Priorities for Bicyclist Protection in Car Impacts – a Real life Study of Severe Injuries and Car Sources

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Abstract

The German database GIDAS was queried to find all cases between 1999 and 2010 where a bicyclist or pedestrian was injured when impacted by a car front. The injury source was determined for each severe injury whether it was the car or its surroundings.

The most common severe (AIS3+ and fatal) injury/source combination for bicyclists was the head-to-windshield area (27%) followed by leg-to-vehicle front, while for pedestrians the same combinations occurred most frequently but leg-to-vehicle front (41%) was most common. For both bicyclists and pedestrians most head injuries from the windshield area were caused by the structural parts, but the bicyclists' head impact locations were more commonly from higher impact locations.

The results of this study indicate that car-mounted countermeasures designed to mitigate pedestrian injury have the potential to be effective even for bicyclists if redesigned to also protect higher frame parts of the windshield. Both bicyclist and pedestrian crashes should be evaluated to see whether current hood and windshield countermeasures designed to mitigate head injury could also mitigate chest injury.

Keywords Bicyclist, car impact, severe (AIS3+) injury, body region, injury source

I. Introduction

Pedestrians have been the dominant vulnerable road user group studied in car impacts. Regulations and consumer rating tests for pedestrians have influenced car design during the last decade. Cars are now equipped with energy absorbing bumpers and hoods, as well as deployable hoods. These measures have proven effective in reducing pedestrian injury. Strandroth et al. [1] showed a significant correlation between car EuroNCAP pedestrian score and injury outcome in real-life car to pedestrian crashes. Furthermore, airbags for the windshield area have also been introduced [2].

Another large group of vulnerable road users are bicyclists. There are indications that bicycle use is increasing [3], especially in larger cities due to traffic density, higher fuel prices and an increased environmental awareness within the general population. Pedestrians and bicyclists already make up roughly half the traffic fatalities in urban areas in EU countries [4], with the risk that fatalities will increase with increased bicycle use. It is therefore important to study bicycle crashes to understand how proposed pedestrian countermeasures can be designed to mitigate injuries for bicyclists in vehicle impacts. Consequently, the aim of this study was to study severe car-to-bicyclist crashes to better understand the most frequently injured body regions and their sources.

II. Methods

This paper presents a follow-up study of an earlier study of pedestrians [5]. The same database, inclusion criteria and analytical methodology as in the previous pedestrian study were used. More details of the method can therefore be found in the previous study. However, while the previous study included cases from 1999-2008 this study included cases from 1999-2010; thus pedestrian cases were updated with newer cases from the expanded time period.

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Database and inclusion criteria

The German In-Depth Accident Study (GIDAS) database was used to extract crash data for this study. GIDAS accident investigation teams operate in Dresden and Hannover and their surroundings. The sample area contains both rural and urban traffic and is chosen to represent, as closely as possible, a “mini Germany”. Work shifts are equally distributed between night and day, attending accident sites using “blue-light” vehicles along with police and ambulance personnel when personal injuries are suspected. To investigate both vehicular and human factors in maximum detail, the GIDAS teams consist of both technical and medical personnel. At least one confirmed personal injury is required for inclusion in the database.

In this study, bicyclist and pedestrian accidents from 1999 to 2010 were analyzed. The combined group of bicyclists and pedestrians will be referred to as “vulnerable road users” (VRU) in this paper. Attention was restricted to VRUs struck by passenger car or van fronts. Striking vehicles coded as passenger cars or vans (also known as multi-purpose vehicles, MPV) were included. Sport utility vehicles (SUV) have a different front geometry than passenger cars. Since GIDAS contained very few SUV-to-VRU crashes, they were excluded from this study. Finally, cases where VRUs sustained more than one vehicle impact or were lying on the ground prior to impact were excluded. This resulted in 2327 bicyclist and 1195 pedestrian AIS1+ cases with sufficient information concerning the injury, reconstruction, vehicle and personal data to allow for analysis. In summary, the following inclusion criteria were applied:

- GIDAS VRU cases collected 1999-2010
- Both VRU and vehicle information available
- All VRU ages
- VRU hit only once by one vehicle
- Impacting vehicles: passenger cars and vans
- VRU impacted by vehicle front
- VRU upright (not lying)

Injuries

GIDAS uses the Abbreviated Injury Scale injury classification system (1998 version), dividing the body into eight different body regions: head, face, neck, thorax, abdomen, spine, and upper and lower extremities [6]. In this study, head and face were combined in a new category called “head”. Thorax, abdomen and spine (excluding cervical spine) were combined in a category called “chest”. Cervical spine injuries were grouped with “neck”. Further, lower and upper extremities were called “leg” and “arm”, respectively.

The AIS scale comprises six levels of injury severity, where AIS1 denotes minor injury, 2 = moderate, 3 = serious, 4 = severe, 5 = critical, and 6 = maximal injury. The distribution of AIS3+ (AIS3 and higher) injuries (henceforth referred to as “severe” injuries in this study) to the different body regions is often provided in the literature. However, since most head injuries are documented separately while some injuries to the chest are combined in a single AIS code (e.g. flail chest and multiple rib fractures), it is reasonable to document each injured body region as adapted for this study only once per VRU, using the maximum AIS value of that body region. In this way, a more balanced picture of the regions most often severely injured in car-to-VRU crashes was obtained. Furthermore, this approach (using the maximum AIS value sustained by each body region) can be used to derive the risk of sustaining severe injury to respective body regions.

For statistical tests the chi-square test was used to compare proportions between groups and $p<0.05$ was regarded as statistically significant.

Injury sources

Vehicles were divided into impact regions based on the (more detailed) GIDAS variable “vteil1” (injury source) as follows: “front end”, “hood edge” (bonnet leading edge), “hood area” (including top part of wings), “windshield area” (including A-pillars and roof front edge) and “other”. Finally “ground” (including other areas in the surroundings) was assigned as a possible injury source. See [5] for detailed descriptions of source definitions.

Each AIS3+ injury in the GIDAS dataset was assigned one of the injury sources listed above. By aggregating on both the injury and injury source level, it was possible to investigate the number of VRUs receiving AIS3+ head, chest and leg injury from each of the injury sources (other body regions were also considered).

"Head-to-windshield area" impacts

Since the windshield area is a less homogeneous area than other parts of the car front it was decided to study this area in more detail. For all AIS3+ head injured from the windshield area, crash-scene pictures of the cars involved were gathered from the database and analyzed (see examples in Figure 1). The impact points were manually placed in a generic windshield area graph, following the procedure from the previous pedestrian study [5]. The generic windshield area graph was created as a 22 column by 22 row matrix. The left- and rightmost columns represented the A-pillars, the top row represented the roof front edge and the bottom row the lower frame part. This area was defined as the "frame area" (see Figure 3). The columns situated closest to the A-pillars, as well as the rows situated closest to the roof front edge and lower frame part, were used for impacts where the central head impact remained in the glass area but part of the head was judged to impact the frame. This area was called the "near frame area". The rows immediately above the lower frame represented the glass area where the instrument panel was situated to obstruct the head's line of motion (called the "instrument panel", or IP area in this study). By combining the "frame", "near frame" and "instrument panel (IP)" areas, the "structural area" was obtained. The name reflects the possibility of the head being exposed to structural parts at some instant during the head impact. The remaining area was the "pure glass area". Naturally, cars have different windshield glass widths and heights and different instrument panel sizes, so in each case an estimate had to be made for the relative position of the impact in the generic windshield area graph. For the glass area it was therefore first decided if the head impacted the glass only or the instrument panel area. Secondly, the relative impact position in the selected area was determined.

Figure 1. Examples of crash scene pictures with head impact location marked

III. Results

The focus of this paper is on bicyclists, but a comparison with pedestrians was made to better understand similarities and differences. Data were therefore gathered with the same inclusion criteria to enable a direct comparison.

A total of 2327 bicyclist cases and 1195 pedestrian cases on all injury levels met the inclusion criteria. Of these, 139 bicyclists and 191 pedestrians were severely (AIS3+) or fatally injured. Eighteen of the 139 bicyclists respectively 47 of the 191 pedestrians were fatally injured. The mean age was 48 years for both groups and the victims were males in 55% of the bicyclist cases and 58% in the pedestrian (Table I). The impacting vehicle was, in 134 of the bicyclist cases and in 186 of the pedestrian cases, a passenger car. In the remaining 5 bicyclist and 5 pedestrian cases the impacting vehicle was a van. The bicyclist cases occurred significantly more often in daylight and at a lower impact speed. The dominating impact type was the bicyclist or pedestrian crossing and impacted from the side. The dominating body regions sustaining severe injury were the head, leg and chest for both groups. (Head here includes face injuries, chest includes thorax and abdomen, and leg includes lower extremity and pelvis). The clearest difference could be seen for leg injuries where a significantly larger fraction of the pedestrians sustained severe leg injury. See Figure 2. Twenty-four bicyclists sustained severe injuries to two body regions and ten bicyclists to three or more body regions. (This is reflected in Figure 2 where the numbers add up to more than 100%.) Four bicyclists were wearing a helmet, and none of these victims sustained a severe head injury.

Table I
Data sample

		Bicyclists	Pedestrians	
	N	139	191	
Road				
	Daylight	74%	48%	*
Car				
	Median model year	1997	1996	
	Braking**	53%	46%	
	Mean crash speed (km/h)	36	44	*
Person				
	Lateral impact	78%	89%	
	Mean age (years)	48	48	
	Male ratio	55%	58%	
	Median height (cm)	170	169	
	Median weight	73	70	
	Mean bicycle speed (km/h)	14	N/A	
	Helmet	3%	N/A	

** Significant difference (p<0.05), **of known cases*

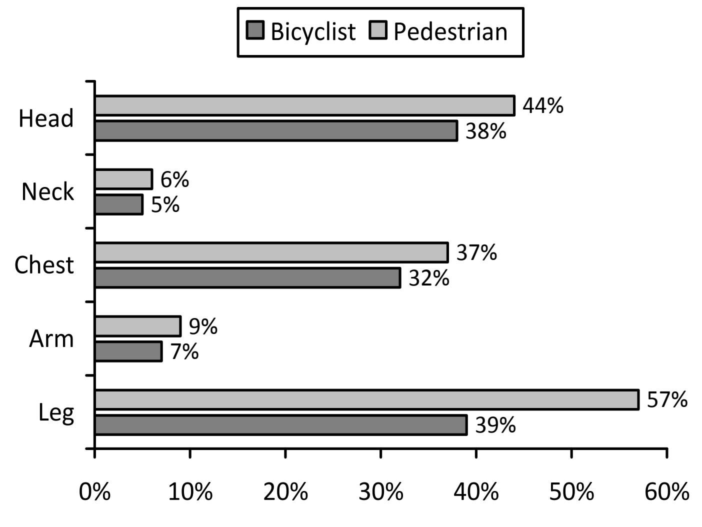

Figure 2. Percentage of bicyclists/pedestrians who sustained at least one AIS3+ injury to respective body region

Body regions severely injured (AIS3+) were further linked to the sources of injury. Table II displays the percentage of VRUs severely injured to a given body region and its injury source. The percentages were calculated with respect to the total number of severely injured VRUs (in each group) with known injury source (N=139 bicyclists, N=191 pedestrians). Since a person can sustain severe injuries to more than one body region, the numbers add up to more than 100%. For the bicyclists the head-to-windshield injury mechanism was most common while the leg-to-front was most common for pedestrians, although these two combinations were the highest two for both groups. Following these two combinations, chest-to-hood, chest-to-windshield and head-to-ground were more or less equally frequent combinations for both groups. All other combinations occurred in less than 10% of the cases for both groups.

Table II
AIS3+ (including fatal) injury source vs. bicyclist body region (pedestrian values in parenthesis)

	Leg	Arm	Chest	Neck	Head
Front end	**22% (41%)***	0% (1%)	2% (5%)	1% (0%)	0% (1%)
Hood edge	1% (5%)	0% (0%)	0% (2%)	0% (0%)	0% (1%)
Hood area	4% (7%)	2% (3%)	**11% (13%)**	0% (1%)	1% (5%)
Windshield area	1% (2%)	1% (1%)	**11% (14%)**	1% (3%)	**23% (27%)**
Ground	8% (5%)	4% (4%)	8% (9%)	1% (2%)	**14% (14%)**
Other or unknown	4% (3%)	0% (0%)	4% (3%)	1% (1%)	4% (2%)

The 5 most common are marked in bold. Significant difference (p<0.05) marked with asterisk

Since the head-to-windshield injury/source combination was most frequent, and this area is complex with structures with a large variety in stiffness, a more detailed impact location analysis was performed in the bicyclist cases with severe head injuries from the windshield area. Twenty-seven of the 32 cases could be included in this study (in the excluded five cases pictures were either missing or of insufficient quality to allow for detailed analysis). The crash pictures were analyzed case-by-case to decide the most probable head impact location and these locations were plotted in a standardized windshield graph (see Figure 3).

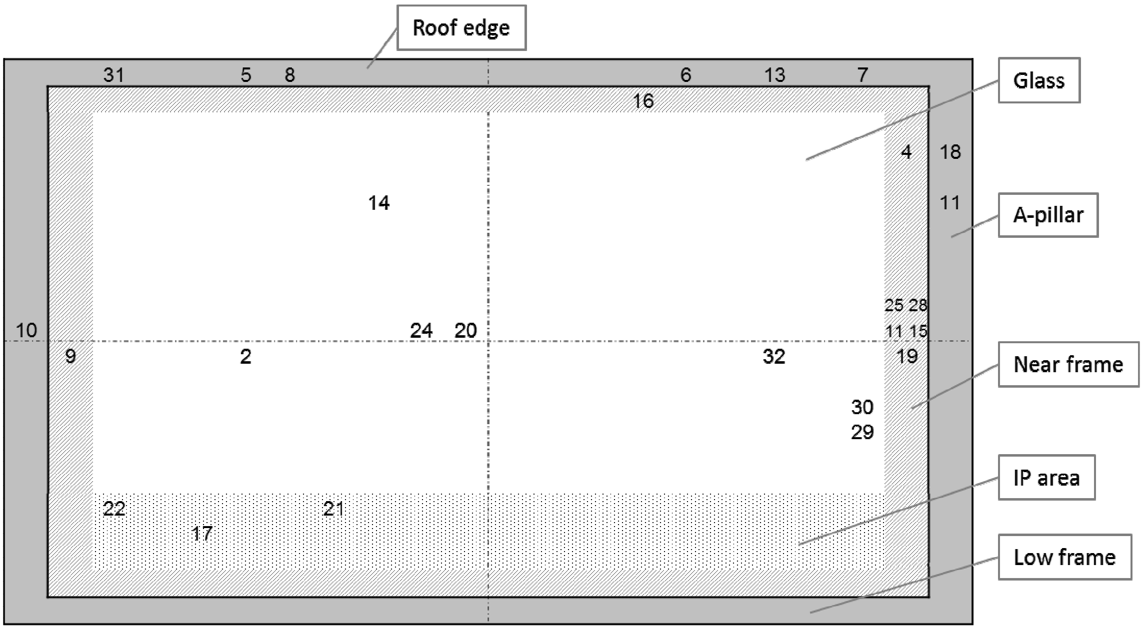

Figure 3. Detailed windshield head impact locations of bicyclists AIS3+ head injured

When grouping the head impact locations into windshield impact areas (see method for exact definitions), the data could be compared to the earlier pedestrian study [5] which used the same database, method and inclusion criteria, but for pedestrians. See Figure 4. The bicyclists' heads impacted the structural parts (roof edge, A-pillars or I-panel/low frame) fully or partially in 74% of the windshield cases, and pedestrians in 72%. The comparison also shows that the bicyclists' heads less frequently impact the lower frame and instrument panel, and more frequently the roof edge, compared to pedestrians. The difference in roof edge impact frequency proved significant (p<0.05).

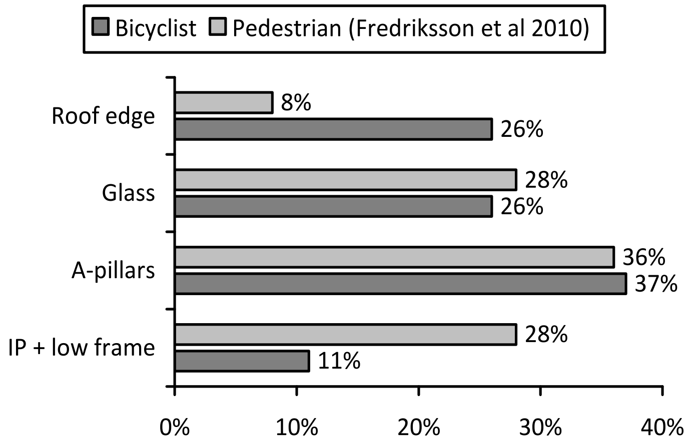

Figure 4. Summary of head impact locations in windshield area, including comparison with pedestrians in earlier study (IP=instrument panel, roof edge and A-pillars include near-frame (partial frame) impacts)

The wrap around distance (WAD) to head impact location was compared for the two groups. For the cases with known data (N=46 bicyclists, N=100 pedestrians) the average WAD value to head impact was 226 cm (95% CI 211-240 cm) for the bicyclists and 193 cm (95% CI 185-201 cm) for the pedestrians. It should be noted that WAD in GIDAS is measured following the impact points of the VRU from leg impact to bumper to head impact (not in the car's longitudinal direction as in legal and rating test method definitions).

IV. Discussion

Bicyclists were impacted at lower car impact speeds than pedestrians in this study. This is in line with another study on German (GIDAS) data but studying all injury levels [7]. However, it should be noted that this is the speed of the impacting car and that bicyclists themselves have a high speed which could mean that the delta-V between the VRU and the car differs less between the two groups than what these data suggest. It was also notable that bicyclists were more frequently impacted in daylight than pedestrians. This is valuable input for pre-crash sensor design, and can compensate for the increased complexity of the sensors due to the higher velocity of bicyclists (compared to pedestrians) and the fact that they are frequently approaching perpendicular to the car. Further, it was found that the driver in half of the cases performed no braking, which was similar for pedestrian data. This shows that the recently introduced automatic emergency brake (AEB) systems to protect pedestrians could also be effective to protect bicyclists if the sensor can detect them in a reliable way.

It was found that the dominating body regions sustaining severe injury, for both bicyclists and pedestrians, were the head, leg and chest. This was in line with previous studies of pedestrians [8]-[10]. Maki et al. [9] also showed similar figures for car-to-cyclist crashes in Japan. Analyzing at an injury level and excluding fatal injuries, leg injuries were, in the Japanese crashes, more dominating in both groups than in this study, but less dominant for bicyclists than pedestrians, which was in line with our study.

The two dominating injury/source combinations were leg-to-front end and head-to-windshield area. It was found that leg injuries caused by front ends were less frequent than for pedestrians, where it was the dominating injury/source combination. Two possible reasons for this are linked to the person's position on the bicycle compared to a person walking. First, the center of gravity of a person is likely to be higher for a bicyclist, than the same person walking, resulting in the legs positioned higher relative to the bumper. Further, when bicycling, legs are bent resulting in the knees situated higher and therefore less likely to impact the bumper. The knee height position relative to bumper height is important since the knee is often sustaining severe injuries, and the bumper is the most protruding and first part of the car to impact the leg. Bicyclist chest injuries were frequently caused by both the hood and windshield areas, which was similar for pedestrians. Another large injury/source combination was head injury from the windshield area. This implies that car-mounted countermeasures for the bicyclist's head should focus on this area for highest effectiveness. The detailed head impact analysis further shows that such a countermeasure should be concentrated to the frame parts of the windshield area. Finally, results indicate that bicyclist head impacts leading to severe (AIS3+) injury are located higher on the windshield area. This was also shown by Maki et al. [9] where the car (longitudinal) wrap around distance to head impact (WAD) divided by the person's height (stature) was calculated. The bicyclists then had a 20% higher WAD/stature ratio than pedestrians for hood-type vehicles. For VRUs impacting mini-van vehicles (more vertical front) this difference was not observed. The mini-van cases imply that Japanese bicyclists are not positioned so that the head is substantially higher than when walking. For hood-type vehicles we know, for pedestrians, that sliding on the hood can be extensive before head impact, which was also shown for bicyclists both in this study and in the study by Maki et al. The higher head impact locations for bicyclists could therefore possibly be explained by the different leg and pelvis position. The straight legs of a pedestrian may prevent more of the sliding than the bent legs of a bicyclist. The bicyclists could also have a higher pelvis position (a parameter shown to be sensitive to the sliding effect for pedestrians) even if the head is at the same height (due to the upper body posture of a bicyclist often leaning forward), although this difference is likely marginal compared to pedestrians.

In conclusion, the results show that effective car-mounted injury countermeasures to protect bicyclists should concentrate on leg injuries from the bumper; chest injuries from the hood and windshield areas; and head injuries from the windshield area. The results also indicate higher head impact locations for bicyclists, which implies that the windshield countermeasure to mitigate bicyclist head injury should cover higher parts of the windshield area than current pedestrian protection countermeasures. Future studies should investigate whether current pedestrian countermeasures for head-to-hood and windshield areas can also be effective in mitigating chest injury. If they prove to do so (or if they can be redesigned to mitigate both head and chest injury), and the windshield countermeasure can be redesigned to protect higher parts as well, then we have potentially effective countermeasures for both bicyclists and pedestrians.

Limitations

This study is limited by the number of cases, which makes it difficult to divide the data into more subgroups. Therefore some of the results, which did not prove significant in this study, could become significant if a larger dataset was collected.

Naturally it is a difficult task to estimate the injury producing car impact location for a certain body part after the crash has occurred. However, in the GIDAS database an injury source is given the "unknown" value if not enough certainty can be concluded in the determination. The focus on severe injuries increases the certainty since these crashes involve higher impact energy and produce residual deformation on the car to a larger extent than less severe crashes. Further, the comparison between bicyclists and pedestrians should not be influenced significantly by this possible coding error since the two datasets have been collected using the same personnel and data collection and analysis techniques.

This study is based on crashes occurring in one country, which limits the conclusions for other countries or regions of the world. Germany, where the data were collected, is likely to have a car fleet different from other parts of the world. It is likely that southern Europe, Asia and Africa have a larger share of smaller vehicles, which would probably result in a different distribution of injury sources, especially for the head. The USA on the other hand has larger vehicles, and other types, such as SUVs, are more frequent, which could again result in different results.

V. CONCLUSIONS

This study shows that car-to-cyclist impacts are fairly similar to car-to-pedestrian impacts in many aspects but especially in terms of distribution of injured body regions and injury sources. However, it seems that the different body posture of bicyclists result in some differences compared to pedestrians. Leg injuries from the front end are less frequent and head injuries tend to be linked to higher impact locations.

The results of this study indicate that the current pedestrian leg and head countermeasures have the potential to be effective even for bicyclists if redesigned to also protect higher parts of the windshield frame. Both bicyclist and pedestrian crashes should be evaluated to see whether current hood and windshield countermeasures designed to mitigate head injury could also mitigate chest injury.

VI. Acknowledgement

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VII. References

[1] Strandroth J, Rizzi M, Sternlund S, Lie A, Tingvall C, The correlation between pedestrian injury severity in real-life crashes and Euro NCAP pedestrian test results. *22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Washington D.C., USA, Paper no 11-0188, 2011.

[2] Volvo Cars, Press release: "The all-new Volvo V40", *Volvo Car Corporation Global News Room*, Internet: https://www.media.volvocars.com/global/enhanced/en-gb/media/preview.aspx?mediaid=42212, Accessed: 2012-03-27.

[3] Thiemann-Linden J, Bicycle use trends in Germany. *German Institute of Urban Affairs (Deutsches Institut für Urbanistik)*, Berlin, 2010.

[4] EC, "CARE database - reports and graphics 2010", *European Commission*, Internet: http://ec.europa.eu/transport/road_safety/specialist/statistics/care_reports_graphics/index_en.htm, Accessed 2010-12-27.

[5] Fredriksson R, Rosén E and Kullgren A, Priorities of pedestrian protection – A real-life study of severe injuries and car sources. *Accident Analysis & Prevention*, 42:6, pp 1672-81, 2010.

[6] AAAM, The abbreviated injury scale: 1990 revision, update 1998. *Association for the Advancement of Automotive Medicine*. Barrington, IL, USA, 2001.

[7] Otte D, Jänsch M, Haasper C, Injury protection and accident causation parameters for vulnerable road users based on German In-Depth Accident Study GIDAS, *Accident Analysis & Prevention*, 44:1, pp 149-153, 2012.

[8] Longhitano D, Henary B, Bhalla K, Ivarsson J, Crandall J, Influence of vehicle body type on pedestrian injury distribution. *SAE (Society of Automotive Engineers) World Congress*; Detroit, Michigan, USA, 2005

[9] Maki T, Kajzer J, Mizuno K, Sekine Y, Comparative analysis of vehicle-bicyclist and vehicle-pedestrian accidents in Japan. *Accident Analysis & Prevention*, 35:6, pp 927-40, 2003.

[10] Zhang G, Cao L, Hu J, Yang KH A field data analysis of risk factors affecting the injury risks in vehicle-to-pedestrian crashes. *Annals of Advances in Automotive Medicine (AAAM),* 52, pp 199-213, 2008.