Analysis of pedestrian accident leg contacts and distribution of contact points across the vehicle front

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Abstract - Determining the risk to pedestrians that are impacted by areas of the front bumper not currently regulated in type-approval testing requires an understanding of the target population and the injury risk posed by the edges of the bumper. National statistics show that approximately 10% of all accident casualties are pedestrians, with 20% to 30% of these pedestrian casualties being killed or seriously injured. However, the contact position across the front of the bumper is not recorded in national statistics and so in-depth accident databases (OTS, UK and GIDAS, Germany) were used to examine injury risk in greater detail. The results showed that some injury types and severities of injuries appear to peak around the bumper edges. Although there are sometimes inconsistencies in the data, generally there is no evidence to suggest that the edges of the bumper are less likely to be contacted or cause injury.

INTRODUCTION

Throughout the world each year, thousands of pedestrians and cyclists are struck by motor vehicles. In most countries, including those of the European Union (EU), pedestrians and other vulnerable road users form a significant proportion of all road user casualties. Measures to improve car design, to mitigate pedestrian injuries in collisions, are effective in reducing injury risk measures in physical testing and are assumed to be effective in reducing the number of fatalities and serious injuries [1]. While the number of pedestrian injuries and fatalities continues to decline, year on year, within the EU, it is not decreasing as quickly as the decline in total traffic fatalities [2].

Fractures to the shaft of the tibia are the second most commonly observed primary injury for pedestrians recorded in the Hospital Episode Statistics (HES; [3]). Whilst simple fractures of the long bones may generally be expected to have a good prognosis, fractures involving multiple regions of both lower limbs are associated with a very long duration of stay in hospital (mean of 33.9 days). Consequently, lower limb injuries sustained by pedestrians may not be the most costly on an individual basis but their high rate of incidence means that they are by far the most costly based on hospital admissions. The estimated annual cost for lower limb injuries in England was over £14.5 million [3].

The most frequent cause of all leg injuries in car-pedestrian accidents is contact with the front bumper. Therefore, this is the most important cause of non-minor leg injuries [4]. Contact with the ground is the second most frequent cause of leg injuries, although the vast majority of these are likely to be minor injuries.

In order to sell a vehicle in Europe, manufacturers must be granted vehicle type-approval by passing a series of tests set out in Annex I of the Commission Regulation. The tests are based on three principal procedures, each using different sub-system impactors to represent the main phases of a car-to-pedestrian impact. The three impactor types are:

- A legform impactor representing the adult lower limb
- An upper legform impactor representing the adult upper leg and pelvis
- Child and adult headform impactors

Each impactor is propelled into the car and the output from the impactor instrumentation is used to establish whether the energy-absorbing characteristics of the car are acceptable. A minimum of three legform to bumper tests are required, one to each section of the bumper when divided into equal thirds (Figure 1). The outer third test points have to be a minimum of 66 mm (the nominal radius of the EEVC legform) inside the defined corners of the bumper to ensure that the full contact region is within the area defined between the bumper corners.

Figure 1. Bumper tests are divided into thirds for three tests

The area to be assessed in the legform to bumper test is specified in Commission Regulation (EU) No. 631/2009. The corner of the bumper is determined through the following definition:

> "… the vehicle's point of contact with a vertical plane which makes an angle of 60° with the vertical longitudinal plane of the vehicle and is tangential to the outer surface of the bumper."

The level of pedestrian protection may be degraded from the original intent of the legislation. If vehicle manufacturers produce vehicles where the defined corner of the bumper is a substantial distance from the side of the vehicle, the testable area can be significantly reduced. In extreme cases, the testable area can be as little as 40 % of the full frontal width of the car [2]. Assuming that pedestrians can be struck by any part of the vehicle front then there could be degradation in safety levels if the tested area is now smaller than it has been in the past.

Previous research regarding pedestrian contacts with vehicle bumpers has assumed an equal distribution of impact points across the width of the vehicle front. If, instead, there was an increased risk of contact towards the edge of the bumper then it may have important consequences for the effectiveness of a change to the corner definition. To investigate this assumption accident case data from the UK and Germany have been reviewed.

METHODOLOGY

Although the national accident datasets such as STATS19 and CARE can provide an indication of the target population (i.e. pedestrians hit by the front bumper of cars), information about the location on the bumper where the pedestrian struck the vehicle is not available. In depth accident studies such as On-The-Spot (OTS) in the UK and German-In-Depth-Accident-Study (GIDAS) in Germany provide detailed information on a small, but representative, sample of the road accidents to help understand the accident situation in more detail. Specifically, where on the bumper are pedestrian casualties struck and if there is a difference in this distribution by age, sex or movement of the casualty, speed or registration year of the vehicle. Each accident case is also supplemented with detailed medical records of the injured parties. This was used to analyse injury severity with contact distribution across the bumper and the risk of injury outside the testable area of the bumper. The sampling plans and sample areas chosen in both the GIDAS and OTS studies ensured that the accident data was representative of the accidents severities and approximated the distribution of accidents occurring on a national scale.

The initial hypothesis stated there was an equal probability of a pedestrian being struck across the length of the bumper. If the distribution is not uniform, then the second part of the hypothesis was that the relationship is linear, approximately. This arises from the fact that pedestrians are more likely to be hit by a vehicle when crossing from the nearside of the vehicle as the car driver has less time to see the pedestrian before the point of impact. The data were then broken down by injury type and severity to determine if there is a greater risk of injury at the outskirts of the bumper compared with the centre or if injury risk is also linear across the bumper.

OTS sample

The OTS accident data collection study gathered in-depth information on over 4,700 road traffic accidents from two distinct geographical areas between 2000 and 2010. Filtering the database for a suitable sample of pedestrian accidents resulted in a total of 232 pedestrian accidents out of 304 total pedestrian cases.

The following exclusion criteria were then applied:

- The pedestrian was struck by the side of the vehicle, side swiped or the pedestrian ran into side of vehicle;
- The vehicle was stationary and the pedestrian collided into the vehicle;
- The vehicle reversed over the pedestrian;
- The pedestrian was not impacted by the front of the vehicle.

This resulted in 116 relevant pedestrian accident cases for analysis each with 1 pedestrian involved. The point of contact where the pedestrian was struck on the vehicle's bumper was divided into five equal segments stretching across the full width of the bumper. These segments are displayed as percentage ranges of the vehicle width starting from 0% to 100% from the offside to the nearside (see Figure 2). This was determined using a combination of vehicle and pedestrian paths, case summary, recorded evidence and vehicle photos from the OTS database. The segments are labelled the other way around for GIDAS as vehicle drive on the other side of the road in Germany.

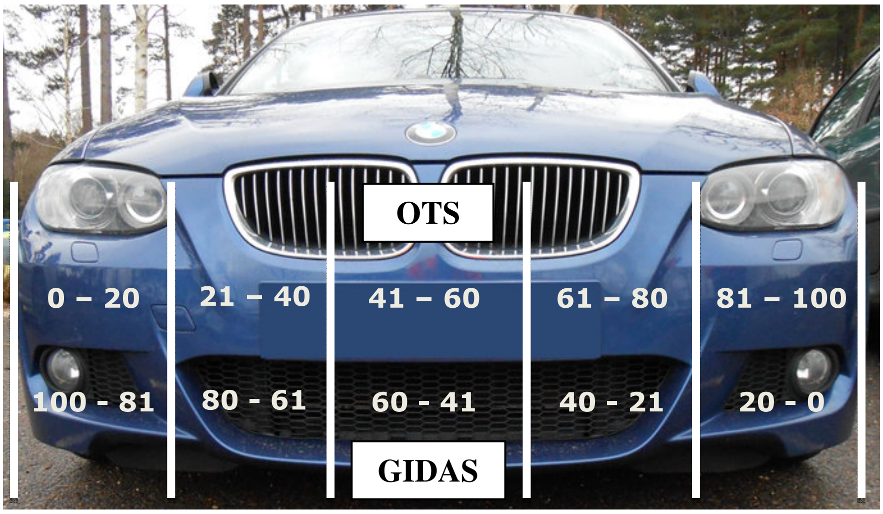

Figure 2. Contact point is divided into five equal segments across the bumper displayed as percentages of the vehicle width (OTS percentages are on top, GIDAS underneath).

GIDAS sample

This study is based on the GIDAS dataset available from January 2013. Currently there are 23,444 reconstructed accidents from both investigation areas Dresden and Hanover. 27,690 passenger cars were involved in these accidents. In 2,271 accidents a car hit a pedestrian. 758 pedestrians had their first contact with the legs on the bumper. Pedestrians whose exact contact point location could not be determined were excluded from the dataset.

The information recorded in the GIDAS database allowed a higher degree of precision in determining the pedestrian contact point on the bumper and so the bumper was divided into 10 segments of the vehicle width, but for comparison with the OTS data the data was grouped in to 5 segments. The segments are also labelled 0% to 100% from the offside to the nearside of the vehicle front (Figure 2).

Statistical analyses

To assess the first hypothesis, a chi-squared goodness-of-fit test was used (Tables 1 and 2). This tests for a difference between the numbers of casualties struck in each of the contact positions and the theoretical number if the distribution of contact positions was uniform across the bumper.

The second part of the hypothesis was tested using a linear regression which will indicate if the probability of pedestrian contact position across the front bumper can be described as a linear relationship (Figures 3 and 4).

Statistical analysis of the injury risk was not possible due to low sample numbers in both the OTS and GIDAS datasets. Instead, the datasets have been broken down into injury types and severities across the bumper sections and observations made on the results (Tables 3 to 8).

RESULTS

All of the results are presented against the contact position on the front bumper as per Figure 2. It is important to note that the segments across the bumpers have been labelled so that 0-20% is always the offside of the vehicle and 81-100% is the nearside to the kerb for both datasets.

Contact distribution

Table 1 and Table 2 show the number of OTS and GIDAS cases by contact position across the bumper. The chi-squared test of the hypothesis (excluding those with unknown contact position) shows that the distribution of casualties across contact position groups is not significantly different from that of a uniform distribution for the OTS sample ($p = 0.11$).

Table 1. Number of OTS cases by contact position across the bumper

Contact position	Number of casualties
0-20	18
20-40	14
40-60	23
60-80	22
80-100	31
Unknown	8
Total	116

The chi-squared test for the GIDAS sample shows that the distribution of casualties across categories of contact position is significantly different from that of a uniform distribution ($p < 0.05$).

Table 2. Number of GIDAS cases by contact position across the bumper

Contact position	Number of casualties
0-20	113
20-40	130
40-60	168
60-80	166
80-100	181
Total	758

The second part of the hypothesis has been tested in Figure 3, which shows the distribution of casualties across contact points of the bumper in the OTS sample; a line of best fit is included. Figure 4 shows the equivalent data from the GIDAS sample. The R^2 value (a measure of the variance explained by the linear regression model) is also shown.

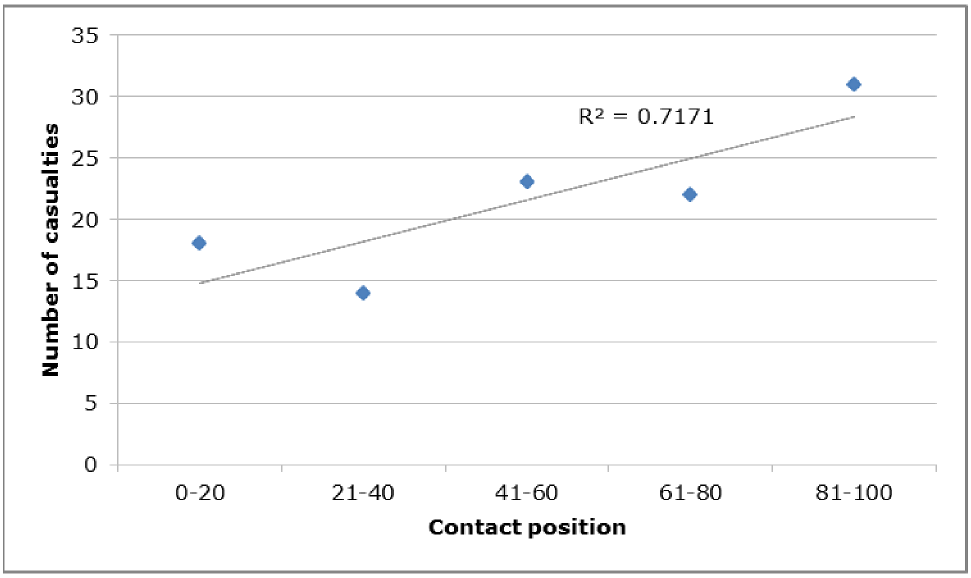

Figure 3. Distribution of casualties across contact points of the bumper (OTS)

Figure 3 shows that more pedestrian casualties were struck between contact positions 81-100 (i.e. the nearside of the vehicle in the UK) than those struck by the offside. The regression line demonstrates that the contact position explains 71% of the variability in the number of casualties. The linear trend between number of casualties and contact position seems a reasonable approximation in this instance.

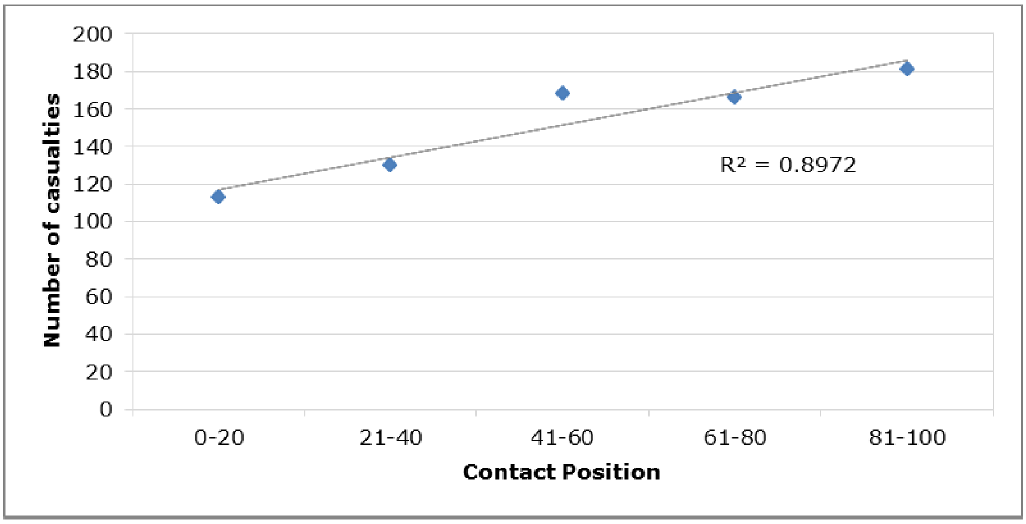

Figure 4. Distribution of casualties across contact points of the bumper (GIDAS)

Figure 4 shows that more pedestrian casualties were struck by the nearside of the vehicle than those struck by the offside. The regression line shows the contact position explains approximately 90% of the variability in the number of casualties. Therefore, the relationship between contact position and number of casualties in the GIDAS can be approximated as being linear.

Injury risk

The next part of the analysis aims to determine if there is a greater risk of injury at the outskirts of the bumper compared with the centre or if injury risk is also linear across the bumper. Injury severities have been coded using the Abbreviated Injury Scale (AIS). It should be noted that the GIDAS MAIS is based on the AIS 1998 edition, whereas the OTS MAIS was a mixture of AIS 1990 and 2005, but for simplicity is presented here based on the 1990 coding. This is not expected to alter the general impressions provided by the data in Tables 3 and 4, substantially.

In the first instance, the whole-body Maximum AIS score (MAIS) for each pedestrian was considered. This gives an overall indication of the severity of the accident for the pedestrian. The results from the OTS sample and GIDAS are shown in Tables 3 and 4.

Although sample numbers are relatively low in both datasets, the data indicate that approximately 90% of pedestrians incur injuries of a maximum severity of MAIS 3 or below and the most severe injuries are relatively uncommon. These data also show that severe MAIS 4, 5 or 6 casualties can be caused by contacts from any fifth of the vehicle front in both datasets. Furthermore, less severe injuries with MAIS 1, 2 or 3 can also occur at any point along the bumper front but they appear to have a similar distribution to the contact position with slightly more injuries occurring at the nearside of the vehicle, in general.

Table 3. Number of OTS cases by whole-body MAIS and contact position

	Contact Position							
MAIS	Unknown	0-20	21-40	41-60	61-80	81-100	Total	% Total
0	3	2	2	2	4	4	17	14.7
1	3	8	7	9	6	8	41	35.3
2	1	5	2	8	2	6	24	20.7
3	1	2	0	2	3	8	16	13.8
4	0	0	1	1	4	1	7	6.0
5	0	0	0	1	2	1	4	3.4
6	0	0	0	0	0	0	0	0.0
9	0	1	2	0	1	3	7	6.0
Total	8	18	14	23	22	31	116	

Table 4. Number of GIDAS cases by whole-body MAIS and contact position

	Contact Position						
MAIS	0-20	21-40	41-60	61-80	81-100	Total	% Total
0	0	0	0	0	0	0	0.0
1	15	19	26	24	21	105	43.0
2	20	12	11	20	25	88	36.1
3	2	3	1	2	5	13	5.3
4	2	3	2	1	3	11	4.5
5	1	1	1	4	1	8	3.3
6	0	2	0	0	3	5	2.0
9	2	3	4	0	5	14	5.7
Total	42	43	45	51	63	244	

The GIDAS database allows injuries to be assigned to an injury causing vehicle part. Therefore it is possible to look at the maximum AIS of the lower extremity injuries caused by the bumper (Table 6). An equivalent analysis of the OTS sample was not possible, therefore all lower extremity injuries are considered regardless of the contact causing the injury (Table 5). The advantage of doing this with the GIDAS data is that injuries caused as the pedestrian was thrown to the ground are excluded. The injuries reported are thought to have been caused by the primary interaction with the vehicle bumper by the investigators at the scene of the accident. This exclusion of alternative injury sources is not available for the OTS data.

Tables 5 and 6, show the numbers of injuries in the OTS and GIDAS samples, grouped according to the contact position as well as the part of the lower extremity which sustained the injury. Despite low sample number, the OTS dataset shows the lower leg is the body region with the most frequent injuries, but has a clear peak in the centre section of the bumper. While the majority of injuries have an unknown or unclassifiable body region and appear to be slightly more frequent in the nearside sections (61-80% and 81-100%) of the bumper. The total number of injuries also appears to follow the trend of being skewed towards the nearside bumper sections.

The lower leg is by far the most frequently injured body region of the lower limb in the GIDAS dataset, followed by the knee. The frequency of injuries in the lower leg, and to a certain extent the knee, demonstrate a skew to the nearside sections of the bumper (61-80% and 81-100%). This is also apparent in the total injuries to all body regions of the lower leg which demonstrates the same skew as the OTS total injuries. However, both datasets also show that injuries to the lower leg and other regions can occur across the bumper width.

Table 5. Number of OTS injuries by body region and contact position for all injury severities

	Contact Position						
Body Region	Unknown	0-20	21-40	41-60	61-80	81-100	Total
whole leg	0	0	0	0	0	0	0
upper leg	0	1	0	1	3	4	9
knee	0	3	0	1	2	2	8
lower leg	1	3	7	11	4	7	33
ankle	0	0	0	1	0	0	1
foot	0	0	0	0	1	4	5
unknown or unclassifiable region of the leg	5	14	15	23	29	35	121
Total	6	21	22	37	39	52	177

Table 6. Number of GIDAS injuries (caused by bumper contacts only) by body region and contact position for all injury severities

	Contact Position					
Body Region	0-20	21-40	41-60	61-80	81-100	Total
whole leg	0	0	0	0	1	1
upper leg	2	4	3	2	3	14
knee	8	17	11	15	15	66
lower leg	16	25	23	34	35	133
ankle	1	1	0	2	2	6
foot	0	4	1	2	5	12
unknown or unclassifiable region of the leg	1	2	3	0	2	8
excluded (hip or pelvis)	1	1	0	0	0	2
Total	29	54	41	55	63	242

The previous two tables included injuries of all severities to each of the various parts of the lower extremity. However, the injuries occurring most frequently in hospital admissions and likely to lead to the greatest burden of disability and cost are AIS 2 injuries to the knee and lower leg [3]. To investigate these injuries specifically, the breakdown of number of injuries by contact point and region of the lower extremity injured was limited to AIS 2 injuries only. These results are shown in Tables 7 and 8.

The majority of the lower leg injuries in the OTS dataset are AIS 2 severity so the distribution of injuries to this body region still reflects the peak in the centre sections of the bumper seen in the total injury distribution in Table 5. The other body regions of the lower limb have very few sample numbers in Table 7. The GIDAS dataset still contains primarily lower leg, and some knee injuries, and maintains the higher frequency towards the nearside of the bumper which is also reflected in the distribution of total injuries across the bumper (Table 8).

Table 7. Number of OTS injuries by body region and contact position for AIS 2 injuries

	Contact Position						
Body Region	Unknown	0-20	21-40	41-60	61-80	81-100	Total
whole leg	0	0	0	0	0	0	0
upper leg	0	0	0	0	0	0	0
knee	0	3	0	1	1	2	7
lower leg	1	2	5	11	4	7	30
ankle	0	0	0	1	0	0	1
foot	0	0	0	0	0	4	4
unknown or unclassifiable region of the leg	0	0	0	3	0	1	4
Total	1	5	5	16	5	14	46

Table 8. Number of GIDAS injuries by body region and contact position for AIS 2 injuries

	Contact Position					
Body Region	0-20	21-40	41-60	61-80	81-100	Total
whole leg	0	0	0	0	1	1
upper leg	0	0	0	0	0	0
knee	3	3	2	2	3	13
lower leg	7	10	10	21	16	64
ankle	0	0	0	0	0	0
foot	0	1	0	0	0	1
unknown or unclassifiable region of the leg	1	0	0	0	0	1
excluded (hip or pelvis)	0	0	0	0	0	0
Total	11	14	12	23	20	80

DISCUSSION

Both datasets display a linear relationship of contact point distribution skewed towards the nearside of the vehicle. The contact point distribution of the OTS dataset is not statistically different from a uniform distribution; however, this may be a consequence of a small sample size. It is close to being significant at the 90% confidence level and the linear regression suggests that the relationship is not uniform as well as linear.

Although the contact distribution is skewed, the linear relationship means that the risk of contact across the bumper is equal, assuming a symmetrical design of the vehicle's bumper and substructures. The increased risk to the nearside is cancelled out by the reduced risk mirrored on the offside in both datasets. This assumes that either the vehicles are symmetrical in design or that any asymmetry doesn't affect the risk of injury from the impact. It also takes a broad approximation of the contact point data, where a larger dataset could show small deviations from this approximation to be more important. However, bumper design can vary with certain vehicles that have offset licence plates such as the Alfa Romeo MiTo and most vehicles will have a tow-eye present on one side underneath the bumper.

The low sample sizes of the datasets prevent any statistical analysis of the data, instead, observations on the trends in the data can provide useful conclusions, although less robust. The data in Tables 3 and 4 seem to support the assertion that, whilst relatively uncommon, MAIS 4, 5 or 6 casualty severities can be caused by contacts from any fifth of the vehicle front. Unfortunately, the sample size is not large enough to determine whether a particular region of the vehicle width is more likely to cause these injuries than other regions.

MAIS 1, 2 or 3 pedestrian injuries seem to follow the same trend as the overall number of casualties, with a greater proportion occurring from contacts to the nearside than to the offside. There doesn't appear to be any one region which causes such injuries much more than would be expected based on an equal risk of injury across the whole vehicle width. Any MAIS severity of casualty injury can seemingly be caused by any fifth of the vehicle front.

Considering the contact distribution data with the region of the leg that was injured (Tables 5 and 6), gives an indication as to whether any region of the vehicle offers a substantially more injurious contact for the pedestrian lower extremity than another. Based on the results it can be observed that upper leg, knee, lower leg, ankle and foot injuries can be caused by a contact in any of the five fifths of the vehicle front.

Again, in Tables 7 and 8, it is evident that AIS 2 injuries can be caused through contacts with any fifth of the vehicle front. In the context of a bias in injury occurrence towards the nearside of the vehicle, it is not obvious that any region is particularly injurious. Equally, it does not appear that there is a substantial decrease in injury risk towards the extremity of the bumper (based on the division into five portions). Using the more detailed breakdown of the vehicle front from the GIDAS data, into ten parts, there is some suggestion that fewer AIS 2 injuries are caused by the outer 10 percent of the vehicle front either side, although the numbers are small for all regions.

The datasets were also examined for any variables that may cause bias in the distribution of contact position along the vehicle front. This is potentially important if, for instance, a group of casualties was more likely to be hit by the extremities of the vehicle and that group was more or less susceptible to injury than the rest of the pedestrian population. OTS and GIDAS provide information on the age, sex and movement of the pedestrian, the vehicle registration year and the speed of the collision, which were examined for bias (data not published here).

The age of the pedestrian and the vehicle appears to have no influence on the contact point distribution. However, both datasets show that males are more likely to be impacted by vehicles than females and that the distribution of contact points is different for males and females.

- It could be important for investigating injury risk across the bumper width if certain regions are associated with more males or females than another. In general terms, female leg bones tend to be narrower and have thinner cortical walls than males (e.g. [5]). Therefore one could speculate that female pedestrians may be more susceptible to some types of leg injury than male pedestrians.

- Whilst the distribution of males and female contact points was different, no obvious dominating trends were evident which would suggest one part of the vehicle front should be designed with a specific attention to protecting female pedestrians more than any other part.

Further study

One of the limitations of this work relates to the relative injurious nature of cars that have a pronounced tapered or angular bumper design and vehicles (perhaps older models) without those design features. This additional investigation was not carried out within this analysis because the case numbers from the OTS study would not allow such detailed investigation. In principle there may be enough cases in the GIDAS data and therefore it would be useful to investigate the differences in injury risk between these types of vehicles. However, care should be taken when defining this future study for the following reasons:

- There has been a trend for newer vehicle designs to have smaller bumper test areas. However, there are examples of car designs in the modern vehicle fleet where the bumper corners are still wider apart than is normal for most high-selling models. Therefore, there may be other design reasons to explain such differences. The comparison between cars with angled or curved bumpers and those with larger test areas could be compromised by other vehicle design changes in those two groups.

- Case numbers are limited even in the GIDAS groups. Features of the crash conditions that will have to be taken into account when considering the injurious nature of vehicle designs are: the severity of the collision, the fragility of the pedestrian and the contact position on the vehicle. There were 242 leg injuries of all severities (133 to the lower leg and 66 to the knee), of which 80 were AIS 2 in the GIDAS sample. This number would allow statistical treatment of the crash conditions and then investigation of the relationship of vehicle age and vehicle design. However, there were only 51 lower leg injuries from contacts to the two outer segments of the vehicle front, which would preclude such an analysis. Therefore, it is still marginal as to whether meaningful results can be obtained from the investigation of whether front-end shape affects injury risk for pedestrian accidents.

CONCLUSIONS

The frequency of pedestrian contacts is skewed towards the nearside in both the UK and Germany (statistically significantly in the case of Germany). However, the distribution is approximately linear, so the risk of being struck across the bumper (i.e. by the centre or outer parts) is equal assuming vehicles are symmetrical.

The sample numbers were too small for statistical analysis of the relationship of bumper impact location to injury severity. However, observations of the GIDAS dataset show that lower leg injuries, and injuries in general, occurred at a greater frequency towards the nearside of the bumper suggesting the bumper is equally injurious across its full width. The OTS dataset is far smaller than its German counterpart so the trends shown in the data are not as reliable. The data show that injuries to regions of the lower limb occurred at all points along the bumper, while there is a peak in lower leg injuries occurring at the centre of the bumper. However, the overall number of injuries (of all severities) to the lower limb does follow the same tendency of occurring at the nearside of the bumper.

Such low sample numbers prevent robust conclusions being drawn; however, there is no evidence in either dataset to suggest that the edges of the bumper are less injurious than the centre.

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- Participants at the Bumper Test Area Task Force meetings, who provided information regarding performance of current vehicles and detailed discussion of the technical issues raised by this project.

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- VUFO GmbH for contributing accident data from GIDAS (German In-Depth Accident Study) to the study. GIDAS is the largest in-depth accident study in Germany. The data collected in the GIDAS project is very extensive, and serves as a basis of knowledge for different groups of interest. Due to a well defined sampling plan, representativeness with respect to the federal statistics is also guaranteed. Since mid 1999, the GIDAS project has collected on-scene accident cases in the areas of Hanover and Dresden. GIDAS collects data from accidents of all kinds. Due to the on-scene investigation and the full reconstruction of each accident, it gives a comprehensive view on the individual accident sequences and the accident causation.
  The project is funded by the Federal Highway Research Institute (BASt) and the German Research Association for Automotive Technology (FAT), a department of the VDA (German Association of the Automotive Industry). Use of the data is restricted to the participants of the project. However, to allow interested parties the direct use of the GIDAS data, several models of participation exist. Further information can be found at http://www.gidas.org.

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