PEDESTRIAN HEAD IMPACT - WHAT DETERMINES THE LIKELIHOOD AND WRAP AROUND DISTANCE?

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ABSTRACT

The current study evaluates the influence of impact speed, pedestrian stature, and vehicle geometry on the likelihood and location of head-vehicle contact in a frontal pedestrian crash. Information on 408 pedestrian crashes in which the striking vehicle was either a car, pick-up truck, or an SUV was obtained from the Pedestrian Crash Data Study (PCDS), German In-Depth Accident Study (GIDAS), and Crash Injury Research and Engineering Network (CIREN) databases. Logistic regression was used to evaluate the importance of factors that determine the likelihood of head contact and sliding up the hood prior to head contact. Multiple linear regression was used to study the relative influence of impact speed, pedestrian stature, bumper height, hood height, and hood length on the wrap around distance (WAD) to head contact and to evaluate whether it is possible to predict this distance from these five parameters. As expected, the likelihood of head-vehicle contact increased with increasing impact speed and pedestrian to hood height ratio. The likelihood of sliding up the hood prior to head contact increased with increasing impact speed and was significantly higher in cases for which the pedestrian stature to hood height ratio was greater than two than in cases in which it was less than two. Of the variables considered, stature was the single most important predictor of WAD to head contact explaining 24% of the variation alone. Other significant predictors included the impact speed, whether the pedestrian was taller than twice the hood height, and hood length, which, together with pedestrian stature, explained a total of 40% of the variation. The low explanatory effect of this model suggests that additional factors, such as the presence or absence of pre-impact braking and pedestrian stance and orientation, also affect the WAD to head contact.

INTRODUCTION

Injuries to pedestrians involved in pedestrian versus motor vehicle crashes are a significant contributor to death and disability in all motorized societies. The World Bank has estimated that 41-75% of worldwide road traffic fatalities are pedestrians (World Bank, 2006). Several epidemiological studies on various populations of pedestrian victims have indicated that, together with the lower extremities, the head is the most frequently injured body region (Chidester and Isenberg, 2001; Mizuno, 2003; Ballesteros et al., 2004; Ivarsson et al., 2005). Considering only serious to fatal injuries (AIS 3+), the head ranks higher in injury frequency than any other body region (Lane et al., 1994; Harruff et al., 1998; Otte, 1999; Crandall et al., 2002; Ivarsson et al., 2005; Ono et al., 2005). Although head injury can occur as a result of the pedestrian's secondary impact with the ground, head contact with various vehicle components has been reported to be the primary source for moderate to fatal head injuries (Ashton, 1975; Ashton et al., 1978; Mizuno, 2003; Kendall et al., 2006). Mizuno (2003) summarized the findings of a total of 1605 pedestrian cases that occurred in Australia, Germany, Japan, and the US and reported that 80% of the recorded AIS 2+ head injuries were due to contact with vehicle components including, but not limited to, the hood, windscreen, and windscreen frame. The widespread area of head contact locations on the vehicle shown by Mizuno (2003) has also been documented in other epidemiological studies. Chidester and Isenberg

(2001) analyzed the 420 frontal pedestrian crashes included in the Pedestrian Crash Data Study (PCDS) and reported that the wrap around distance (WAD) to head contact in the 228 cases for which there was evidence of head contact on the vehicle ranged from less than 60 cm to over 250 cm. Otte (1994) analyzed 372 frontal pedestrian crashes involving adult pedestrians ranging in height from 150 to 190 cm and found that the "throwing up distance" (the horizontal distance from the front end of the vehicle to the point of head contact) in the cases for which there was evidence of head contact on the vehicle ranged from approximately 40 to 210 cm.

The widespread distribution of potential head contact locations on the vehicle has led to the proposal of several different safety concepts for reducing the frequency and severity of pedestrian head injury. Windscreen airbags have been proposed for preventing the head from contacting the stiff windscreen shuttle and A-pillars (Crandall et al., 2002), whereas examples of safety concepts that provide increased deceleration space in the event of head contact with the hood include pyrotechnic devices that rapidly raise the hood (Fredriksson et al., 2001) and flexible and collapsible hood hinges (Kirkeling et al., 2005). Other indirect efforts taken towards reducing the overall aggressiveness of the vehicle towards the pedestrian head include the pedestrian test protocol that is part of the New Car Assessment Program (NCAP) in Europe (EuroNCAP), Japan (JNCAP), and Australia (ANCAP) and the legislative directives for pedestrian protection that recently have gone into effect in Europe (2003/102/EC) and Japan (TRIAS63-2004). Both NCAP and the legislative directives evaluate the aggressiveness of the vehicle towards the pedestrian head by measuring the impact response of adult and/or child sized headforms that are propelled into different spots within specified zones on the vehicle in which pedestrian head contact is deemed likely to occur. In NCAP, the child and adult head impact zones comprise the area of the vehicle front structure that falls within the geometric traces of the 1000-1500 mm (JNCAP: 1000-1700 mm) and 1500-2100 mm (JNCAP: 1700-2100 mm) WAD, respectively, whereas the current phase of the legislative directives limits the test zone to the hood top.

While the safety concepts and evaluation procedures described above should lead to an overall reduction of the frequency and severity of pedestrian head injury, it may be possible to achieve an even higher protective efficiency if vehicles could be designed to minimize the likelihood of pedestrian head contact, minimize the head contact velocity, and force the head to contact the vehicle in regions that offer extensive deceleration space. Several previous investigators have reported that the likelihood and speed of head contact as well as the amount of slide up the hood prior to head contact (WAD to head contact minus pedestrian stature) are dependent on the impact velocity and the height of the pedestrian relative to geometrical vehicle parameters such as bumper height, hood height, and hood length (Ashton, 1975, 1980; Ashton et al., 1978; Niederer and Schlumpf, 1984; Otte, 1994; Roudsari et al., 2005).

The current study aims to evaluate the influence of impact speed, pedestrian stature, and vehicle geometry on the likelihood and location of head contact on the vehicle in a frontal pedestrian crash based on information from three detailed registries of real world pedestrian crashes. More precisely, we aim to evaluate how impact speed and pedestrian stature relative to bumper height, hood height, and hood length affect the likelihood of head contact on the vehicle and the likelihood of pedestrian slide up the hood prior to head contact (WAD to head contact > pedestrian stature). In addition, we aim to quantify the relative influence of impact speed, pedestrian stature, bumper height, hood height, and hood length on the WAD to head contact and evaluate whether it is possible to predict the WAD to head contact in a frontal pedestrian crash from these five variables.

METHODOLOGY

Data Sources

Data came from three real world pedestrian crash databases. The PCDS trauma registry is a compilation of detailed information on a total of 552 pedestrian crashes that occurred during the period from 1994 through 1998 in six metropolitan areas in the US (Chidester and Isenberg, 2001). A "pedestrian" was defined as any person located in a traffic-way, on a sidewalk or path contiguous with a traffic-way, or on private property. The striking vehicle had to be forward moving and of model year 1990-1996. Crashes in which a person was lying or sitting while struck were not included. The pedestrian impact had to be the only impact and the first point of contact had to be forward of the top of the A-pillar. The PCDS data are not weighted since the study was designed to be clinical rather than providing a national sample of all US pedestrian crashes.

The second data source was the German In-Depth Accident Study (GIDAS). This database consists of detailed information on several thousand traffic crashes that occurred in the areas of Hanover and Dresden in Germany. The current study only

used data from the pedestrian crashes included in GIDAS.

The third data source was the CIREN (Crash Injury Research and Engineering Network) pedestrian database from the Honda INOVA Fairfax Hospital CIREN center in Fairfax, Virginia (Longhitano et al., 2005). This database currently includes in-depth information on approximately 50 recent pedestrian crashes that occurred in the Washington, DC metropolitan region. The model year of the striking vehicles ranged from 1986 to 2004. The database consists of the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) set of 650 data elements plus an additional 250 medical and injury data elements including complete injury documentation by means of Abbreviated Injury Scale, 1990 Revision (AIS-90) coding.

Filtering of the Data Sources

The three data sources were filtered to include only the cases fulfilling the following criteria:

- Frontal crash (pedestrian struck by the front of the vehicle),
- Striking vehicle a passenger car, sport utility vehicle (SUV), or pick-up truck
- Pedestrian in an upright position while struck,
- Information provided on:
  - Estimated impact speed,
  - Pedestrian stature,
  - Whether head contact on the vehicle occurred,
  - Bumper height (vertical height above ground of the top surface of the frontal bumper)
  - Hood height (vertical height above ground of the leading edge of the hood),
  - Hood length (flat plane distance from the leading edge of the hood to the trailing edge at the windshield),
- Pedestrian stature/hood height $\geq$ 1.40 (to avoid the potential inclusion of cases in which head contact occurred as a result of direct impact by the front of the vehicle rather than secondary to the pedestrian wrapping around the vehicle front).

The filtering procedure left 258 cases from PCDS and 32 from CIREN for analysis. GIDAS does not include any information on the height and length of the hood of the vehicle. However, from information provided in the library of vehicle models included in the Expert AutoStat® software (4N6XPRT Systems, La Mesa, CA, USA), these measurements were identified for 118 of the GIDAS cases that fulfilled all the other inclusion criteria. Thus, a total of 408 cases fulfilling all the inclusion criteria were available for analysis.

Analysis

Logistic regression was used to derive functions for the likelihood of head-vehicle contact and WAD to head contact > pedestrian stature. The independent variables were impact speed, pedestrian stature to bumper height ratio (PS/BH), pedestrian stature to hood height ratio (PS/HH), and pedestrian stature to hood length ratio (PS/HL). The logistic regression models were developed according to the approach outlined by Hosmer and Lemeshow (1989), which briefly includes the following eight steps:

- Screening of the individual importance of the potential predictors by means of univariate analyses.
- Multivariate analysis including variables of known biological importance plus any additional variables that demonstrated p-values less than 0.25 in the univariate analyses.
- Identify variables that do not significantly contribute to the multivariate model using likelihood ratio tests.
- Quartile grouping analysis to make sure that the logit for any of the variables identified as insignificant is not a symmetric or u-shaped function (any of these functional forms could explain why a linear fit has a zero slope).
- Fit a new model excluding all variables that have been found to be either biologically or statistically unimportant.
- Box-Tidwell transformation and subsequent quartile grouping analysis of the included variables that have been modeled as continuous to obtain their correct scale in the logit.
- Assessment of the importance of possible interaction terms using likelihood ratio tests.
- Fit a new model that, in addition to the main effects that already have been found to be important, also includes the statistically significant interaction terms that make sense from a biological perspective.

Three goodness-of-fit tests (Pearson, Deviance, and Hosmer and Lemeshow) were used to evaluate the null hypothesis of adequate model fit. In addition, the predictive ability of the models was evaluated using two measures of association (Kruskal's Gamma and Somers' D) based on percent concordance and discordance. A pair of observations with different outcomes ("event" and "no event") is concordant if the model predicts a higher likelihood of event occurrence for the event case than for the non-event case. A pair of observations is discordant if the event case has a lower model-predicted likelihood than the

non-event case. Kruskal's Gamma is defined by the number of concordant and discordant pairs in the dataset, so it is a measure of the model's ability to discriminate event from non-event cases:

$$\gamma = \frac{N_{concordant} - N_{discordant}}{N_{concordant} + N_{discordant}} \quad (1)$$

where $N_{concordant}$ is the number of concordant pairs and $N_{discordant}$ is the number of discordant pairs in the dataset. A Kruskal's Gamma value of zero indicates that the model has no predictive ability, whereas a value of one indicates perfect prediction. Somers' D *(SD)* is Kruskal's Gamma modified to penalize for any tied pairs of observations in the dataset:

$$SD = \frac{N_{concordant} - N_{discordant}}{N_{concordant} + N_{discordant} + N_{tied}} \quad (2)$$

Best subsets multiple linear regression was used to determine the relative importance of impact speed, pedestrian stature, bumper height, hood height, and hood length on the WAD to head contact and to evaluate whether it is possible to predict the WAD to head contact in a frontal pedestrian crash from these five variables. In addition to the "main effect" variables, all possible interaction terms were included as potential predictors in the analysis. All logistic and linear regression analyses were conducted using the statistical software package MINITAB (Minitab, Inc., State College, PA, USA, version 14).

RESULTS

The Likelihood of Head-Vehicle Contact

Of the 408 cases available for analysis, 210 showed evidence of head contact on the vehicle. Table 1 shows mean ± SD and range of the potential predictors by outcome and for all cases combined as well as the individual p-values from the univariate analyses. As shown, both impact speed and PS/HH were significant variables while PS/BH demonstrated a p-value above 0.25 and therefore was excluded. Further analysis confirmed that PS/HL had no association with the occurrence of head contact and it was therefore excluded as well. Box-Tidwell transformations and subsequent quartile analyses of impact speed and PS/HH suggested that PS/HH should be modeled as continuous and linear and impact speed as continuous but logarithmic in the logit. Table 2 shows estimated coefficients, log-likelihood, goodness-of-fit, and measures of association for three models based on log(impact speed) only (model 1), log(impact speed) and PS/HH (model 2), and log(impact speed), PS/HH, and the interaction between these two variables (model 3). According to the goodness-of-fit measures, all three models appear to provide adequate fit of the data. However, while the measures of association indicate that model 2 and 3 are equally good in discriminating between events and non-events, the likelihood ratio test comparing these two models indicate that model 3 fits the data better (p = 0.029) and consequently, that the individual effect of impact speed on the likelihood of head contact should not be evaluated without accounting for PS/HH and vice versa. Henceforth, model 3 is used to study the effects of impact speed and PS/HH on the likelihood of head contact on the vehicle.

Figure 1 shows the likelihood of head-vehicle contact as a function of impact speed for the 10, 25, 50, 75, and 90 percentiles of PS/HH. For the purpose of comparison, the corresponding curve determined from the univariate model 1 is shown as well. As shown, the likelihood of head-vehicle contact increases rapidly with impact speed up to approximately 50 km/h after which the rate of increase levels off. Also shown in Figure 1 is that for any impact speed exceeding approximately 15 km/h, an increase of the pedestrian stature or a reduction of the hood height is associated with an increasing risk of head-vehicle contact. This finding is further illustrated in Figure 2 which shows the likelihood of head-vehicle contact as a function of PS/HH for the 10, 25, 50, 75, and 90 percentiles of impact speed. For impact speed below 15 km/h, the model suggests a slightly decreasing risk of vehicle-head contact with increasing PS/HH (Figures 1 and 2). This is most likely not the case in the real world but instead a reflection of that the likelihood of head-vehicle contact is insensitive to PS/HH for low impact speeds.

Figure 3 provides a comparison of the individual effects of impact speed reduction and hood height increase on the odds of head-vehicle contact for the particular reference case of a pedestrian of height 177.3 cm (50-percentile male height) struck at 40 km/h by a vehicle with a hood height of 70 cm (50-percentile hood height of the 349 passenger cars included in the analysis). As an example of how to interpret the data in the figure, it shows that a reduction of the impact speed by 9 km/h (from 40 to 31 km/h) or an increase of the hood height by 17.5 cm (from 70 to 87.5 cm) would both reduce the odds of head-vehicle contact by 50%. It is important to emphasize that Figure 3 is only valid for the particular reference case used here.

Table 1.
Head-vehicle contact characteristics by outcome and for all cases combined along with the individual p-values from the univariate analyses

Independent variable	No head-vehicle contact (N = 198) mean ± SD (range)	Head-vehicle contact (N = 210) mean ± SD (range)	Total (N = 408) mean ± SD (range)	p-value
Impact speed (km/h)	20.04 ± 13.10 (2-74)	42.03 ± 19.66 (8-118)	31.36 ± 20.06 (2-118)	$<10^{-9}$
Pedestrian stature/ bumper height	3.13 ± 0.46 (1.90-4.94)	3.17 ± 0.45 (1.88-4.56)	3.15 ± 0.45 (1.88-4.94	0.297
Pedestrian stature/ hood height	2.25 ± 0.38 (1.42-3.40)	2.35 ± 0.40 (1.42-3.54)	2.30 ± 0.40 (1.42-3.54)	0.010
Pedestrian stature/ hood length	1.53 ± 0.22 (0.87-2.10)	1.56 ± 0.23 (0.94-2.14)	1.54 ± 0.22 (0.87-2.14)	0.188

Table 2.
Estimated coefficients, log-likelihood, goodness-of-fit, and measures of association for three logistic regression models predicting the likelihood of head-vehicle contact. P-values in brackets denote the significance levels of individual variables in the models

Model	Variables				Log-likelihood	Goodness-of-fit	Measures of association
	Constant	Log(impact speed) (km/h)	PS/HH	Log(impact speed)×(PS/HH) (km/h)			
1	-7.444 (p<0.0005)	5.311 (p<0.001)			-202.363	P = 0.986 D = 0.992 HL = 0.346	γ = 0.68 *SD* = 0.67
2	-9.220 (p<0.0005)	5.317 (p<0.001)	0.772 (p = 0.014)		-199.254	P = 0.604 D = 0.512 HL = 0.478	γ = 0.69 *SD* = 0.69
3	1.026 (p=0.826)	-1.911 (p=0.557)	-3.749 (p=0.072)	3.193 (p=0.029)	-196.877	P = 0.899 D = 0.565 HL = 0.373	γ = 0.69 *SD* = 0.69

Abbreviations: PS/HH = Pedstrian stature/hood height, P = Pearson, D = Deviance, HL = Hosmer and Lemeshow, γ = Kruskal's Gamma, *SD* = Somers' D.

Figure 4 shows the likelihood of head-vehicle contact at an impact speed of 40 km/h as a function of the hood height for pedestrian statures corresponding to the 50-percentile adult male, 5-percentile adult female, 95-percentile adult male, and 50-percentile 6-year-old child. The curves are only shown for the hood height intervals for which the model is valid ($1.42 \leq$ PS/HH ≤ 3.54), which explains why the risk of head contact for the 6-year-old child is not shown for hood heights exceeding 81 cm. As shown, there is a substantial difference in the likelihood of head-vehicle contact between the different anthropometries. Comparing for instance the 50-percentile adult male and the 6-year-old child struck by a vehicle with a hood height of 60 cm, the 50-percentile adult male is approximately four times as likely to sustain head contact on the vehicle.

The Likelihood of WAD to Head Contact > Pedestrian Stature

Of the 210 cases for which there was evidence of head contact on the vehicle, eleven did not include any information on the WAD to head contact and therefore had to be excluded. Of the remaining 199 cases available for analysis, 42 had a WAD to head contact that was less or equal to the stature of the pedestrian, whereas the remaining 157 cases had a WAD to head contact that was greater than the pedestrian stature. Table 3 shows mean ± SD and range of the potential predictors by outcome and for all cases combined as well as the individual p-values from the univariate analyses. As shown, impact speed, PS/BH, and PS/HH were all significant predictors of WAD to head contact > pedestrian stature while PS/HL demonstrated a p-value above 0.25 and therefore was excluded.

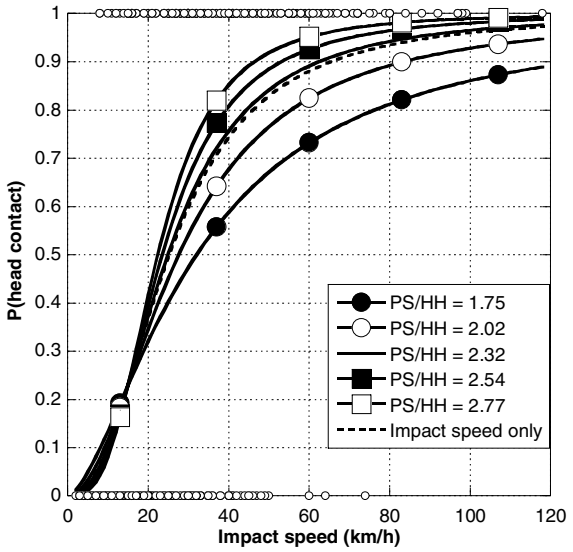

Figure 1. Likelihood of head-vehicle contact as a function of impact speed for the 10 (PS/HH = 1.75), 25 (PS/HH = 2.02), 50 (PS/HH = 2.32), 75 (PS/HH = 2.54), and 90 (PS/HH = 2.77) percentiles of PS/HH. Also shown is the corresponding risk function predicted by the univariate model HC1.

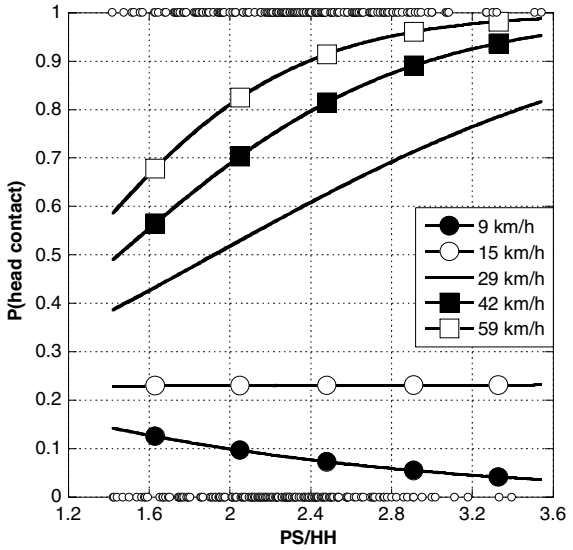

Figure 2. Likelihood of head-vehicle contact as a function of PS/HH for the 10 (impact speed = 9 km/h), 25 (impact speed = 15 km/h), 50 (impact speed = 29 km/h), 75 (impact speed = 42 km/h), and 90 (impact speed = 59 km/h) percentiles of impact speed.

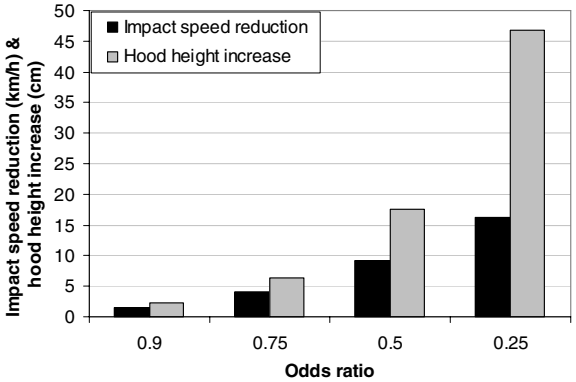

Figure 3. Individual effects of impact speed reduction and hood height increase on the odds of head-vehicle contact for the reference case of a pedestrian of height 177.3 cm struck at 40 km/h by a vehicle with a hood height of 70 cm.

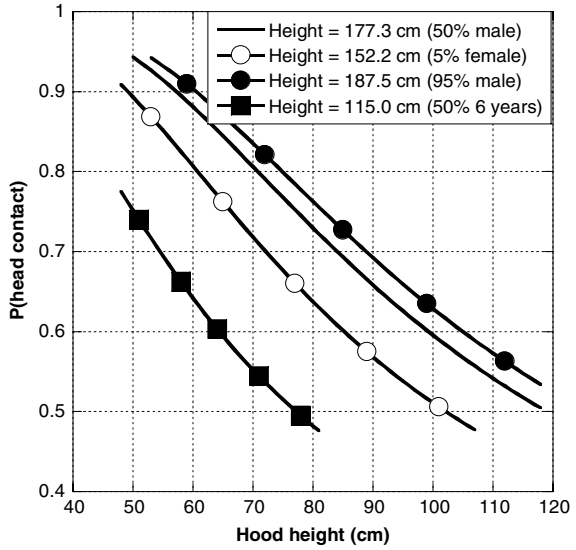

Figure 4. Likelihood of head-vehicle contact at an impact speed of 40 km/h as a function of hood height for pedestrian statures corresponding to the 50-percentile adult male, 5-percentile adult female, 95-percentile adult male, and 50-percentile 6-year-old child.

Subsequent analysis of the multivariate model with impact speed, PS/BH, and PS/HH as independents revealed that PS/BH did not add any explanatory effect (a model with impact speed and PS/HH as the only two dependents performed equally well) and was therefore excluded. Box-Tidwell transformations and subsequent quartile analyses of impact speed and PS/HH suggested that PS/HH should be modeled as a binary variable, PS/HH_bin, taking the value 0 for PS/HH < 2 and 1 for PS/HH ≥ 2, whereas the dependence on impact speed appeared to be best described by a logarithmic relationship. Table 4

shows estimated coefficients, log-likelihood, goodness-of-fit, and measures of association for three models based on log(impact speed) only (model 4), log(impact speed) and PS/HH_bin (model 5), and log(impact speed), PS/HH_bin, and the interaction between these two variables (model 6). According to the goodness-of-fit measures, both model 5 and 6 provide adequate fit of the data. However, while the measures of association indicate that they are equally good in discriminating between events and non-events, the likelihood ratio test comparing these two models indicate that model 6 fits the data better (p = 0.007) and consequently, that the individual effect of impact speed on the likelihood of WAD to head contact > pedestrian stature should not be evaluated without accounting for PS/HH_bin and vice versa. Henceforth, model 6 is used to study the effects of impact speed and the ratio of pedestrian stature to hood height on the likelihood of WAD to head contact > pedestrian stature.

Table 3.
WAD to head contact versus pedestrian stature by outcome and for all cases combined along with the individual p-values from the univariate analyses

Independent variable	WAD to head contact ≤ pedestrian stature (N = 42) mean ± SD (range)	WAD to head contact > pedestrian stature (N = 157) mean ± SD (range)	Total (N = 199) mean ± SD (range)	p-value
Impact speed (km/h)	30.07 ± 19.33 (8-99)	45.12 ± 18.65 (8-118)	41.94 ± 19.73 (8-118)	$<10^{-5}$
Pedestrian stature/ bumper height	2.94 ± 0.51 (1.88-3.82)	3.22 ± 0.40 (1.96-4.56)	3.16 ± 0.44 (1.88-4.56)	<0.001
Pedestrian stature/ hood height	2.15 ± 0.48 (1.47-3.54)	2.40 ± 0.36 (1.42-3.32)	2.35 ± 0.40 (1.42-3.54)	<0.001
Pedestrian stature/ hood length	1.55 ± 0.23 (1.01-2.00)	1.56 ± 0.23 (0.94-2.14)	1.56 ± 0.23 (0.94-2.14)	0.78

Table 4.
Estimated coefficients, log-likelihood, goodness-of-fit, and measures of association for three logistic regression models predicting the likelihood of WAD to head contact > pedestrian stature. P-values in brackets denote the significance levels of individual variables in the models

Model	Variables				Log-likelihood	Goodness-of-fit	Measures of association
	Constant	log(impact speed) (km/h)	PS/HH_bin	log(impact speed)×(PS/HH)_bin (km/h)			
4	-5.41306 (p<0.001)	4.43038 (p<0.001)			-88.274	P = 0.010 D = 0.754 HL = 0.129	γ = 0.55 *SD* = 0.54
5	-6.96059 (p<0.001)	4.51352 (p<0.001)	1.92757 (p<0.001)		-78.638	P = 0.648 D = 0.636 HL = 0.133	γ = 0.70 *SD* = 0.69
6	-2.79316 (p=0.138)	1.81872 (p=0.131)	-5.74775 (p=0.042)	5.11781 (p=0.007)	-74.990	P = 0.946 D = 0.803 HL = 0.701	γ = 0.70 *SD* = 0.69

Abbreviations: P = Pearson, D = Deviance, HL = Hosmer & Lemeshow, γ = Kruskal's Gamma, *SD* = Somers' D.

Figure 5 shows the likelihood of WAD to head contact > pedestrian stature as a function of impact speed for pedestrians shorter (PS/HH < 2) and equal or taller (PS/HH ≥ 2) than twice the hood height of the striking vehicle. As shown, the likelihood WAD to head contact > pedestrian stature increases with impact speed. Also shown in Figure 5 is that for any impact speed exceeding approximately 13 km/h, pedestrians equal to or taller than twice the height of the hood are more likely to slide up the hood prior to head contact than pedestrians shorter than twice the hood height. For impact speed below 13 km/h, the model suggests the exact opposite, i.e. that the likelihood of WAD to head contact > pedestrian stature is greater for pedestrians shorter than taller than twice the hood height. This is most likely not the case in the real world but instead a reflection of that the likelihood of .that the likelihood of WAD to head contact > pedestrian stature is insensitive to PS/HH for low impact speeds.

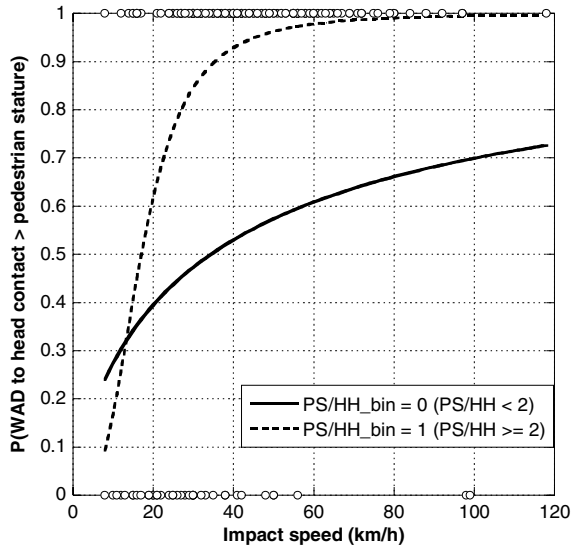

Figure 5. Likelihood of WAD to head contact > pedestrian stature as a function of impact speed for pedestrians shorter (PS/HH < 2) and equal or taller (PS/HH ≥ 2.00) than twice the hood height of the striking vehicle.

WAD to Head Contact

Preliminary analyses demonstrated that the influence of impact speed on the WAD to head contact was better described by a logarithmic than a linear relationship. Consequently, the logarithm of impact speed instead of impact speed was included as a potential predictor in the multiple regression analyses. Based on the results from the logistic regression analysis of the likelihood of WAD to head contact > pedestrian stature, the binary version of PS/HH (PS/HH_bin) which takes the value 0 for PS/HH < 2 and the value 1 for PS/HH ≥ 2, was added as a potential predictor. Thus, a total of 21 potential predictors (six "main effects" and fifteen interactions) were included in the analyses.

Table 5 lists the estimated coefficients, R^2 or multiple correlation coefficient (the fraction of variance in the dependent variable collectively explained by all of the independent variables), and R^2-adjusted (the multiple correlation coefficient adjusted for the number of predictors included in the model) for the best models (highest R^2-adjusted) including one, two, three, four, five, and six, predictors. The last column in Table 5 shows the p-value obtained from F-tests of the difference in R^2-adjusted between the two best models with k and k + 1 predictors. Not surprisingly, pedestrian stature is the single most important predictor explaining 24% of the variance in WAD to head contact. Additional variables of significant importance include impact speed, the binary version of PS/HH, and the hood length that, together with pedestrian stature, explain 40% of the variance in WAD to head contact. As shown in Table 5, the only additional variable that seem to have an explanatory effect on the WAD to head contact is the interaction between pedestrian stature and hood length ($p = 0.072$). However, inclusion of this term results in a net increase of R^2-adjusted of only one percentage unit.

DISCUSSION

The current study used information on impact speed, pedestrian stature, bumper height, hood height, and hood length, whether head-vehicle contact occurred, and WAD to head contact from three detailed registries of real world pedestrian crashes to:

- develop logistic regression models predicting the likelihood of pedestrian head contact on the vehicle and likelihood of WAD to head contact > pedestrian stature,
- determine the relative importance of impact speed, pedestrian stature, bumper height, hood height, and hood length on the WAD to head contact, and
- evaluate whether it is possible to predict the WAD to head contact from impact speed, pedestrian stature, bumper height, hood height, and hood length.

The study was limited to cases in which the striking vehicle was a passenger car, SUV, or pick-up truck. Other vehicle types, like mini-vans and large vans, generally lack the relatively horizontal hood that characterize passenger cars, SUVs, and pick-up trucks and therefore cause slightly different pedestrian response kinematics. Also excluded were the thirteen cases in which the pedestrian stature to hood height ratio did not exceed 1.40. This was to avoid the potential inclusion of cases in which head contact occurred as a result of direct impact by the front of the vehicle rather than secondary to the pedestrian wrapping around the vehicle front.

In agreement with the findings of Ashton (1975, 1980, 1997) and Ashton et al. (1978), the results indicated that the likelihood of head-vehicle contact increases with impact speed as well as with PS/HH. These two variables are, however, not independent of each other with the PS/HH having a stronger influence on the likelihood of head-vehicle contact when the impact speed is high than low. It is important to emphasize that although an increased hood height reduces the likelihood of head-vehicle contact for pedestrians taller than 1.4 times the hood height, it may increase the injury risk and injury severity for other body regions such as the torso and also increase the risk of head injury for the pediatric pedestrian population.

Table 5.
Estimated coefficients, multiple correlation coefficients R^2, and adjusted multiple correlation coefficients R^2-adjusted for the best linear regression models of WAD to head contact including one, two, three, four, five, and six predictors. The last column shows the p-value for the difference in R^2-adjusted between the two best models with k and k + 1 predictors. Values in brackets denote the p-values of individual variables in the models

No. of predictors	Predictors							R^2	R^2-adj	p-value
	Const	PS (m)	Log(IS) (km/h)	PS/HH_bin	HL (m)	PS*HL (m^2)	Log(IS)*HL (m×km/h)			
1	-10.51 (0.686)	1.24 (<0.001)						0.244	0.240	N/A
2	-72.38 (0.008)	1.14 (<0.001)	49.4 (<0.001)					0.335	0.328	$<10^{-6}$
3	-55.1 (0.038)	0.925 (<0.001)	48.4 (<0.001)	25.0 (<0.001)				0.389	0.380	$<10^{-4}$
4	-100.9 (0.001)	0.914 (<0.001)	45.1 (<0.001)	25.4 (<0.001)	0.488 (0.009)			0.411	0.399	0.014
5	409.5 (0.098)	-2.11 (0.148)	44.0 (<0.001)	24.6 (<0.001)	-4.25 (0.063)	0.028 (0.038)		0.424	0.409	0.072
6	596.9 (0.027)	-1.69 (0.251)	-119.2 (0.205)	24.7 (<0.001)	-5.96 (0.017)	0.024 (0.078)	1.51 (0.082)	0.433	0.414	0.202

Abbreviations: Const = Constant, PS = Pedestrian stature, IS = Impact speed, PS/HH_bin = Binary version of pedestrian stature to hood height ratio, HL = Hood length, R^2-adj = R^2-adjusted.

Neither PS/BH nor PS/HL had any influence on the likelihood of head contact. The absence of influence of PS/BH may be a consequence of that any initial effect on the pedestrian response kinematics from bumper contact is "washed out" by the subsequent interaction with the leading edge of the hood. The independence of PS/HL is not as easily explained. Intuitively, one would expect a reduction of the hood length to increase the likelihood of head contact since the wrap around distance to the windshield decreases. However, based on the results from the current study, this does not appear to be the case.

The likelihood of WAD to head contact > pedestrian stature also demonstrated strong positive correlation with the impact speed but showed a binary dependence of PS/HH with pedestrians taller than twice the hood height being more likely to slide up the hood prior to head contact than those shorter than twice the hood height. Similar to the case of the likelihood of head-vehicle contact, impact speed and PS/HH are not independent of each other with PS/HH having a greater effect on the likelihood of WAD to head contact > pedestrian stature at high than low impact speeds. The underlying reason for the increased likelihood of WAD to head contact > pedestrian stature for pedestrians taller than shorter than twice the hood height is most likely due to the increased effective mass above the leading edge of the hood, which encourages sliding up the hood. The most likely explanation to the lack of an effect of PS/BH is probably the same as in the case of likelihood of head contact, namely that any initial effect on the pedestrian response kinematics from bumper contact is "washed out" by the subsequent interaction with the leading edge of the hood. According to Otte (1994), the windshield acts like a barrier limiting the distance that the pedestrian slides up the hood prior to head contact. Consequently, PS/HL should influence the WAD to head contact but not whether sliding prior to head contact occurs. This was confirmed in the current study for which the likelihood of WAD to head contact > pedestrian stature showed no association with PS/HL ($p = 0.78$).

The results from the WAD to head contact analysis demonstrated that pedestrian stature alone explained 24% of the variance in WAD to head contact. A total explanatory effect of 40% could be achieved by also accounting for the logarithm of impact speed ($p < 10^{-6}$), whether the pedestrian is taller than twice the hood height ($p < 10^{-4}$), and the hood length ($p = 0.014$). None of the other variables or interactions considered as potential predictors in the current study offered any additional explanatory effect. Consequently, we can conclude that it is not possible to predict the WAD to head contact in a frontal pedestrian crash from pedestrian stature, estimated impact speed, bumper height, hood height, and hood length.

While approximately 60% of the variation in WAD to head contact appears to be due to factors not considered in the analysis, it is important to

emphasize that these factors most likely affect the likelihood of head-vehicle contact and WAD to head contact > pedestrian stature as well. These factors include but are not limited to:

- Whether or not pre-impact braking occurred – Braking causes pitching of the vehicle front end towards the ground and consequently, a reduction of the height of the bumper and hood above ground compared to the non-decelerated state. The current study used the original bumper and hood heights regardless of whether pre-impact braking occurred.
- Front end stiffness – The stiffness of the vehicle front end affects the frictional force between the pedestrian and vehicle during initial contact which, in turn, influences subsequent response kinematics including the WAD to head contact (Ashton, 1980, Okamoto et al., 2003).
- Pedestrian stance and orientation - Results from computer simulations of pedestrian crashes indicate that the stance and orientation of the pedestrian relative to the vehicle at impact influence the subsequent response kinematics (Meissner et al., 2004; Kendall et al., 2006).
- Vehicle front end shape - Passenger cars of recent design have a relatively rounded front end without the distinct edge that demarcates the grille from the hood in older designs. The majority of vehicles included in the current study were of model years 1990 or newer but a few vehicles from the GIDAS database dated as far back as 1983.
- Bumper lead – According to Ashton (1983), bumper lead (the distance by which the bumper is further forward than the leading edge of the hood) has an influence on the relative importance of the bumper and hood leading edge as sources of injury. Consequently, bumper lead may also affect pedestrian response kinematics.

Finally, it needs to be pointed out that despite that the registries used in the current study are believed to be among the most accurate and comprehensive real world pedestrian crash databases currently available, the uncertainty associated with some of the parameters including the impact speed, whether head contact on the vehicle occurred, and head contact location on the vehicle, most likely influenced the results as well.

DISCLAIMER

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