Source of head injury for pedestrians and pedal cyclists: Striking vehicle or road?

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Abstract

The potential effectiveness of vehicle-based secondary safety systems for the protection of pedestrians and pedal cyclists is related to the proportion of cases where injury arises by contact with the road or ground rather than with the striking vehicle. A detailed case review of 205 accidents from the UK On-the-Spot study involving vulnerable road users with head injuries or impacts indicated that contact with the road was responsible in 110 cases. The vehicle however was associated with a majority of more serious casualties: 31 (vehicle) compared with 26 (road) at AIS 2+ head injury level and 20 (vehicle) compared with 13 (road) at AIS 3+ level. Further analysis using a multivariate classification model identified several factors that correlated with the source of injury, namely the type of interaction between the striking vehicle and vulnerable road user, the age of the vulnerable road user and the nature of injury.

Keywords: road accident, vulnerable road user, pedestrian, pedal cyclist, head injury, injury source

1. Introduction

The development of advanced vehicle safety technologies has continued steadily in recent years and some of these offer considerable potential for the protection of vulnerable road users (VRU). The high number of casualties among pedestrians and pedal cyclists—not only in major industrialised nations but throughout the world—has maintained a focus on these groups from governments, manufacturers, insurers, researchers and others in the road safety community. Although vehicle safety technologies are increasingly being integrated into unitary systems, it is still meaningful to distinguish those that aim to avoid or mitigate collisions such as autonomous emergency braking from those

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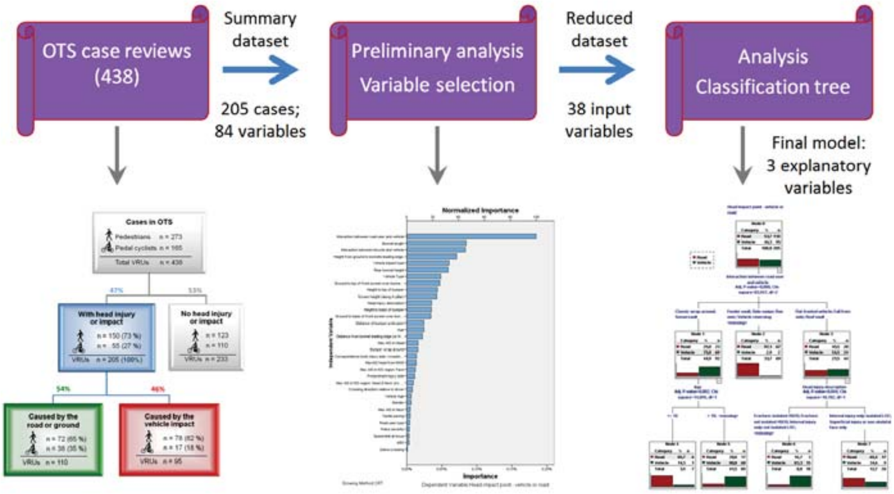

Figure 0: Graphical abstract.

that aim to avoid or mitigate injury such as external airbags or pop-up bonnets (hoods): these are referred to as primary and secondary safety measures respectively. It has been discussed for many years how resources should be allocated between these two categories to achieve casualty reductions in the most cost-effective manner. In this context it is relevant to have some sense of the maximum benefit offered by a particular technology or category of technology. For vulnerable road users, unlike vehicle occupants, there is the special consideration that they generally fall to the ground or road after impact with the striking vehicle. The extent to which they incur injuries from this second impact places an upper limit on the effectiveness of vehicle-based secondary safety systems since these deal with the initial impact against vehicle components such as the bumper, leading edge, bonnet, windscreen (windshield) and A-pillar (A-post). The relative importance of the road as a source of injury compared to the vehicle has not been extensively reported.

Recent published studies from different fields aimed at reducing casualty levels among pedestrians and pedal cyclists have a set of common findings. It is widely agreed that the lower limbs and head are the two body regions with the most frequent and severe injuries for pedestrians. Arregui et al. (2010) published a study based on hospital data from eight European countries comprising 10,341 pedestrians with 19,424 injuries. The study showed that traumatic brain injuries constitute 26% of all injuries and overall head injuries represent 33% of the total. An earlier study of 5000 in-patients from pedestrian accidents in Los Angeles County (Peng and Bongard, 1999) showed that head and neck injuries represent 30% of the total, 29% when only intracranial and facial injuries are included. Another analysis Fredriksson et al. (2010) based on the German In-Depth Accident Study database (GIDAS) showed that for 161 severely injured (AIS 3+) pedestrians out of 1030 total cases, the rates for leg and head injuries were 58% and 43% respectively.

Simms and Wood (2009) maintained that the kinematics of pedestrian impacts are similar to that of pedal cyclists. The bent-knee riding posture, the higher location of the body and the typically higher velocity of the cyclist can however result in a different kinematic response. The authors also mentioned that there is no evidence of differences in the mechanisms by which pedestrians and cyclists contact the ground and this should be a focus of future research. Maki et al. (2003) examined Japanese national and in-depth accident data and showed that head injuries represent 22% and 21% of all severe injuries among pedestrians and pedal cyclists respectively. The head was the second most frequently injured body region after the lower extremities. When only fatal injuries were considered, head injuries had the highest proportion—64% for pedestrians and 72% for pedal cyclists—while fatalities as a result of injuries to the legs were a minor proportion for both groups.

Otte et al. (2012) published an extensive study based on GIDAS which summarised the main injury mechanisms and the distribution of head impact on the vehicle surface for 8204 pedestrians, motorcyclists and pedal cyclists. Head injuries were incurred more frequently by pedestrians (50.4%) than by pedal cyclists (35.6%) or motorcyclists (16.8%). The distribution of head impact points on the vehicle surface showed a concentration on the rearward area of the bonnet. When only severe head injuries (AIS 3+) were considered, the impacts were more concentrated on higher regions, particularly the windscreen. The distinction between the initial contact with the vehicle and the secondary impact on the road, and the influence of this on head injury outcome, was not explicitly discussed in this paper.

Among vulnerable road users there is a distinction to be drawn between injuries caused by the vehicle and those caused by falling onto the road or ground after impact with the vehicle. Some authors have examined sources of injury with a focus mainly on the vehicle impact (e.g. Roudsari et al., 2005; Kendall et al., 2006; Yao et al., 2007; Simms and Wood, 2006). Fredriksson et al. (2010) confirmed some of the results of the authors mentioned above and provided a detailed account of the sources of severe injury (AIS 3+) that was not confined to components of the striking vehicle. This research found that the most common source of injury for the lower extremities was the vehicle front-end (44%) while the ground was a relatively minor factor (4%). Furthermore the main source of head injury was the windscreen area (26%), followed by the ground (12%) and bonnet (5%). Using a sample of 71 pedal-cycle accidents, Maki et al. (2003) showed that over 56% of cyclists had a head impact on the striking vehicle and that this proportion varied according to the offset position of the bicycle relative to the vehicle at impact.

The aim of the current study was to assess whether the head injuries incurred among a systematic sample of pedestrians and pedal cyclists came from the initial impact with the vehicle or from a subsequent impact on the road or ground. For this purpose accident data from the UK On-the-Spot (OTS) study was used. This database contains detailed injury descriptions from hospital records, autopsies and other sources. A summary dataset derived from OTS was used to develop a multivariate classification model that associated the road or the vehicle as the source of head injury with a small number of independent parameters.

2. Materials and methods

Detailed case reviews and summary dataset

This work is based on the UK On-the-Spot research study which was commissioned by the Department of Transport and Highways Agency from 2000 to 2010. The OTS database contains detailed information on road traffic accidents obtained from in-depth, at-scene investigations from research teams in two sample regions: South Nottinghamshire and Thames Valley. These teams operated a rotating eight-hour shift, seven days a week and attended accidents to which police were dispatched, in total around 500 per year. The case selection protocol was designed to obtain a representative sample of traffic accidents. In addition to a formal relational database containing several thousand fields, the study compiled individual case files containing photographs, video, sketches, drawings and accident reconstructions (where possible).

Each regular investigation by the OTS research teams covered a wide range of human, vehicle and environmental factors extending over the pre-impact, impact and post-impact phases of the accident. In order to establish confidence in the specific questions addressed in this paper, each relevant case was reviewed in detail by both authors with particular attention to the mechanism of head injuries incurred by pedestrians and pedal cyclists, especially whether these arose by contact with the striking vehicle or the road. During this process, all of the available materials were considered. Objective information such as pictures, videos, scene plans and data provided by the accident investigators following the collection protocols was most useful in assessing the head impact and injury source; subjective information such as comments and opinions from people involved in the accident, witnesses or data from the questionnaires was also taken into account with appropriate regard for possible bias or unreliability. Visual evidence, impact configuration, injury description, AIS severity, and the location and distribution of injury all had a strong influence on the assessment. A summary dataset containing 84 fields for formal analysis was extracted or derived from the OTS database and case files as detailed in Table 1.

The variable 'VRU-vehicle impact interaction' illustrated in Figure 1 is based on the classification of 'Pedestrian impact orientation' proposed by Martinez (2000) which includes wrap, forward projection, fender vault, roof vault and somersault sequences. For the present study, four further sequences were added to cover situations encountered in the case files: sideswipe, tumbling from side, run over and reversing. The aggregated set of nine interaction categories was used to describe both pedal cyclists and pedestrians on the working assumption that the kinematics from vehicle contact to rest are adequately similar for the two road user types. This assumption was supported by previous findings (e.g. Maki et al., 2003; Simms and Wood, 2009). The nine sequences presented in Figure 1 describe the codeable interactions between human and striking vehicle starting from the moment of first contact. Only pedestrians are shown but the same situations are applicable to pedal cyclists.

The variable 'Bicycle-vehicle configuration' was introduced to describe the relative position of the bicycle and vehicle at impact as illustrated in Figure 2.

A qualitative variable 'Head injury description' was introduced to place each VRU into one of five mutually exclusive and exhaustive categories based on their head injuries: (1) subjects with at least one head fracture that is not located on the base of the skull; (2) subjects with fractured base of skull only; (3) subjects with no head fractures but at least one intracranial injury that is not loss of consciousness; (4) subjects with no head fractures and loss of consciousness as the only intracranial injury; and (5) subjects with only superficial injuries to the head. Table 2 provides further characteristics and examples.

Pre-selection of variables for input

A multivariate model was developed for the cohort of 205 pedestrians and pedal cyclists who incurred head injuries or identifiable impacts. The model was built using the 'classification and regression trees' (CRT) method (Breiman et al., 1984). This is a non-parametric statistical technique used to explore and filter relevant variables. It results in a hierarchical model that reveals the relationship between the output and the most significant explanatory variables. Classification trees are used to understand complex phenomena with many parameters. This technique has been applied in the field of accident research with satisfactory results (Chang and Chen, 2005; Chang and Wang, 2006; Badea et al., 2010).

The response variable of the model is 'Main head impact' (MHI), a binary variable related to the impact that caused the main head injury or injuries to each road user. The two possible categories for this output are vehicle or road (V/R), so the result is a classification tree of hierarchical nature in which the independent variables and their interactions explain the main head impact.

A pre-selection from the 83 parameters included in summary dataset was performed to obtain a condensed set of variables for the classification tree analysis. The number of parameters was thus reduced to an appropriate proportion of the sample population (205). The CRT method allows ranking the variables by their importance to the model. The selection of the input set of independent variables was made in an iterative process supported by charts of normalised importance. An example of these charts is presented in Figure 3. Based on the chart, one or a few variables are removed, these being parameters with least influence on relevant aspects of the accident and with reduced importance for the model, and then a new chart is drawn up to derive a further reduced set of variables. In this study, the iterative process was continued until a set of 38 variables was obtained, this meeting a set target of having at least four times as many cases (vulnerable road users) as variables for input to the classification tree analysis. This allowed the algorithm to grow a compact tree and facilitated the selection of the explanatory variables during the growing process. The 38 variables from this preliminary selection are highlighted in Table 1.

Classification tree

Different growing methods were tested for the set of independent variables. The best results were obtained with the 'chi-squared automatic interaction detector' (CHAID) growing method (Kass, 1980). The CHAID algorithm evalu-

Table 1: Fields and variables in summary dataset.

Road	
(1) Speed limit before locus [S]	(3) Speed limit beyond locus [S]
(2) Speed limit at locus [S]	(4) Posted speed limit at locus [S]
Human	
(5) Road user type [N]	(15) Off c'way, across drive/parking bay [N]
(6) Age [S]	(16) Off c'way, along drive/parking bay [N]
(7) Gender [N]	(17) Helmet use [N]
(8) Crossed road straight across [N]	(18) Crossing direction relative to driver [N]
(9) Crossed road diagonally across [N]	(19) Frontal [N]
(10) Moving same dir. as impacting veh [N]	(20) Bicycle-vehicle configuration [N]
(11) Moving opp. dir. as impacting veh [N]	(21) VRU-vehicle interaction [N]
(12) Off c'way, approaching c'way [N]	(22) Head impact point—component [N]
(13) Off c'way, moving away c'way [N]	(23) Head impact point—side [N]
(14) Off carriageway, parallel c'way [N]	(24) Main Head Impact—vehicle/road [N]
Medical	
(25) MAIS [O]	(36) Max AIS in ISS region: thorax [O]
(26) Max AIS in head [O]	(37) Max AIS in ISS region: abdomen [O]
(27) Max AIS in neck [O]	(38) Max AIS in ISS region: extremities [O]
(28) Max AIS in chest [O]	(39) Max AIS in ISS region: external [O]
(29) Max AIS in abdomen [O]	(40) ISS [O]
(30) Max AIS in pelvis [O]	(41) Police severity [O]
(31) Max AIS in arms [O]	(42) OTS severity [O]
(32) Max AIS in legs [O]	(43) Predominant injury side [N]
(33) Max AIS in feet [O]	(44) Head injury description [N]
(34) Max AIS in ISS region: head-neck [O]	(45) Body injury side/crossing direction [N]
(35) Max AIS in ISS region: face [O]	(46) Max AIS head from MAIS [O]
Scene	
(47) Day of week [N]	(55) Pelican crossing [N]
(48) Police accident severity [O]	(56) Toucan crossing [N]
(49) Roundabout type [N]	(57) Puffin crossing [N]
(50) Pedestrian facilities [N]	(58) No cycle facilities [N]
(51) Refuge [N]	(59) Advanced cycle reservoir [N]
(52) Drop kerbs [N]	(60) Toucan cycle facilities [N]
(53) Tactile paving [N]	(61) Accident hour [S]
(54) Zebra crossing [N]	
Vehicle	
(62) Vehicle type [N]	(75) Ground to base of w/s over bonnet [S]
(63) Year of manufacture [S]	(76) Ground to top of w/s over bonnet [S]
(64) Vehicle age [S]	(77) Screen height (along A pillar) [S]
(65) Vehicle classification code [N]	(78) Screen top length (header rail) [S]
(66) Gearbox type [N]	(79) Screen lower length (scuttle) [S]
(67) ABS [N]	(80) Height: ground to base of bull bar [S]
(68) Height to base of bumper [S]	(81) Height: ground to top of bull bar [S]
(69) Height to top of bumper [S]	(82) Width of bull bar [S]
(70) Distance of bumper protrusion [S]	(83) Clearance bull bar to leading edge [S]
(71) Bumper lead (from bonnet edge) [S]	(84) Bumper wrap around [S].
(72) Height from ground to leading edge [S]	
(73) Bonnet length [S]	
(74) Rear bonnet height [S]	

Variable type: S = scale; O = ordinal; N = nominal.

Figure 1: Interaction between vulnerable road user (pedestrian or pedal cyclist) and striking vehicle.

Table 2: Values and meaning of parameter 'Head injury description'.

1	Value	Fracture—not isolated #BOS
	Characteristics	Fractures of skull or face from focal contacts, possibly including base of skull.
	Examples	Fractured nose; left temporal facture and base of skull fracture
2	Value	Fracture—isolated #BOS
	Characteristics	Fractured base of skull but no other fractures from direct contacts.
	Examples	Basilar skull fracture only; superior sphenoid fracture.
3	Value	Internal injury only—not isolated LOC
	Characteristics	Internal brain and neurological injuries, including loss of consciousness but no severe external injuries.
	Examples	Subdural haematoma; brain swelling; subarachnoid haemorrhage.
4	Value	Internal injury only—isolated LOC
	Characteristics	Loss of consciousness without other external or internal head injury.
	Examples	Concussion; blackout; LOC and retrograde amnesia.
5	Value	Superficial injury or non-skeletal face only
	Characteristics	Superficial injuries to face or scalp without any skeletal fractures or internal injuries.
	Examples	Scalp laceration; facial bruising, forehead abrasion and haematoma.

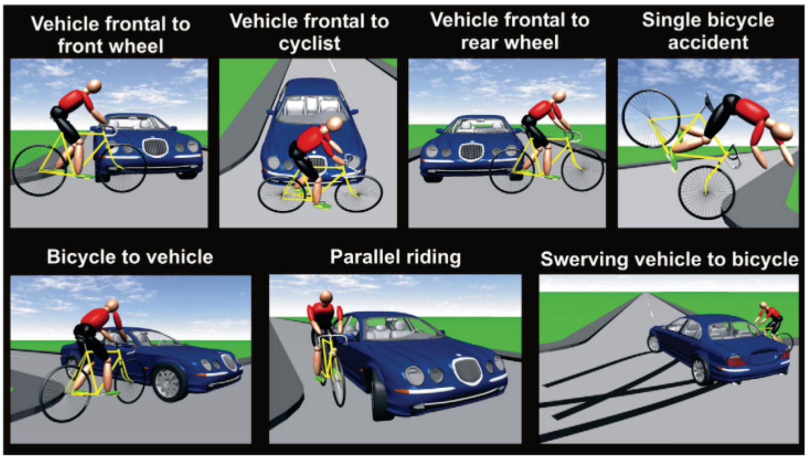

Figure 2: Configuration of bicycle and striking vehicle at impact.

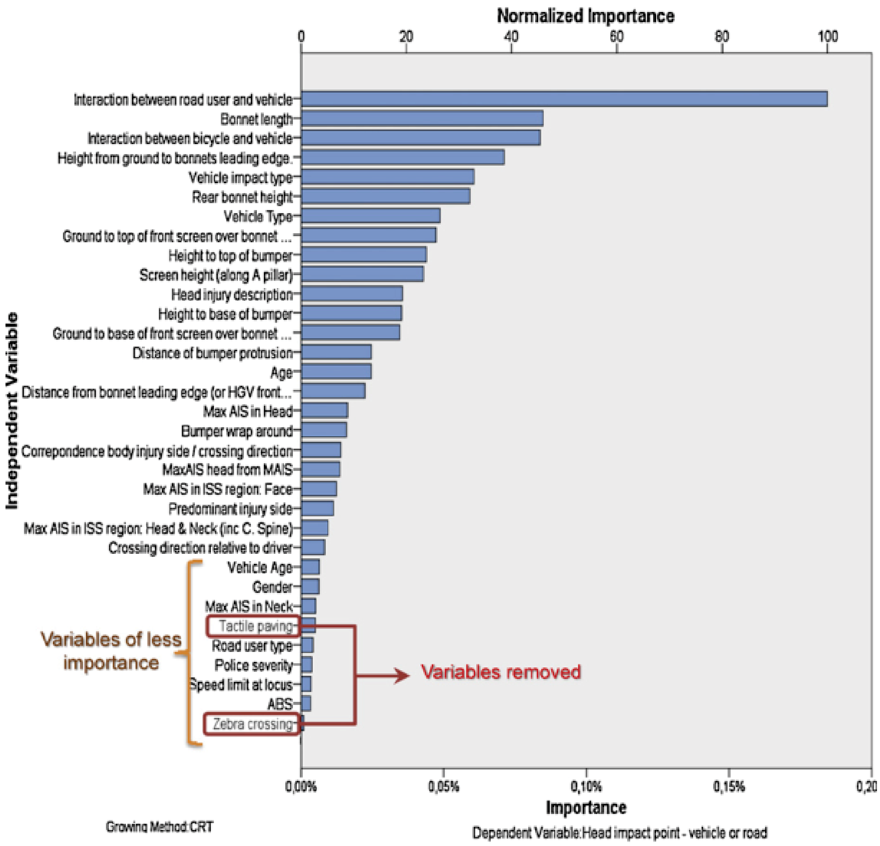

Figure 3: Sample chart of normalised importance.

ates each one of the independent variables to find the categories that best split each node, starting from the root. Since the dependent variable of this model is categorical, the p-values are computed for chi-squared tests for independence of the classes and the levels of the categorical predictor present at each node. First the non-significant categories of the considered variable are merged, then the best explanatory variable is selected to split the node, the process continues until one of the stopping rules are reached. The Bonferroni adjustment, which is optionally used to increase the possible merge combinations of categories within each independent variable, was not used in this case since most of the explanatory variables are binary or have few categories. Cross-validation performed well for the model obtained, providing confidence that the sample was correctly sized. The same model was then obtained using the exhaustive CHAID growing method (Biggs et al., 1991). This algorithm is similar to CHAID but performs an exhaustive search when merging categories and only splits of the highest significance are allowed. Obtaining the same model with both growing methods indicates robustness of the model. The chi-square measure mentioned above is an index of the goodness of fit of the model and the p-value sets the significance of a split. The algorithm works by looking for splits that maximise the reduction of the goodness of fit over a threshold of significance, which in this case was set at 0.05.

As a check on the implications of grouping pedestrians with pedal cyclists in the main analysis, a supplementary model was created by forcing the variable 'Road user type' to make the first split from the root node. Apart from this change, no other parameters were modified and the same variables and growing method were employed as for the original (aggregated) classification tree.

3. Results

The outcome of the case-by-case review of relevant cases on the OTS database, the first step of the analysis, is presented in Figure 4 as a flow chart showing (a) the distribution of head injuries and impacts among pedestrians and pedal cyclists and (b) the frequency of the vehicle or road as the source of the head injury or impact. Of a total of 438 vulnerable road users on the database, 205 (47%) incurred a head injury or left clear evidence of a head impact. These are separated on the first split, carrying over 150 (55%) of the 273 pedestrians and 55 (33%) of the 165 pedal cyclists. In this sample, pedestrians were more likely to incur head injuries than cyclists. No evidence of head

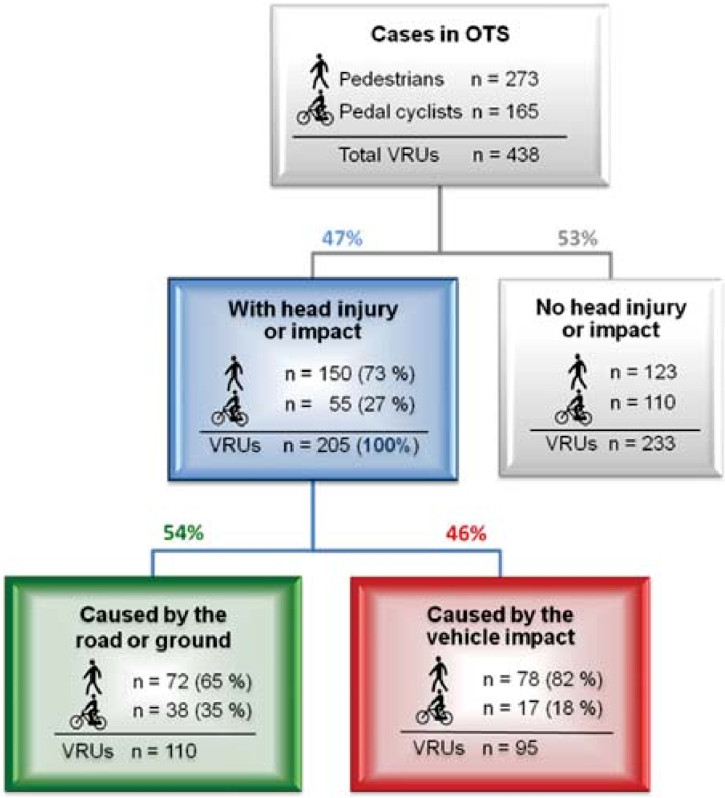

Figure 4: Source of head contact for pedestrians and cyclists.

injuries or head impacts was observed in the 233 cases excluded at this stage from the analysis. For the 205 cases with a head injury or impact, the road or ground was assessed as the source in 110 cases (54%) and the vehicle in 95 cases (46%). Head contact with the ground was the source of head injury for 48% of pedestrians (72 of 150) and 69% of pedal cyclists (38 of 55).

The distribution of age and sex for the 205 vulnerable road users with a recorded injury or evidence of head impact is provided in Table 3. In this table, age is rounded to the nearest 10 years, e.g. subjects from 15 to 24 years of age are grouped as 20. Males outnumbered females by 91 (61%) to 57 (38%) among pedestrians and 44 (80%) to 9 (16%) among cyclists, with some cases (4) not recorded. Where known, the median age of pedestrians and pedal cyclists was 23 and 26 years respectively.

The severity of injury to the head for these 205 vulnerable road users is

Table 3: Age and sex of pedestrians and pedal cyclists with head injury or impact.

	Pedestrian				Pedal cyclist			
Age	M	F	Unk	N	M	F	Unk	N
0	3	1	0	4	0	0	0	0
10	25	13	1	39	13	2	0	15
20	12	15	0	27	8	1	1	10
30	10	1	0	11	1	3	0	4
40	8	9	1	18	4	1	1	6
50	5	3	0	8	6	0	0	6
60	2	1	0	3	3	2	0	5
70	4	4	0	8	3	0	0	3
80	4	5	0	9	4	0	0	4
90	8	1	0	9	0	0	0	0
Unknown	10	4	0	14	2	0	0	2
Total	91	57	2	150	44	9	2	55

detailed in Table 4. Of the 110 cases where the impact was with the road, 26 had an AIS 2+ head injury compared with 31 of the 95 cases where the impact was with the vehicle. Head impacts with the road were therefore on the whole more numerous but less severe. This tendency was even more pronounced for VRUs who incurred an AIS 3+ injury to the head: 13 were attributed to the road and 20 to the vehicle.

The type of striking vehicle involved in the 205 cases where head injury or impact occurred is detailed in Table 5. The collision partner is a passenger car in 167 accidents (81%), followed by 13 light goods vehicles (6%), nine buses (4%), seven heavy goods vehicles (3%) and five motorcycles (2%). One pedestrian was struck by a tram (trolley car). Three pedal cycles did not make physical contact with any other vehicle or fixed object and these were classified as single vehicle accidents. In two of these cases the cyclist was thrown forwards over the handlebars upon braking heavily to avoid imminent impact with another vehicle. The possibility of incurring a head injury by contact with a vehicle is therefore not excluded even in these cases. In the third case it appears that no other vehicle (or fixed roadside object) was involved in the causation of the accident or injuries.

The distribution by vehicle type of head impact points on the frontal components is presented in Figure 5 and Figure 6 for pedestrians and pedal cyclists separately. Passenger cars were more commonly involved than other vehicles. Where head injury arose from vehicle impact, the windscreen glazing was most

Table 4: Maximum AIS injury level to the head for impacts from road or vehicle.

	Road or ground			Vehicle		
	Pedestrian	Cyclist	Total	Pedestrian	Cyclist	Total
Nil	2	3	5	8	3	11
AIS 1	50	28	78	35	10	45
AIS 2	9	4	13	11	0	11
AIS 3+	10	3	13	17	3	20
Unknown	1	0	1	7	1	8
Total	72	38	110	78	17	95

Table 5: Striking vehicle in pedestrian and pedal cycle accidents with head injury or impact.

	Pedestrian	Cyclist	Total
Single vehicle accident	0	3	3
Car	124	43	167
Light goods vehicle	7	6	13
Heavy goods vehicle	5	2	7
Bus	9	0	9
Motorcycle	4	1	5
Other	1	0	1
Total	150	55	205

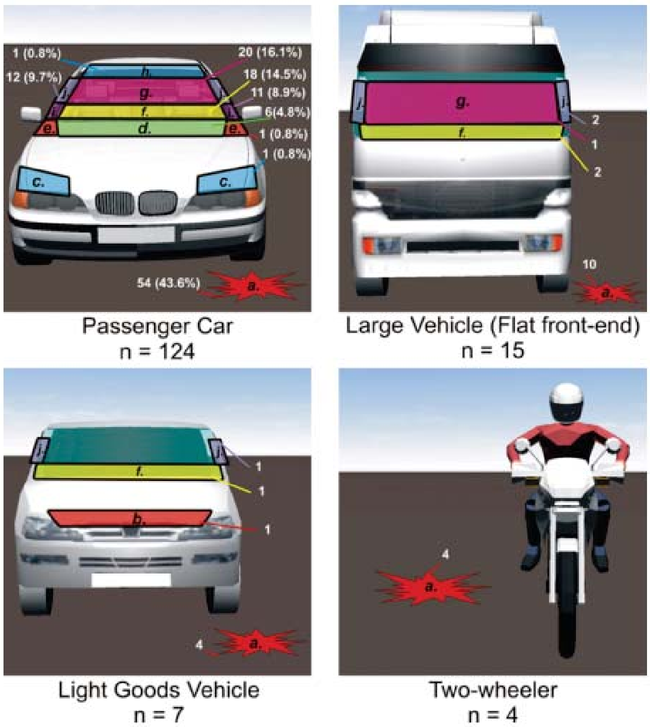

Figure 5: Head impact distribution by vehicle type for pedestrians: (a) pavement or road; (b) bonnet leading edge (sides excluded); (c) corners of the leading edge; (d) scuttle panel or rear of the bonnet; (e) outer edges of the scuttle and top of the bonnet; (f) base of windscreen; (g) windscreen middle area; (h) header rail; (i) base of A-pillar; (j) A-pillar above base.

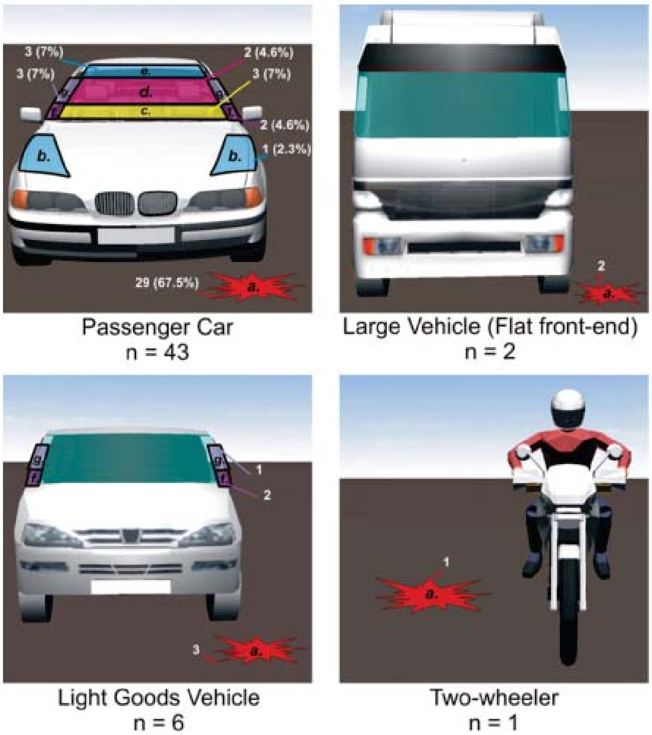

Figure 6: Head impact distribution by vehicle type for pedal cyclists: (a) road or ground; (b) outer edges of bonnet; (c) base of windscreen; (d) windscreen middle area; (e) header rail; (f) base of A-pillar; (g) A-pillar above base.

common component for both pedestrians and pedal cyclists. For impacts with passenger cars, the glazing accounted for 38 of 70 pedestrians and 5 of 14 pedal cyclists. The outer edges of the windscreen and adjacent areas such as the A-pillars and the scuttle panel collectively accounted for fewer cases than the glazing but more than the bonnet.

Although the frontal geometries of different vehicle types are quite variable, the distribution of impact location was comparable although it should be noted that passenger cars were more commonly involved than large vehicles with flat front ends, vans, people carriers and powered two-wheelers. For the four pedestrians and single pedal cyclist involved in collisions with motorcycles, the head injury arose by contact with the road.

As discussed above, the set of 83 variables from the summary dataset was reduced by eliminating variables found to be less determining of the head impact and with less importance for the model based on charts of normalised importance. This represented stage 2 of the analysis. This pre-selection resulted in a set of 38 variables for input to the classification tree analysis as presented in Table 1. The classification tree arising from this in the third stage of the analysis is shown in Figure 7. The tree grew in two levels using the exhaustive CHAID method and explains the target variable (main head impact MHI) present on its root (node 0) quite accurately based on a few independent variables that the growing algorithm selected as the most significant predictors or explanatory variables. The model illustrates how the selected independent variables and their interactions relate to vehicle and road impacts.

The variable 'Interaction between vulnerable road user and striking vehicle' (Figure 1) makes the first split from the root (node 0) and this is the most significant split for the classification with a chi-square of 83.95 and a p-value of less than 0.001. Two branches and one leaf (terminal node) sprout from the root at the first level. One of the branches (node 1) comprises collisions in which the vulnerable road user was hit either in a classic wrap-around or somersault sequence. These configurations are quite similar, the main difference being in the way that the struck road user is thrown from the vehicle to the rest position depending on the contact angles and the impact velocity. For these cases the vehicle impact was the most frequent source of head injury (75%). The age of the vulnerable road user (10 years) splits this branch into two leaves at the second level (nodes 4 and 5), further explaining some of the uncertain cases with a chi-square of 14.89 and a p-value of 0.002. The rate of vehicle impacts as the cause of head injury rises from 75% in node 1 to 80% in node 5. Within node

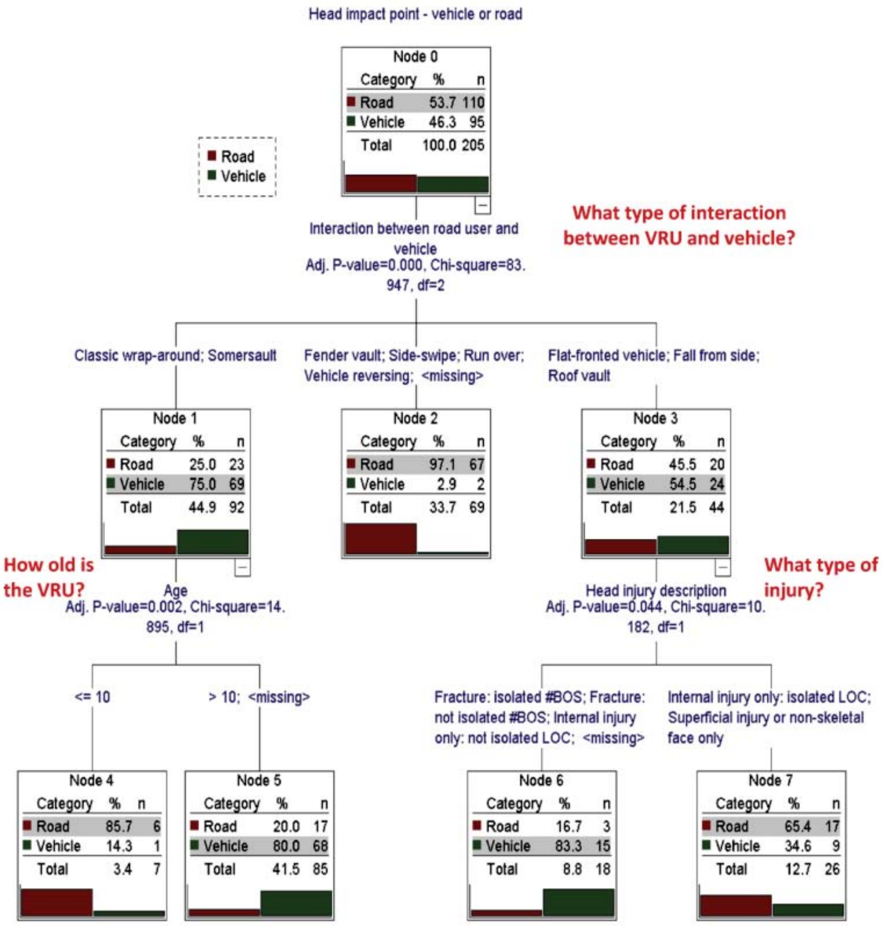

Figure 7: Classification tree for vehicle or road as source of head impact and injury.

Table 6: Predictive capacity of classification tree.

	Predicted		
Observed	Road	Vehicle	Accuracy
Road	90	20	81.8%
Vehicle	12	83	87.4%
Overall			84.4%

1 the road was the source of impact in 23 of 92 cases (25%) while among the subset of children 10 years or younger (node 4) the road impact was applicable to six of the seven cases (86%).

The leaf that terminates at the second level of the tree (node 2) lumps together a variety of sequences in which the road impact is the source of the main head injury: fender vaults, side-swipes, run over and reversing manoeuvres. Cases in which the information about the impact configuration is missing or unknown (9) were also incorporated by the model into this node.

The other branch at the second level (node 3) includes three impact configurations: flat frontal vehicle impacts, falls from the side of the vehicle and roof vaults. The distribution of road or vehicle for the head impact is roughly even in this node and 'Head injury description' is the variable that disentangles this branch with a chi-square of 10.18 and a p-value of 0.044. One leaf (node 6) shows that within this branch, skull fractures and head internal injuries are more closely associated with vehicle impact (83%) while the other leaf of this branch (node 7) shows that superficial and external non-skeletal injures along with isolated loss of consciousness are more closely associated with road impact (65%).

This classification tree was obtained in identical form using CHAID method with and without cross-validation, i.e. it was not sensitive to the growing method and was robust in this sense. The estimated misclassification risk of the model is 0.156 with a standard error of 0.025. Table 6 shows that the model has an overall prediction rate of 84.4%, evenly distributed between the two categories.

Table 7 presents the distribution of maximum AIS injury level to the head for the five terminal nodes of the classification tree (from left to right: 4, 5, 2, 6, 7). Node 5, which encompasses 85 vulnerable road users over the age of 10 who either somersaulted the vehicle or engaged with it in a classic wrap-around, is both the largest group (85) and the group with the most AIS 2+ head injuries

(24). The injuries or impacts in this node were mostly attributed to the striking vehicle (68 of 85). Node 2, which clusters together fender vaults, side-swipes, VRU run over, reversing vehicles and cases where the interaction between vehicle and VRU was unknown, is the second largest group (69) and contains the second most AIS 2+ head injuries (19). The road was considered the source of injury or impact for almost all of these cases (67 of 69). Third place for the number of AIS 2+ head injuries (9) was node 6 which includes vulnerable road users who either interacted with a flat-fronted vehicle, tumbled to the side or vaulted the roof resulting in a face or skull fracture or an intracranial injury not restricted to isolated loss of consciousness. For this group, impact was mostly attributed to the vehicle (15 of 18).

A variation on the preceding classification model was obtained by forcing "Road user type" to make the first split from the root node (Figure 8). This complementary tree grows in three levels. The first split from the root (node 0) separates pedestrians from pedal cyclists as required with a chi-square of 7.2 and a p-value of 0.007. The source of head impacts and injuries for pedestrians is fairly evenly divided between vehicle (52%) and road (48%) while for cyclists the road (69%) is more frequent than the vehicle (31%). The following splits on the branches for both pedestrians and cyclists—the first unforced splits in this tree—are determined by the same parameter, 'Interaction between road user and vehicle'. This common explanatory variable divides each branch into three groups with a chi-square of 58.8 and p-value of less than 0.001 for pedestrians and a chi-square of 30.2 and p-value of less than 0.001 for pedal cyclists. One group of pedestrians was further split by age at a threshold of 10 years with a chi-square of 14.5 and p-value of 0.003. Notable among the similarities between pedestrians and cyclists are that classic wrap-around is associated with head injury from vehicle impact (nodes 3 and 6) while fender vaults, side-swipes and being run over are strongly associated with the road as the source of head injury (nodes 4 and 7). No pedal cyclists in the sample fell into the 'Somersault' or 'Vehicle reversing' categories, hence these interactions are absent from the cyclist branch. The overall predictive capacity of this model is 83.4% and the estimated risk is 0.166.

4. Discussion

The extent to which the vehicle and road could be distinguished as sources of head injury was not clear at the outset of this study. In practice, the loca-

Table 7: Maximum AIS injury level to the head for terminal nodes of classification tree.

	Terminal node identifier					
	4	5	2	6	7	Total
Nil	0	9	2	5	0	16
AIS 1	5	46	47	2	23	123
AIS 2	1	10	8	2	3	24
AIS 3+	1	14	11	7	0	33
Unknown	0	6	1	2	0	9
Total	7	85	69	18	26	205

tion, pattern and nature of injury across the whole body in combination with vehicle damage was generally highly suggestive of the most likely mechanism of injury. Where the vehicle impact and resulting injuries were consistent with the recorded head injury, the vehicle was considered the source. Traces of hair, skin or other bodily tissue were sometimes observed on the vehicle but rarely on the road; in most cases, however, it was reasonably clear whether the pedestrian or cyclist first landed on asphalt, concrete, grass, vegetation or other surface. Although for these accidents— as with the vast majority of real accidents—there is no independent information, measurements or recordings against which the inferred sources of injury can be verified, it is considered that the assessments are likely to be accurate in most cases and that the results from the classification analysis are reasonably robust.

Of the 205 vulnerable road users on the OTS database who incurred a head injury or left evidence of an impact to the head, 110 (54%) were attributed to the road or ground after impact with the vehicle. Among the 57 pedestrians and pedal cyclists who recorded a head injury of AIS 2+ severity, however, the proportion is reversed: 31 (54%) were considered to have been injured by contact with the vehicle. The association of the vehicle with higher severity injuries was even stronger among the 33 pedestrians and pedal cyclists who recorded a head injury of AIS 3+ severity: 20 (61%) were considered to have been injured by contact with the vehicle. Based on these results, it is estimated that secondary safety systems for vulnerable road users such as improved frontal design, pop-up bonnets and external airbags have scope to provide benefits to up to 54% of pedestrians and pedal cyclists with AIS 2+ head injuries and up to 61% with AIS 3+ head injuries.

Although the distinction between vehicle and road as the source of head injury was the main focus of the current investigation, the distribution of head impacts on the frontal or forward-facing areas of the vehicle was also recorded. The importance of the lower to mid A-pillar, the windscreen and the adjacent area (scuttle) was shown in Figure 5 for pedestrians. It was observed that pedal cyclists had more head impacts on upper areas than pedestrians and more often on the A-pillars than in the central region of the windscreen. This could arise from the higher position of the pedal cyclists and their typically greater velocity relative to the vehicle compared with pedestrians. A few contacts responsible for the main head injury were observed at the leading edge of the bonnet for both pedestrians and pedal cyclists. These were mainly children of small stature. These observations are relevant to the choice and specification of external secondary safety technologies. These results are consistent with the distribution reported by Otte et al. (2012) and can be compared to similar distributions obtained by authors like Bovenkerk et al. (2007), Yao et al. (2008) and Fredriksson et al. (2010) for pedestrians and Maki et al. (2003) for both pedestrians and pedal cyclists. At present most head-form impact tests are oriented to the area between the leading edge of the bonnet and the scuttle.

The main question addressed in this paper was the relative extent to which the striking vehicle and the road contribute to the head injuries of vulnerable road users. While the overall result for the available sample of traffic accidents is shown in Figure 4, the classification tree in Figure 7 provides insight into the underlying factors that correlate with the head injury being caused by the vehicle or by the road, where these factors were objectively selected by a computational algorithm. The interaction between the vulnerable road user and the striking vehicle (Figure 1) suggests a physical mechanism: where the pedestrian or cyclist wrapped around the front-end of the vehicle in a classic manner or somersaulted over the vehicle, children up to 10 years old tended to incur their head injuries from the road while for older road users the striking vehicle was mostly responsible; where the pedestrian or cyclist vaulted the fender or was side-swiped, run over or hit by a reversing vehicle, the road or ground was responsible for almost all head injuries; finally, for the remaining types of impact interactions, more severe injuries (fractures and intracranial injuries apart from isolated loss of consciousness) were strongly associated with the striking vehicle whereas other head injuries (loss of consciousness without other identified lesions, superficial injuries and non-skeletal facial injuries) tended to arise from contact with the road or ground. It is surmised that the impact force applied to children up to 10 years old is more often located at or above the centre of

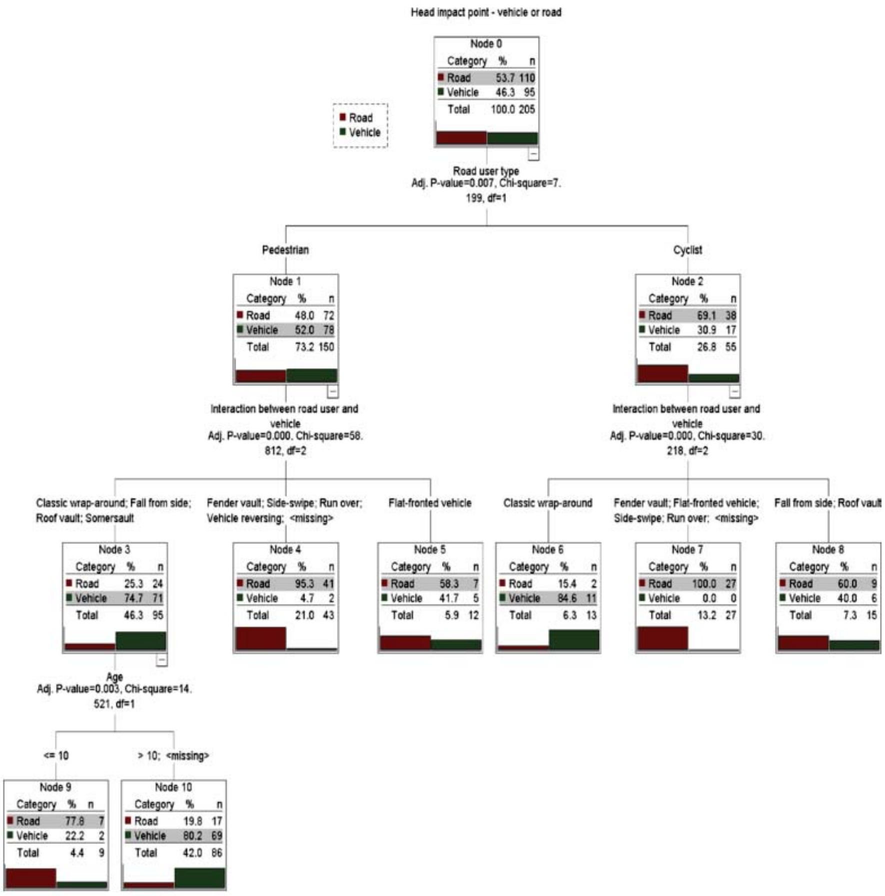

Figure 8: Classification tree for vehicle or road as source of head impact and injury split by road user type.

mass of their bodies, which in broad terms tends to rotate their upper bodies away from the striking vehicle and thereby decrease the severity of any head strike on the vehicle. Hence it is probable that the height of the children, with a direct, explicable influence on the impact kinematics, is the underlying explanatory factor. Side-swipes and fender vaults may tend to rotate vulnerable road users away from the striking vehicle and onto the road. Being run over is likely to involve crushing forces between the vehicle and road. Finally, a reversing vehicle is likely to be travelling relatively slowly, meaning that the velocity of impact may be quite comparable with the velocity of falling to the ground. Several of the links between the accident circumstances and the source of injury identified by the computational algorithms employed in the analysis therefore make physical sense.

A check on the appropriateness of submitting pedestrians and pedal cyclists together as a single group into the main analysis was performed by forcing them apart in a supplementary classification tree (Figure 8). The mode of interaction between the road user and vehicle re-appeared as the primary factor for associating both groups with the vehicle or road as the source of head injury. A second noteworthy feature of this disaggregated tree (Figure 8) is that node 3, containing the largest sub-population of pedestrians including classic wrap-around, is not only split by age in similar manner to node 1 of the aggregated tree (Figure 7), but the same threshold of 10 years is selected. If the split by age is associated with classic wrap-around, it may have been anticipated that the same phenomenon would occur for pedal cyclists in node 6; however this is likely to be precluded by the low numbers in that group, particularly because there are only two cases where head impact or injury was attributed to the road. The broad similarities in the main features of the pedestrian and pedal cycle branches in Figure 8 are consistent with the working assumption that the two types of road user have a comparable post-impact kinematic response and can be lumped together for the aims of this study. This is statistically reflected in the fact that the chi-squared of the forced split (7.2) is the lowest of the model, compared with 58.8 and 30.2 for the splits at the second level (nodes 1 and 2) and 14.5 at the third level (node 3). This indicates that the degree of independence between the two groups is low and that they can be considered as a single group for certain purposes.

It may be noted that the speed limit was present in the summary dataset (Table 1) but not the speed of the vehicle at impact. Impact speed was available for some but not all relevant cases—pedestrian and cycle accidents pose particular challenges for atscene investigation and reconstruction. The percentage of cases for which impact speed was available was considered below the threshold for inclusion in the analysis, especially as the proportion varied considerably for different interaction types. The substitute parameter, speed limit, which in certain contexts correlates statistically with impact speed, was submitted to the analysis but not selected by the algorithm as a key parameter. A similar consideration applied to bicycle helmets, where it can be difficult under working conditions to obtain direct evidence of non-use, particularly for low severity injury accidents. This parameter was consequently not included in the summary dataset for the current analysis.

The accident data used for this analysis is drawn from two sample regions that were chosen to be representative of Great Britain. It is possible, of course, that the proportion of pedestrians to pedal cyclists and relative frequency of the interactions types (classic wrap-around, tumble from side, etc.) could be different in other countries and these factors could influence the wider applicability of the results obtained here. On the other hand, where the results seem to based on a physical mechanism, e.g. injury by contact with the ground for children under 10 years of age, it is reasonable to suppose that these relationships may be widely applicable.

5. Conclusions

A detailed review of 205 in-depth case files on accidents involving pedestrians and pedal cyclists indicated that it is possible to distinguish the striking vehicle from the road or ground as the source of head injury or impact with a reasonable level of confidence. Head impacts with the road may actually outnumber impacts with the striking vehicle; however the vehicle accounts for a greater proportion of more serious casualties (AIS 2+ and AIS 3+ head severity). A classification tree analysis associated road impacts with (a) fender vaults, side swipes, being run over and reversing vehicles, (b) children under 10 years of age in classic wrap-around impacts and somersaults and (c) superficial head injuries and loss of consciousness without further internal injuries in other types of collisions. Vehicle impacts were associated with (a) subjects over 10 years of age in classic wrap-around collisions and somersaults and (b) skull and facial fractures and intracranial injuries beyond loss of consciousness. The assumption that the post-impact kinematic response of pedestrians and pedal cyclists is similar enough to allow them to be grouped together for the classification tree analysis was supported by a complementary model that illustrated several points of strong commonality between the cohorts.

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