joint probability) of the two events is obtained. This means that the resultant curves show the probability of sustaining a fatal head injury for a given WAD.
Figure 7(a) represents the probability of dying by head injury after being hit by a medium sedan, impacting the pedestrian against the centre of the vehicle (resulting from WAD distributions in Fig. 5(b) and risk curve in Fig.

6(a)). Figure 7(b) shows also the risk when a medium sedan is involved but the pedestrian impacted against the front side of the vehicle (resulting from Figs 5(b) and 6(b)). Curves for larger sedans are available in the Appendix.

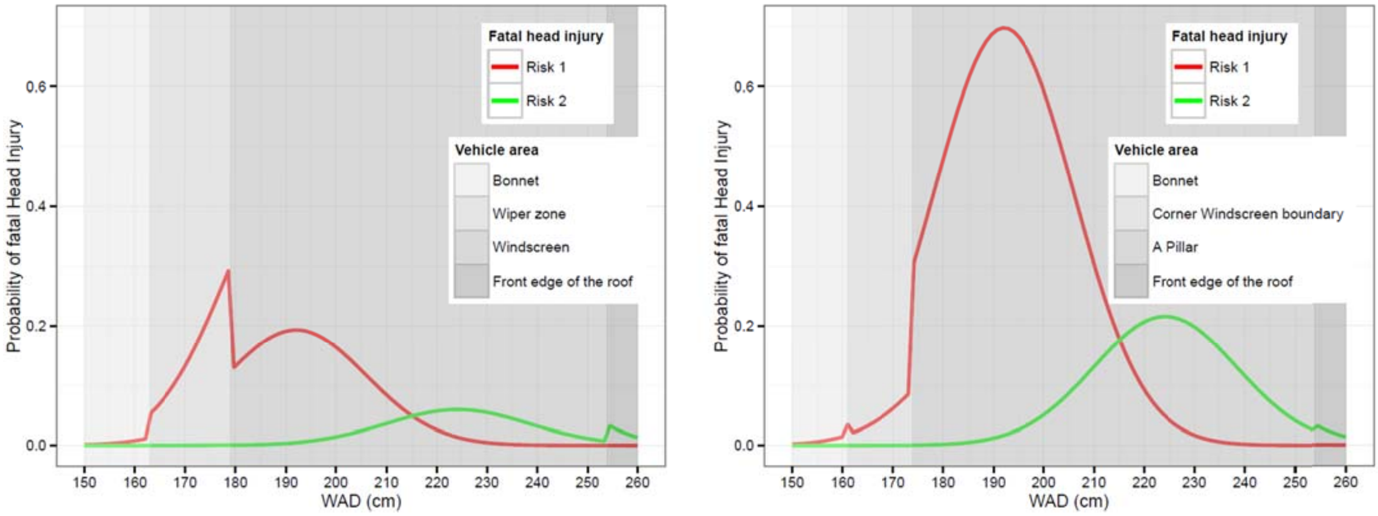


Fig. 7. Probability of fatal head injury on being hit by the centre (a) or side (b) front of a medium sedan.

IV. DISCUSSION

The current study analyses how injury potential and WAD are distributed over the contour of the vehicle front, as well as how other influencing factors, such pedestrian height or impact speed, affect these parameters. The main objective was to predict the risk of suffering a fatal head injury for pedestrians during a collision by using real accident data. The cases were restricted to vehicle–pedestrian events where a passenger car was involved and the victim was older than 14 years. As a result, risk curves were developed to determine the probability of sustaining a fatal head injury in function of the WAD.

Imputation

After analysing the data and achieving an initial sample by applying the filters described in the Methods section, two imputation methods were carried out. The objective was to improve the quality of the data and increase the statistic potential.

The analysis of GIDAS data showed that in many of the cases where there was an impact with the pelvis, thorax or shoulder, an impact with the head also occurred. Furthermore, there was evidence of head impacts that could have existed in some cases without being coded in GIDAS because of lack of severe injuries or marks on the vehicle front. It can be assumed that the majority of the accidents with a pelvis and/or thorax and/or shoulder contact have a high likelihood of associated head impact. By reason of this, a regression method was developed to predict the WAD for cases with shoulder, thorax or pelvic impacts but no head impact coded. WAD distribution before and after the imputation, represented in Fig. 4, provides evidence of the strength of this method.

A second imputation method allowed body height of the pedestrian to be predicted for 58 cases where this data was missing in the database. It is important to highlight that these incomplete data were not used to develop the previous regressions.

A data set with 411 pedestrian–passenger car cases, complete with information about WAD, injuries sustained, crash circumstances, vehicle and anthropometric data, was obtained after the imputations.

Body height of the pedestrian and WAD

The resultant distribution for pedestrian body height has been statistically compared with the distributions obtained for WAD values in the real accident cases analysed. Previous literature [4-5] already defined the pedestrian body height as the main factor influencing the variation of WAD. As shown in Fig. 5(a) and (b), a close relationship between these two parameters may exist and so it is proved by the Pearson correlation coefficients calculated. It should be taken into account that in only 19 cases the WAD was greater than 240 cm, which explains the lower value of the correlation between the second WAD probability distribution (solid green) and the height.

Most frequent values for WAD to the head are between 190 cm and 205 cm. It was also observed a peak of data around 225 cm. The parallel existence of two probability distributions of the WAD means that two different possible WAD values corresponding to the same stature were found and two different risk curves could be developed. This fact could be caused by the multiple factors that influence the WAD. Data show that the vehicle impact speed could be mainly responsible for greater distances, but insufficient accident cases with elevated speed were available in the database to prove that the existence of two WAD probability distributions is owed exclusively to vehicle velocity.

Potential of sustaining fatal head injury for the general car front

The front structure of ten passenger cars was measured, taking into account the areas described in Fig. 1, following the procedure established by Euro NCAP to measure the WAD. The vehicles were classified in two groups due to the significant differences on the front size, which could highly alter impact location. Although Mizuno and Kajzer [5] distinguished three different types of sedan (small, medium and large) on the basis of engine displacement from the front end, here only two groups, medium and large, are considered.

The total of 231 accidents were double-checked and recoded to identify the precise location of head impact against the vehicle. All this information was available in pictures and reconstruction reports. The different areas were coded and associated with the measurements taken. For each case, in function of the severity of the head injuries sustained, a risk value was assigned to the zone where the impact occurred.

As expected, the outcome of injury severity is generally greater on the side of the car, where the stiffest structural components are placed. The front edge of the roof and the A pillar are substantially the most aggressive zones, showing risks of fatal head injury of 35% and 24%, respectively. It is also not surprising that the wiper zone, coincident with the end of the bonnet and the base of the windscreen frame, accounts for almost 22% of fatality risk. Only the bonnet (central and side part), the corner of the windscreen boundary and the windscreen itself show average head injury risks below 13.3%.

It was also interesting to distinguish between normal and larger sedans, giving an overview of the effects of the geometric variations on the head impact location. A WAD between 190 cm and 205 cm would imply a head impact against the windscreen for a medium sedan, but against the A Pillar if the impact occurs on the front side zone. If the vehicle is larger, it is possible that the impact on the centre occurs against the wiper zone or the lower frame of the windscreen, which has a higher injury potential. For those values of the WAD, however, it would be safer hitting the head against the front side zone of a larger sedan than against a medium sedan because the probability of impacting the bonnet instead of the A pillar would be greater. For longer WADs and greater speeds, it would be less risky to hit the centre of the car (windscreen) than the side (A Pillar), as long as the head never comes in contact with the front edge of the roof, accounted to be the most critical part of the front vehicle structure.

Probability of sustaining a fatal head injury during a pedestrian–passenger car collision

Finally, as a result of the intersection between the WAD distribution for the population and the risk of fatal head injury along the vehicle contour, curves expressing the probability of sustaining a fatal head injury for a given WAD were obtained.

The probability of sustaining a fatal head injury is, as expected, higher on the front side of the vehicle, reaching values of 70 % for WADs between 190 cm and 200 cm. In pedestrian accidents where a medium sedan is involved and the person hits the centre of the vehicle front, for a WAD of 180 cm, the probability of sustaining a fatal head injury is almost 30%. When a larger vehicle is involved, the risk could reach 47% for WADs around 190 cm.

The risk curves developed here give an overview of the consequences of the interaction between the human body and the vehicle front structure. This is the first time that a probability distribution for the WAD has been presented and also associated with an injury risk. Furthermore, since the WAD comes from real accident data, it can be said that all the influencing factors are taken into account.

Limitations

The injury curves developed in this study show the probability and the possible fatal head injury outcome for a general population distribution. It is necessary to highlight that it is not possible to obtain a numeric injury severity for a given specific body height or WAD. The values of the probability presented here are also dependent of other accident conditions like initial stance of the pedestrian, gait or braking.

It is also advisable to remind the reader that the accident data used, despite being carefully selected and double-checked, come from the posterior reconstruction of real-life traffic crashes, which has the risk of being miscoded or underreported, or having at least an associated uncertainty. However, the analysis of real accident data provides important and very helpful information and, of course, all the imperfections and inaccuracies associated with on-scene reconstruction is directly applicable to real-life events [22].

The objective of the first imputation was to obtain information about WAD for cases with lower speeds against stiffer parts where there was no mark on the vehicle front. Looking at the speed distribution of the 231 reference cases for the regressions, only 21.5% have an impact speed lower than 30 km/h. It was assumed that cases with lower speeds and head impacts against a stiff zone with no other impact with pelvis, thorax or shoulders against a soft part are not frequent. So these cases would not be a confounder in risk estimations.

It is also necessary to remind that the HD imputation method to obtain the heights missing in function of the WAD ignores the effect of the speed. WAD is very speed dependent up to impact speeds of about 40 km/h [10]. However, at higher impact velocities the WAD reaches a plateau and no longer increases significantly with increases in vehicle speed. From the 231 initial cases, 44% of them had an impact speed greater than 40 km/h.

Imputation methods are general and flexible procedures for handling missing data problems [23], but they can influence the analyst to believe that the data are complete after all when they are not.

V. CONCLUSIONS

- The majority of the pedestrian–passenger car crashes with a pelvis and/or thorax and/or shoulder contact on the vehicle front have a high likelihood of associated head impact. Lack of severe injuries or marks on the car could explain the miscoding in the GIDAS database.
- Two probability distributions for the WAD were found. This leads to the development of two different risk curves and even the association of two different WAD values for the same body height. This fact could be caused by the multiple factors influencing the WAD, but especially because of the higher impact speeds.
- Geometrical differences between the front of normal and large sedans alter the head impact location and the outcome of head injury severity.
- The front edge of the roof and the A pillar are the most aggressive zones on the car front. Bonnet and windscreen showed a lower value of fatal head injury risk.
- Most frequent values of the WAD (between 190 cm and 205 cm) would imply a head impact against the windscreen for a medium sedan, but against the A Pillar if the impact occurs on the front side zone.
- Four different curves expressing the probability of sustaining a fatal head injury for a given WAD during a pedestrian–passenger car crash were developed in this study. The probability of sustaining a fatal head injury is higher on the front side of the vehicle, reaching values of 70% for WADs between 190 cm and 200 cm. In pedestrian accidents where a medium sedan is involved and the person hits the centre of the vehicle front, for a WAD of 180 cm the probability of sustaining a fatal head injury is 30%. When a larger vehicle is involved, the risk could reach 47% for WADs around 190 cm.

VI. REFERENCES

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VII. APPENDIX

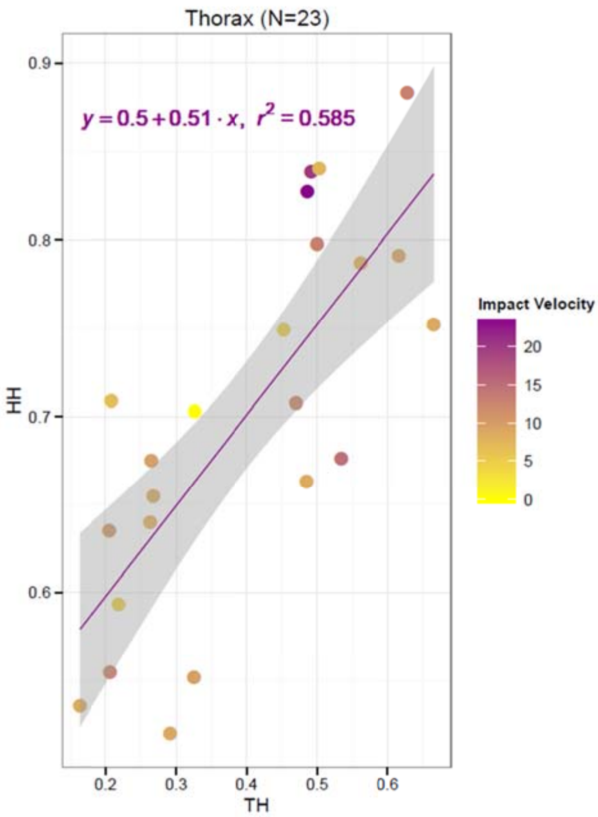


Fig. A1. Accidents with head and thorax impact.

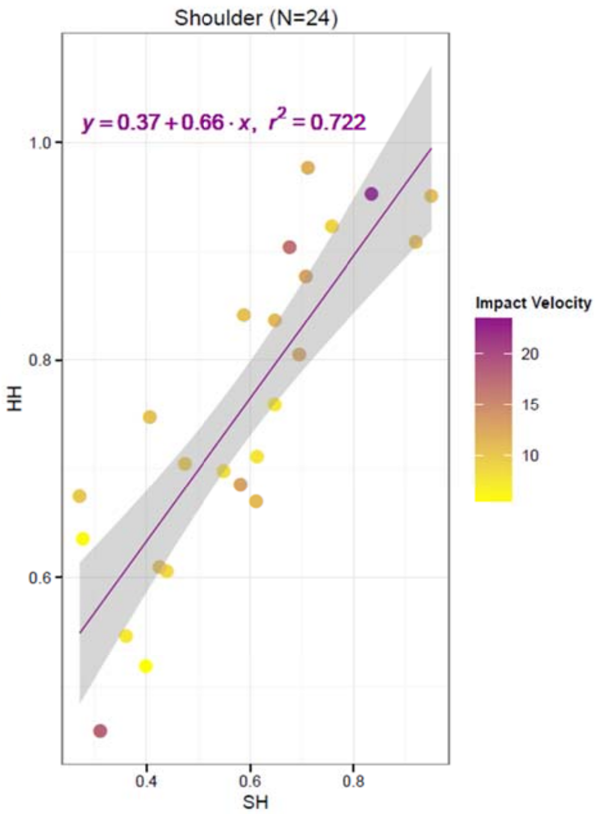


Fig. A2. Accidents with head and shoulder impact.

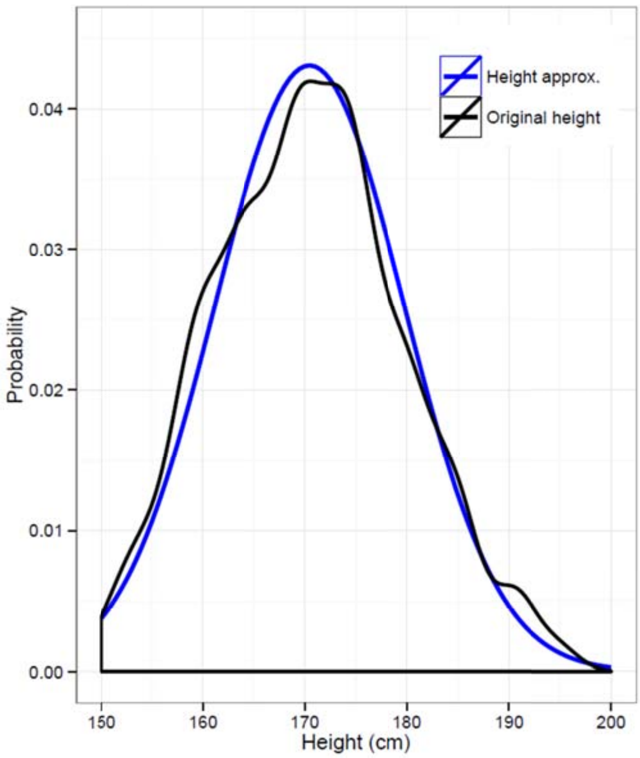


Fig. A3. Approximation of the distribution of the height of the pedestrian by a normal distribution.

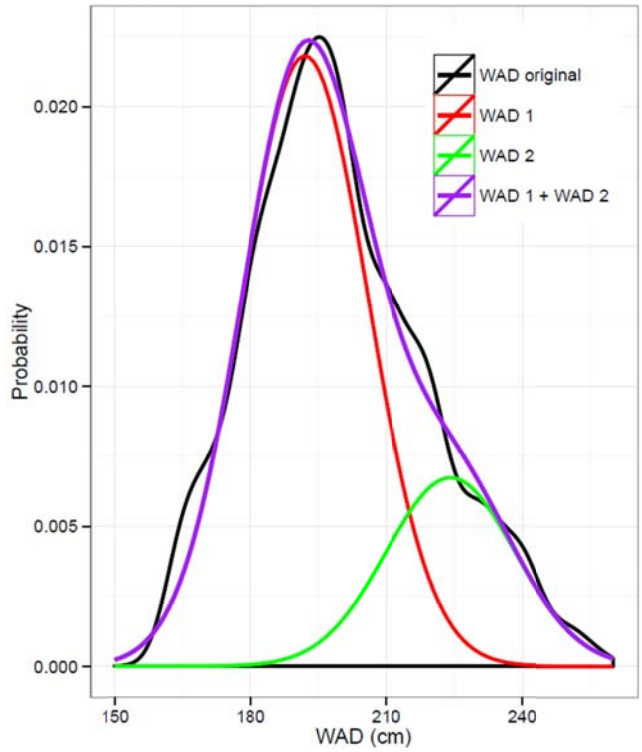


Fig. A4. Comparison between the original WAD distribution and its approximation by the superimposition of two normal distributions.

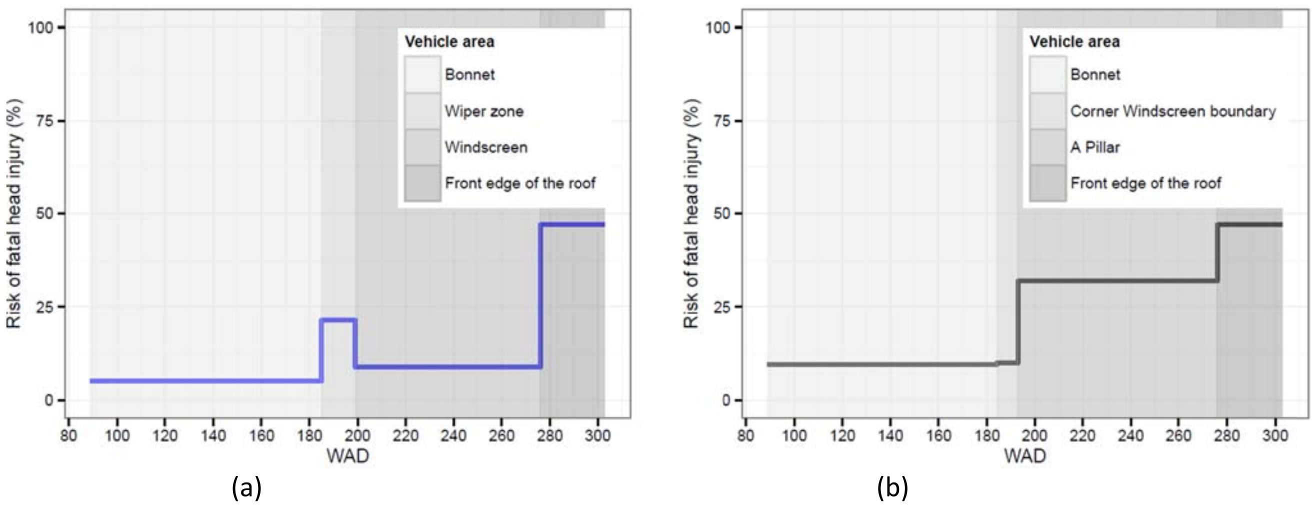
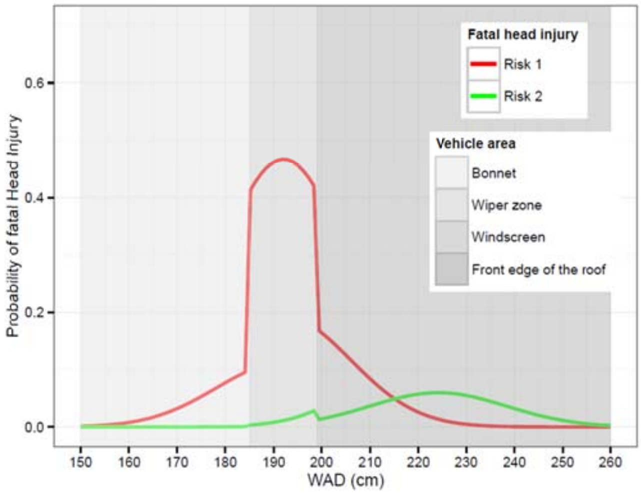
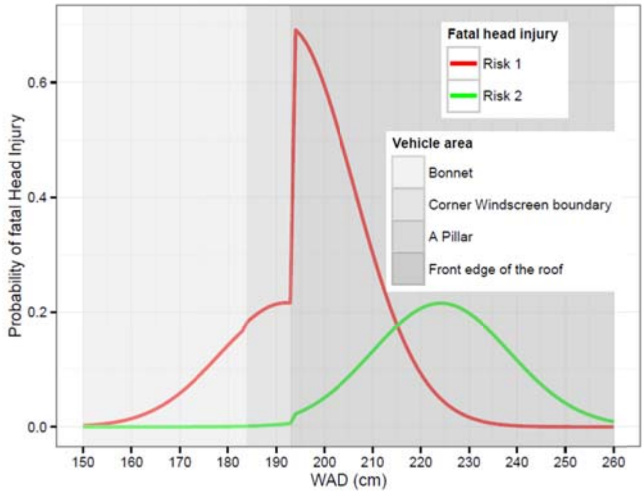


Fig. A5. Risk of fatal head injury by being hit by the centre (a) and the side (b) front of a large sedan.



(a)



(b)

Fig. A6. Probability of fatal head injury by being hit by the centre (a) or side (b) front of a large sedan.