Analysis of Vulnerable Road User Kinematics Before/During/After Vehicle Collisions Based on Video Records

Yong Han, Quan Li, Wei He, Fang Wan, Bingyu Wang, Koji Mizuno

Abstract The vulnerable road users (VRUs) tend to sustain serious injuries in accidents. There are various types of accident scenarios, and VRUs show various behaviors before and after impacts. In this paper, we analyzed 400 VRU accident cases (200 pedestrians and 200 two-wheelers) with video information. The VRUs before/during/after collision parameters (e.g., accident scenarios, VRU avoidance motion, kinematics and trajectory during vehicle impact, and ground contact) were examined. The emergency avoidance motions of the VRUs before collision were: jumping, hands up to prevent, and others. 66% of the pedestrians and 53.5% of the two-wheelers showed avoidance motions before collisions. Pedestrians typically have higher rotation angles than riders on two-wheelers during vehicle collisions, and two-wheeler's riders' kinematics are more complicated especially when caused by the side impact. Pedestrian rotation angles greater than 90 degrees were observed in over 45% pedestrian collisions. The kinematics of the pedestrian and two-wheelers depends on the vehicle front-end shape and impact velocity. In the ground impact, the order of VRU body regions making contact against the ground depends on the landing posture. The analysis of VRUs before/during/after collisions using accident videos would be useful for comprehensive understanding of VRU accidents.

Keywords Vulnerable road user, pedestrian accident, two-wheelers accident, Kinematics, Ground impact

I. INTRODUCTION

Traffic accidents are an important social issue regarding threats to human life. The World Health organization (WHO) pointed out that the number of road traffic deaths each year has not increased but the number is still large with 1.24 million per year; and 50% of the world's traffic deaths occur among motorcyclists (23%), pedestrians (22%) and cyclists (5%) [1]. in 2013, 84,589 people died from road traffic injuries in the European Region – more than 230 every day. In total, 39% of deaths are among pedestrians, cyclists and motorcyclists [2]. According to the Chinese Ministry of Public Security Traffic Management Bureau statistics, there were at least 15,221 pedestrian fatalities in traffic accidents in 2012, which accounts for 25.37% of the annual road accident fatalities in China [3]. The protection of vulnerable road users (VRUs) such as motorcyclists and pedestrians are an increasingly important issue in the field of vehicle safety.

In-depth investigation of traffic accidents is a basis of automobile safety design. The United States, Japan, Europe, Australia and other countries or regions have established a thorough traffic accident investigation system conducted by research institutions such as the National Automotive Sampling System (NASS) in the US and the Australian Monash University Accident Research Centre, GIDAS organized by the German Federal Highway Research Institute, and CIDAS in China. These institutions provide many data items by their traffic accident analysis. However, accident investigators collect accident information after accidents by using traditional survey methods and accident reconstructions. In fact, it will be difficult to ensure that survey results are completely comparable with the real accidents. The real causes of the accidents are very complicated to judge clearly based on the limited information such as tire trace and debris at an accident site. The vehicles indirectly involved in collisions may leave the accident site and traffic conditions can change. Moreover, the kinematic response of the VRU during a collision is difficult to identify if no trace exists at the accident site though the kinematics of pedestrians or two-wheelers are essential in order to investigate vehicle impact conditions and injury mechanisms including ground impacts.

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Many research studies have been carried out on the kinematics and injury mechanisms of pedestrians and two-wheelers. Since the 1970s, most research efforts have focused on reducing pedestrian injuries from the primary impact with the vehicle. It was shown that the most severe injuries were to the head, followed by chest, pelvic and lower extremities, and pointed out that the vehicle impact velocity and vehicle front-end shape are the two dominant factors that influence the pedestrian kinematics and injury severity [4-8]. However, a pedestrian finally falls to the ground after primary impact against the vehicle. In the last decade, many researchers began to pay attention to pedestrian secondary injuries caused by ground impacts, and found that injury outcome from the pedestrian-ground impact are also very serious in real accident [8-10]. Hamacher et al. [12] studied the pedestrian kinematic after the vehicle impact based on Madymo simulations and experiments by comparing the vehicle type, initial pedestrian gait, impact speed, and impact position. Gupta and Yang [13] studied the different vehicle front-end profiles as to how they affect the risk of pedestrian secondary head impact with the ground and found that even though different pop-up hood helped reducing the head injury criterion during primary impact, it changed the overall pedestrian kinematics in some cases. However, there is no reliable accident information to verify their results. Likewise, the researchers also devoted many efforts to reduce the injury risk to two-wheeler riders. Vlahogianni et al. [14] studied the powered-two-wheelers (PTW) kinematic and interactions in urban arterials and pointed out that future work should focus on comparing PTW driving patterns between different countries, cultural contexts, or traffic environments. A study of 205 in-depth cases on accidents involving pedestrian and pedal cyclists indicated that head impacts with the road surface may actually more severe than an impact with the striking vehicle [15]. Also, mathematical simulations were conducted to analyze the kinematics and injury of two-wheelers compared to pedestrians [16, 17]. Schijndel et al. [18] indicated that the wrap around distance (WAD) of the cyclists is larger than for pedestrian, and the head impact speeds of cyclist in tests were generally higher than that for pedestrian. The simulation results can be compared to real accidents, though there remains still unclear points in comparison based on the traces, vehicle deformation, and injuries after collision.

Nowadays, there are many road monitoring cameras in China to record traffic conditions on roads. With road monitoring, VRU accident involving collisions are recorded. According to the VRU accidents videos, pedestrian or two-wheelers riders' behavior before/during/after collisions (accident scenarios, VRU avoidance motion, kinematics and trajectory during vehicle impact, and the ground contact posture) can be observed. In this study, the VRU accidents with video information have been analyzed to provide new knowledge to understand the scenarios in vehicle-VRU collisions.

II. METHODS

Data Samples

400 VRU cases (200 cases of pedestrian and 200 cases of two-wheelers) have been selected and downloaded from the internet (YouTube and Youku). Some keywords were used to search the accident videos *available* on the internet. These included "pedestrian accidents," "pedestrian crashes," "pedestrian running red light," "two-wheelers accidents," "bicycle accidents," "electric bicycle accidents," "motorcycle accidents," "two-wheelers running red light," etc. The videos that met the requirements were selected from the resulting list. There was no selection bias, as these cases were randomly selected from the network. However, the proportion of cases collected during the day at the road junction was larger than the actual case frequency, due to the road monitoring systems at the junctions collecting a larger number of cases and also due to the videos being recorded during the daytime were clearer. Appendix I (Screenshot from video) shows the general quality of the video. The video shooting angle was random, but we could see the road environment. We checked all video cases and found that only one pedestrian case involved having the left-hand traffic laws, while the other cases involved having the right-hand traffic laws.

The video collection standards were as follows: (1) The cases belonged to traffic accidents that were not caused deliberately. (2) The main reason of the accident could be identified clearly. (3) The accident occurred on the traffic road. (4) The accident vehicle was categorized as a road vehicle. (5) The riders were aboard the two-wheelers instead of walking beside and pushing the bikes. (6) The cases were clear enough to determine the pedestrian's body regions, and to collect data regarding the kinematics characteristics, kinematics trajectory and road environment.

Vehicle speed estimation

The vehicle travel distance (S) was calculated by vehicle length multiplied by the numbers of the vehicle lengths traveled during the accident. Also, the length of car was categorized by the average length (*L*) of each vehicle type (minicar (3.5 m), small family sedan (4.0 m), medium sedan (4.5 m), large sedan and SUV (5.0 m).

$$S = L \times Z \tag{1}$$

S: the distance traveled by the vehicle
L: vehicle length
Z: the number of vehicle length travels

The vehicle impact velocity (*V*) was estimated by vehicle travel distance (*S*) within a certain time according to the accident car in the video. The video frame rate was divided into 25 frames per second on average through the use of video studio software which could modify the video into specified frame rates. The vehicle moving distance during each frame was analyzed.

$$V = \frac{S \times 25}{N} \times 3.6 \tag{2}$$

V: impact velocity (km/h)
N: the number of frames

Accident scenarios

The definition of accident scenarios was based on the behavior of a VRU before the accident occurred (Appendix II accident scenarios). There are 15 kinds of scenarios for pedestrian accidents (named from 001 to 015) and 54 kinds of scenarios for two-wheelers accidents in 9 categories based on the vehicle movement direction (straight/turn left/turn right), and six types for each category.

Kinematics and trajectory of VRU

The kinematics and trajectory of the pedestrian were defined based on the classification of 'pedestrian impact orientation' proposed by Ravani et al. which included wrap, forward projection, fender vault, roof vault, and somersault sequences [19]. In this paper, side swipes were added so as to cover almost all of the accident situations. The kinematics and trajectory of VRU were divided into six types: (1) wrap trajectory: VRU wrapped around the hood. (2) Somersault: VRU falls in front of the vehicle after the rotation. (3) Roof vault: VRU is projected upward and falls on the side or rear of the vehicle. (4) Forward Projection: VRU was projected forward in front of the vehicle. (5) Fender vault: VRU collides with the vehicle fender. (6) Side impact: VRU collides with the side of the vehicle. (Appendix III: Definition of the VRU trajectory).

The rotation angle of pedestrian in accidents

In the current study, the pedestrian body rotation angle occurring during the period of time from the primary vehicle impact to the moment of a body region making first landing was accounted as the pedestrian rotation angle (see Fig.1). The positive angle was defined when pedestrian rotates toward the vehicle in the initial impact, and the negative was defined when the pedestrian rotates to the ground in the initial impact.

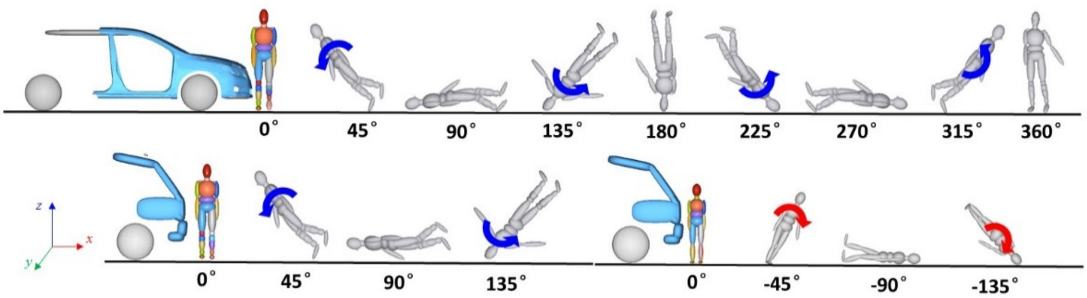


Fig. 1. Definition of the pedestrian rotation angle

III. RESULTS

Accident information

The accident cases are described and analyzed by following eight parts: time, geographical, environment, vehicle type, scene, visual obstacle, and impact velocity. In some accidents, multiple VRUs may have been involved in a case, so the overall number of VRUs may be more than the number of cases. For example, there were more than 200 pedestrians in the 200 pedestrian crashes. That is, in these 200 cases, there were a few cases that had multiple pedestrians impacted by the same subject vehicle in a given case.

Time and geographical

From the video record data, 239 cases (59.8%) were collected with date information and 30.2% of cases were collected without date information due to the video being short and incomplete. These accidents cases mainly occurred in the year from 2011–2016. 325 cases (81.25%) occurred in China, and 18.75% cases were from other countries. Among them, 60.6% of the cases had location information in China, for which most of them these were from the eastern coastal areas of China.

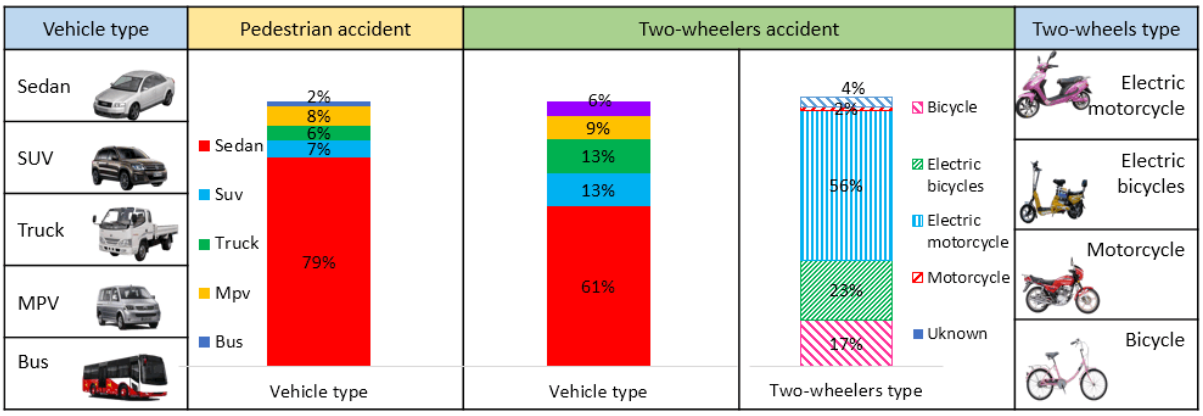
Environment conditions

Statistical results show that 70.5% of the accidents occurred in good view with sunny weather conditions, 29.5% in poor road and weather conditions (i.e., included night, rain, and/or snow). 22.5% of the accidents occurred at night, and 17.5% occurred in rainy or snowy weather.

Vehicle type

Table 1 shows the vehicle types involved in the accidents. Five types of vehicles (sedan, SUV, truck, MPV, and bus) were classified in the pedestrian and two-wheelers accidents. Sedans account for 79% in pedestrian accidents and 61% in the two-wheelers cases. According to the traffic situation in China, two-wheeled vehicles were divided into four types: (1) bicycles; (2) electric bicycles; (3) electric motorcycles; and (4) motorcycles with oil power. Among these, electric motorcycles (56%) had the highest frequency, followed by electric bicycles (23%), bicycles (17%), and motorcycles (2%).

TABLE I VEHICLE TYPE IN VRU ACCIDENTS



Scene of accident

Table II presents the scene of pedestrian accidents. The pedestrian was observed coming from the right of the vehicle in 110 cases (accounting for 55%), and most accident scenes are types 001 and 002. Pedestrians coming from the left account for 37.5%, rear-end and head-on collisions account for 7.5%. Most of the vehicles were travelling straight ahead (95%), while 5% were turning toward the pedestrian in these accidents.

TABLE II SCENE OF PEDESTRIAN ACCIDENTS

◄···· Pedestrian ◄── Vehicle

Pedestrian coming from right of vehicle（110,55%）						
Number	70	23	10	4	3	0
Type	001	007	009	012	013	other
Pedestrian coming from left of vehicle(75,37.5%）				Rear-end collision（15,7.5%）		
Number	45	16	11	3	7	7	1
Type	002	008	010	other	005	standing 015	other

For two-wheelers accident, most of the accident scenes were 101 and 102 and accounted for 54% of the total cases, where the locations were mostly in the crossroads and were different from the pedestrian accidents which mostly occurred on a straight road. Moreover, compared to pedestrian accidents, the accidents that two-wheeled vehicles experienced come from the left side and accounted for 53% as compared to the two-wheelers coming from the right of vehicle (Table 3). Most of the vehicles were travelling straight ahead (80%), while 20% were turning.

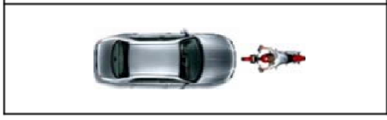
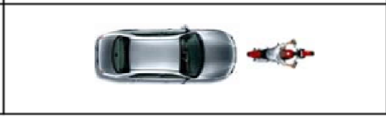
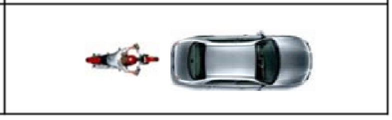
TABLE III SCENE OF TWO-WHEELERS ACCIDENTS

◄-- Two-wheels ◄── Vehicle

Two-wheelers coming from right of vehicle（87,43.5%）							
Number	33	9	5	6	7	18	9
Type	101	103	204	206	404	703	other
Two-wheeled vehicle coming from left of vehicle（106,53%）						Rear-end or head-on collision（7,3.5%）	
Number	76	5	10	5	10	4	3
Type	102	104	203	701	other	or 105	106

Table 4 shows the two-wheeler collision accidents categorized by three types: vehicle head on to the two-wheelers side (V-head-on-TW-side), two-wheelers head on to vehicle side (TW-head-on-V-side) and head on to rear. Moreover, the "V-head-on-TW-side" of the collision were divided into three types: (1) V-head-on-TW-head; (2) V-head-on-TW-middle; (3) V-head-on-TW-rear. The "V-head-on-TW-side" of the collision include: (1) TW-head-on-V-front; (2) TW-head-on-V-middle; and (3) TW-head-on-V-middle with an angle. In the 200 cases, 59.5% of the cases were those in which the vehicle collided with the side of the two-wheelers. Also, two-wheelers impacting into the side of a vehicle were observed in real world accident (26.5%).

TABLE IV COLLISION TYPE IN VRU ACCIDENTS

V-head-on-TW-side（59.5%）			TW-head-on-V-side（26.5%）		
26%	28.5%	5%	10%	10%	6.5%
					
Head-on-rear（14%）					
8%		5%		1%	
					

Impact velocity

Fig. 4 shows the impact velocity distribution in pedestrian and two-wheeler accidents and were estimated by using equations (1) and (2). For vehicle-to-pedestrian accidents, the vehicle impact velocity was estimated between 30-50 km/h due to most of the accidents occurring in an urban area. Some accidents were found in the fast traffic lane or highway that led to high impact velocities ranging from 80-100 km/h. For the two-wheeler' accidents, the traveling speed of the two-wheelers vehicle mostly were in the range from 10-30 km/h and vehicle in 30-50 km/h.

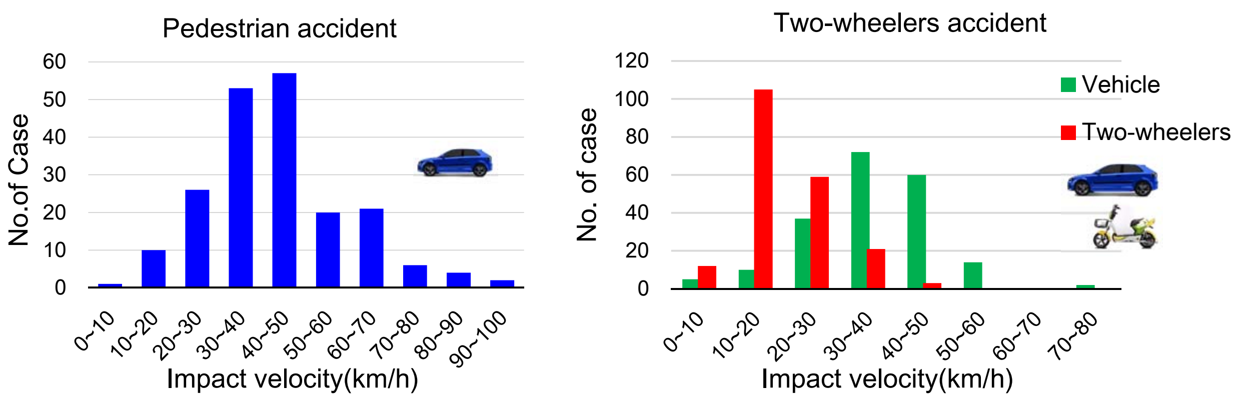


Fig. 4. Impact Velocity Distribution in pedestrian and two-wheelers accidents (Estimate)

VRU before collisions

VRU avoidance motion

The VRU behavior before collision (VRU position and avoidance motion) was examined. Fig. 5 shows the avoidance motions and postures of VRUs observed in the videos. In some cases, the pedestrian and two-wheelers showed emergency avoidance motions when faced with a dangerous situations before impact, such as jumping, hands up for preventing contact, and legs up. It was found that pedestrians showed higher frequency of avoidance motions compared with the two-wheeler riders. In the pedestrian accidents, 66% of the pedestrians made an emergency avoidance motion before collisions occurred, and 53.5% of the two-wheelers showed an emergency avoidance motion (Fig. 6). Since the videos often were incomplete, 14% of the pedestrian accidents and 22% of the two-wheelers accidents could not be categorized for their avoidance motions. In the Fig. 7, the bicycles were used only to show the avoidance motions taken by the two-wheeler riders.

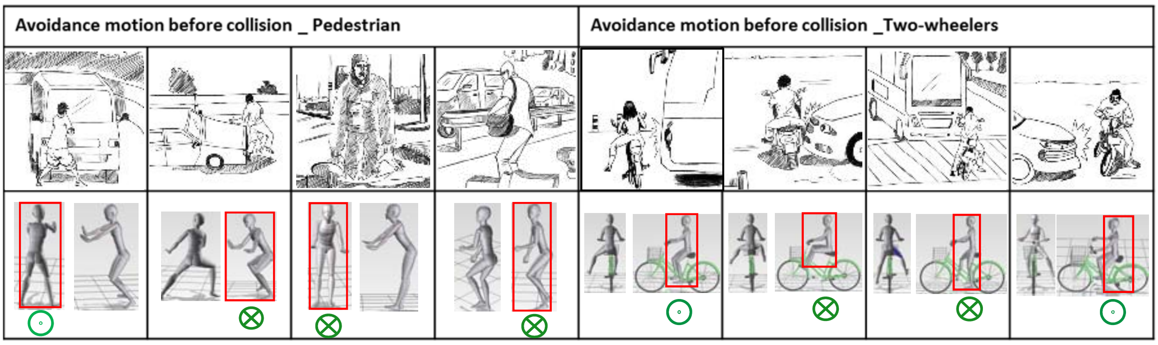


Fig. 5. Avoidance motion and posture of VRU
(Note that symbols of "shooting arrows" in physics are used to show the direction that the vehicle collided)

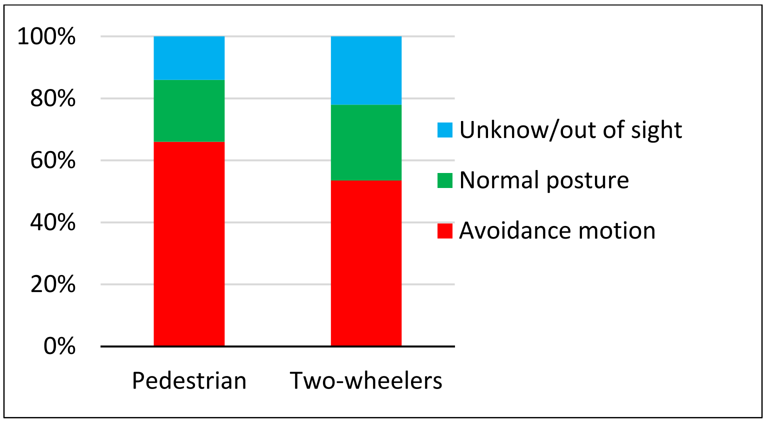


Fig. 6. Distribution of avoidance motion

VRU during collisions

<u>Trajectory of VRU during collisions.</u>

In order to compare the kinematics and trajectories of the pedestrians and two wheelers, the trajectories were defined by six types: wrap trajectory, somersault, fender vault, roof vault, forward projection, and side impact. Fig. 7 shows the distribution of the pedestrian and rider trajectories. In the pedestrian accidents, where 214 pedestrians were impacted in the 200 accident cases, the wrap trajectory and somersault were the main types in the sedan and SUV and MPV collisions. For track/bus impacts, the forward projection was the main type. For the two-wheelers, the wrap trajectory and fender vaults were the main types in sedan and SUV collisions. The somersault was the most frequent in pedestrian accidents, but were the least in the two-wheelers accidents. On the other hand, the number of the side impacts was large in the two-wheelers accidents but few in the pedestrian accidents.

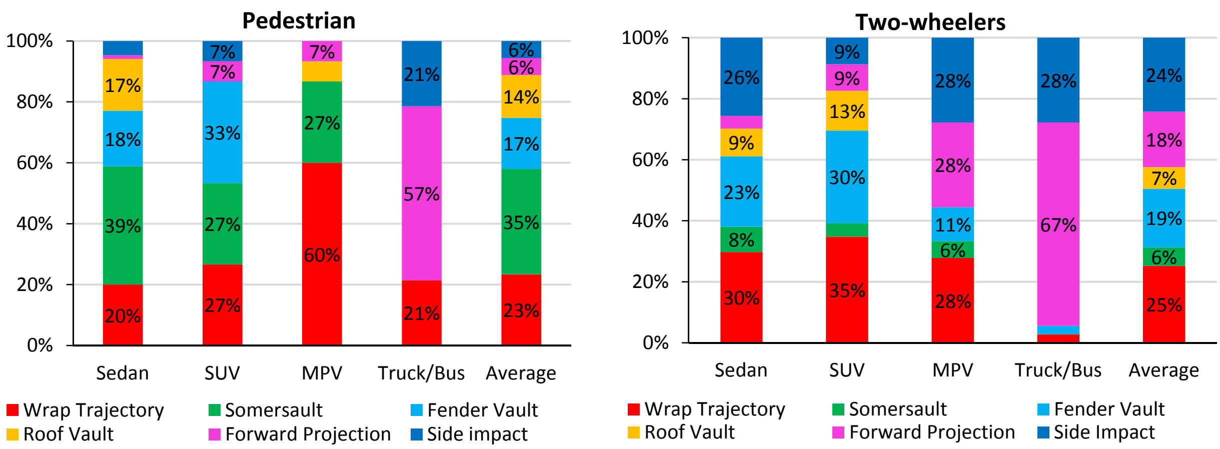
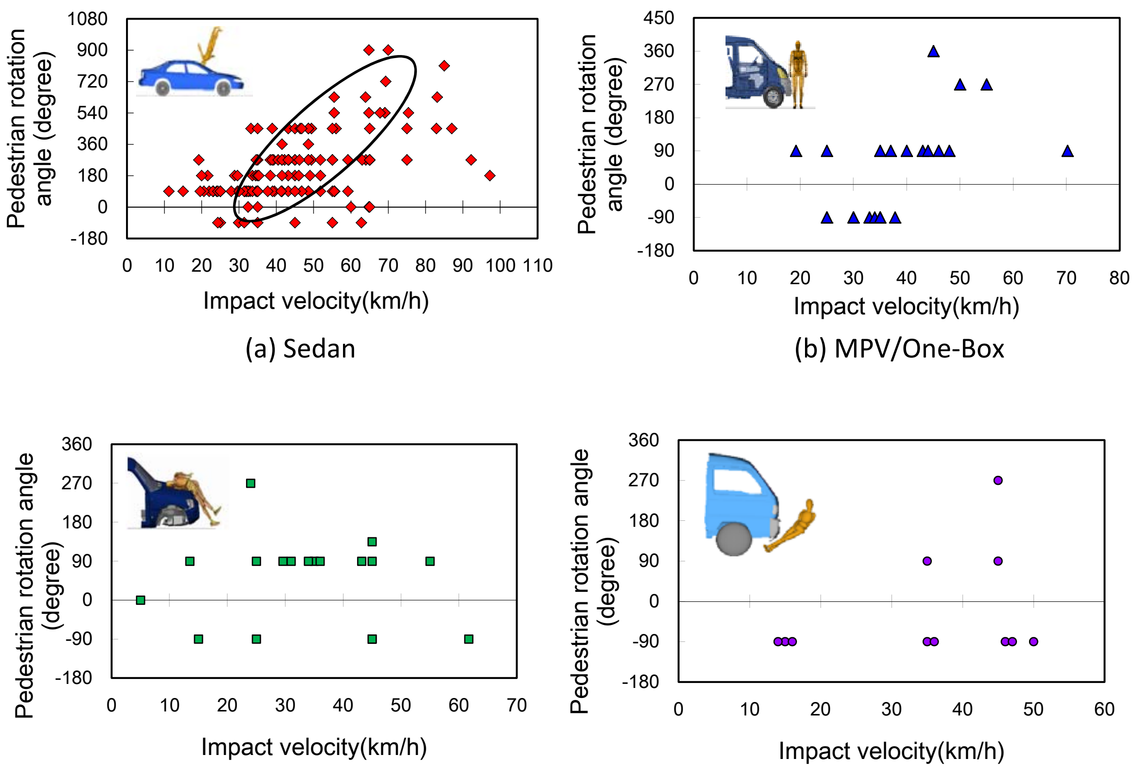


Fig. 7. Distribution of the pedestrian (214) and rider (200) trajectories

Pedestrian rotation angle

Fig. 8 shows the relations between impact velocity and pedestrian rotation angle by vehicle types. Pedestrian were more likely to rotate in a collision than were the two-wheelers based on the statistical analysis. Over 45% of pedestrian rotation angles were larger than 90 degrees. The pedestrian rotation angle depended on vehicle types and impact velocity. In sedan collisions, the rotation angle increased with increasing impact velocity. It seems that the low height of the hood leading edge led to a high rotation velocity of the pedestrian thereby causing a large rotation angle (Fig. 8a). In MPV/one-box collisions, the high hood leading edge and relatively flat shape of the front-end led to the pedestrian upper body directly to have contact with the front panel and the head to make contact with the windshield. When the impact velocity ranged from 30-50 km/h, the rotation angles were +90 degree, while the lower impact velocities could cause -90 degree rotation angles (Fig. 8b). In SUV collisions, due the high hood leading edge as compared to the sedan, the pedestrian rotated around the front shape and fell from the bonnet, and the rotation angles mostly were ±90 degrees (Fig. 8c). In truck collisions, the impact velocity had a small influence on the rotation angle, as the flat front-end shape caused a forward projection trajectory and a rotation angle that was -90 degree in many cases (Fig. 8d)



(a) Sedan (b) MPV/One-Box

(c) SUV (d) Truck

Fig. 8. Pedestrian rotation angle

Contact between of vehicle and two-wheelers rider

In vehicle-to-pedestrian collisions, the pedestrians were impacted by the vehicles bodies. However, the two-wheeler rider was found not to have contact with the vehicle body in some V-to-TW accidents. Therefore, there was a difference in the contact classification between pedestrian accidents and two-wheelers accidents. In the two-wheeler accidents, it was found that there were three collision possibilities: vehicles, two-wheelers, and riders. The two wheelers and riders were moving together before the collision, but the kinematics were different during impact. Thus, it was necessary to distinguish between the two wheelers and the riders to analyze a case, especially in those cases in which the rider made contact with the vehicle.

In the current study, the "first impact" was defined for the situation in which the first contact was between the vehicles and the riders, while the "second impact" was defined for the situation that the two-wheelers had the contact by the vehicle body, followed by the rider being impacted by the vehicle body.

Four contact types could be classified during V-to-TW accidents: (1) The two-wheelers rider and vehicle made direct contact in the first impact when the vehicle impacted the side of the two-wheeler; (2) The two-wheelers rider and vehicle made contact in the second impact when the vehicle impacted the front or rear of the two-wheeler; (3) The two-wheelers made contact with the vehicle but the rider did not make contact with vehicle body; and (4) The two-wheeler rider fell down before the vehicle collision when the two-wheelers rider noticed an impending dangerous situation, and the rider and two-wheeler did not make contact with the vehicle. It was found that the highest probability of two-wheelers rider contact was with the vehicle in the second collision, accounting for 54% of all the cases. The case of the two-wheelers rider having contact with the vehicle in the first collision comprised 26% of the cases. 13% of the two-wheelers rider showed no contact with the vehicle; and 1% of the two-wheelers riders fell down before the collision, but injuries could be caused by ground impact (Fig. 9).

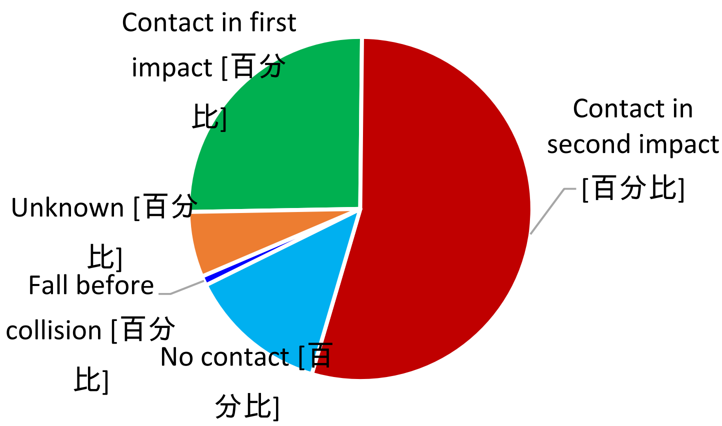


Fig. 9. Distributions of contact of vehicle and two-wheeler rider

VRU after collisions (Ground impact)

<u>Landing Posture of VRUs</u>

The VRUs' landing posture was classified according to the first impact region of the VRU to the ground, and identified by the first contact body region of the head/back/hip/lower limbs to the ground (Table 5). In some cases, the landing posture of the VRU could not be judged due to the video shooting angle and clarity; therefore, such cases were excluded from the statistics. According to statistics, the head first contact with ground occupied 27% of the cases in pedestrian accidents and 26% of the cases for the two-wheelers accidents. The lower limbs were the most frequent of the body regions to contact ground firstly.

TABLE V PROBABILITY DISTRIBUTION OF LANDING POSTURE OF VRU
(PEDESTRIAN: 144 CASES, TWO-WHEELERS:160 CASES)

VRU landing posture		
Head first contact ground		Pedestrian :27%
		Two-wheelers:26%
Back first contact ground		Pedestrian :8%
		Two-wheelers:5%
Hip first contact ground		Pedestrian :15%
		Two-wheelers:14%
Lower limbs first contact ground		Pedestrian :49%
		Two-wheelers:51%
Shoulder first contact ground (pedestrian:1%,Two-wheelers:4%)		

VRU Body Region against Ground

The distributions of the body landing regions are shown in Fig. 10. It was found that the distributions of the body landing region order of pedestrians were similar to that of the two-wheel riders. The lower limbs were the first body landing region, followed by the head and hips. For the second body landing region, the hips were largest. The third body landing regions were the hip/back/shoulder, accounting for about 25% respectively. For the fourth body landing order, the head and lower limbs were the most frequent regions.

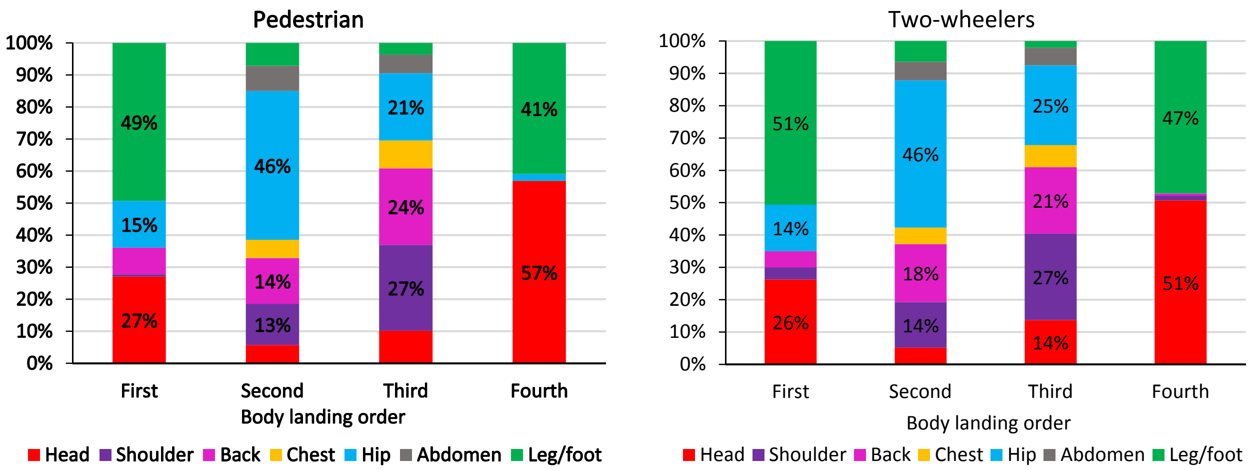


Fig.10. Distribution of body landing region (pedestrian: 160 cases, two-wheelers: 144 cases)

IV. DISCUSSION

This research investigated the behavior of vulnerable road users' before/during/after vehicle collisions based on video records which included 200 pedestrian and 200 two-wheelers cases. Most of the video records were from China, and the number of cases were useful samples for analyzing the VRUs. VRUs often entered the traffic road without obeying the traffic rules, as well as entering and encountering drivers' aggressive driving behavior.

Scene of accident

From the statistical analysis of the scenario of the pedestrian accidents, the types 001 and 002 scenarios were the most frequently observed for pedestrians. This result was consistent with study of Kong et al. [20], who obtained these results from in-depth investigation of vehicle traffic accidents in Changsha (IVAC). Most of the vehicles were found travelling straight ahead and had impact with the pedestrians (comprised 95% of cases), but only 5% involved vehicles turning to make contact with the pedestrian. Ding et al. [21] found similar scenario of pedestrian accidents in the China In-Depth Accident study (CIDAS) database, in which the vehicles were travelling straight ahead (89%), while 11% of vehicles were turning. Similar scenario types in two-wheelers accident were observed. It seems that the driver seated in the left side of the front seat led to a visual obstacle of the driver‘s vision and such that he did not notice the oncoming pedestrian or two-wheelers from the far right side. It is worth noting that the statistics do not have a very good general adaptability due to the influence of the method used for the video sample selection.

Avoidance motion of VRU

The VRU emergency avoidance motions were found in the accident videos (66% of pedestrian cases and 53.5% of two-wheelers cases). The VRU’s motions such as jumping, raising hands up to the get driver’s attention, and raising legs up can affect the kinematics and injury risk of the VRU. The posture of a VRU before a collision is an important parameter regarding VRU injuries in a vehicle impact according to previous studies [22, 23]. Therefore, understanding the pedestrian avoidance motion will be the basis in the future for studying the pedestrian injury mechanisms. However, it is difficult to obtain the initial posture of the pedestrian before a collision using traditional investigation methods or reconstruction methods rather than analyzing a real accident video record. A limited number of cases cannot describe the complete pedestrian postures during an avoidance motion in the accident. More studies are needed to analyze pedestrian postures and their influence on the pedestrian kinematics and injury risk.

Pedestrian trajectory

There was a different result in our study as compared with Ravani et al (1981) regarding the distribution of pedestrian trajectories. Ravani et al. analyzed 460 pedestrian accidents cases in 1981, and the probability of pedestrian trajectory was found as follows: wrap trajectory (45.2%), forward projection (34.4%), fender vault (13.3%), roof vault (5.4%), and somersault (1.7%) [19]. But, the highest probability was for a somersault (35%) trajectory in our current study; and the probability of a forward projection (6%) of trajectory was very small. There was a main reason for the different results: The vehicle front shapes in the 1980’s in American were very different from modern vehicle designs. In the 1980s, the shape of the vehicle was long and high, so it was more likely to cause the “forward projection” trajectory of pedestrians. Nowadays, the vehicle front shape is designed to be short and low; therefore pedestrians are more likely to rotate in pedestrian - vehicle crash accident.

Pedestrian rotation angle

The pedestrian showed larger rotation angles than those for the two-wheelers. The impact velocity and front-end shape are the more important factors that influence the rotation angle in pedestrian accidents. In the bonnet type vehicle collisions, the pedestrian rotation angles were larger than those in other types of the vehicles. In bonnet type vehicles, the height of the hood leading edge was lower than that for an SUV or MPV. The lower hood leading edge can cause a large rotation velocity of the pedestrian, which leads to a high rotation velocity after the primary impact against vehicle. On the other hand, the pedestrian rotation angle more often showed ± 90 degrees in SUV or MPV impacts due to the high front-end.

The pedestrian rotation angle during a fall of VRU can lead to various pedestrian ground impact types. How to control the pedestrian rotation angle to prevent the head-ground impact will be a new challenge for vehicle front-end design. Nowadays, new vehicle active safety device can prevent collisions or can brake the vehicle earlier to reduce the impact speed of an accident. Even in a low velocity impacts, head-to-ground impacts can result in a high injury risk. Optimization of the vehicle front-end shape to reduce injury risks in ground contact likely would be beneficial for the VRUs in all impact velocities.

VRU body-ground impact

The landing posture of the VRU (pedestrian and two-wheeler) has a significant influence on the injuries and risk in ground impacts. Head injury risk would be high if the head makes contact to the ground firstly after a collision. Peng et al [6] analyzed of 402 pedestrian and 940 bicyclist accidents from GIDAS database and found that 26% of head injury was caused by the ground surface. Tamura et al. [24] showed that in fender vault pedestrian collisions, the maximum rotational acceleration of the head resulted in higher values owing to ground impact rather than primary head strikes. Vishal Gupta [13] analyzed the effect of the vehicle front end profiles on the pedestrian secondary head impacts to ground and found that the pop up hood actually led to more severe pedestrian secondary head impacts with the ground. Moreover, Crocetta et al. (2015) analyzed 648 pedestrians-to-vehicle impact simulations using the MADYMO. They distinguished six different pedestrian-ground impact mechanisms, and pointed out that the distribution of impact mechanisms was strongly associated with vehicle [25]. Therefore, more influence factors should be considered to protect the secondary VRU ground impact, though many new active safety and passive safety technologies are being applied to prevent the accident occurring or to prevent serious injuries.

Limitations

The impact velocities were estimated by calculating the change of the length of the vehicle body per frame. The manufacturer and the specific model of the vehicle could not be judged from these videos; however, we were able to determine the shape of the vehicle. Due to the limitation of the image definition and the lack of the exact vehicle length, the calculated impact velocity may be of very poor accuracy.

Keywords were used to search the accident videos available on the internet, and the videos that met the requirements were selected from the resulting list. The method used for selecting the videos from the ranking of the results list could skew the sample. The proportion of cases collected during the day at the road junction was larger than the actual case frequency, due to the road monitoring systems providing a larger number of cases at the junctions and video recordings made during the daytime video were clearer.

V. SUMMARY

In this paper, we have analyzed 400 vulnerable road user accident videos (including 200 pedestrians and 200 two-wheelers). The results are as follows:

i. The pedestrian accidents occurred mostly on the straightway, while two-wheelers accidents occurred mostly at the crossroads based on analyzing the video information.
ii. 66% of pedestrian cases and 53.5% of two-wheelers cases had emergency avoidance motions before colliding with the vehicles.
iii. The rotation angles of pedestrian depended on the vehicle frontal shape and impact velocity. In bonnet-type car collisions, they tended to be large with increasing vehicle impact velocity. The kinematics of the two-wheeler have been defined, but the kinematics were more complicated in a side impact.
iv. In the ground impact, the order of VRU body regions making contact against the ground depends on the landing posture. The landing posture depends on the pedestrian/two-wheelers kinematics after the initial impact.

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VIII. Appendix I Screenshot from video

Fig. 1a. Screenshots from videos

IX. Appendix II accident scenarios

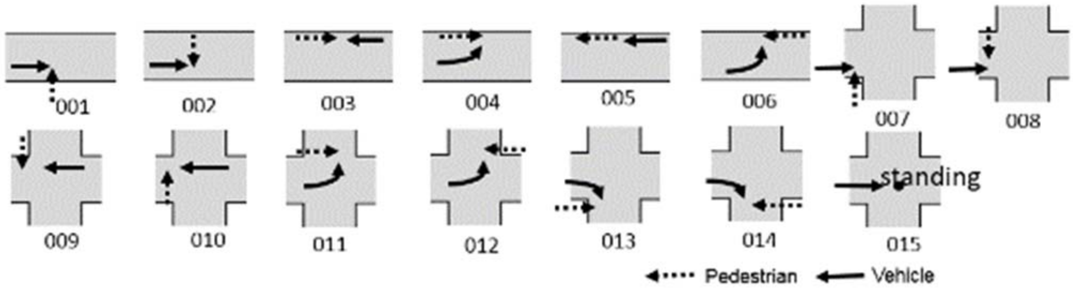

Fig. 2a. Definition of the Pedestrian Accident Scenarios

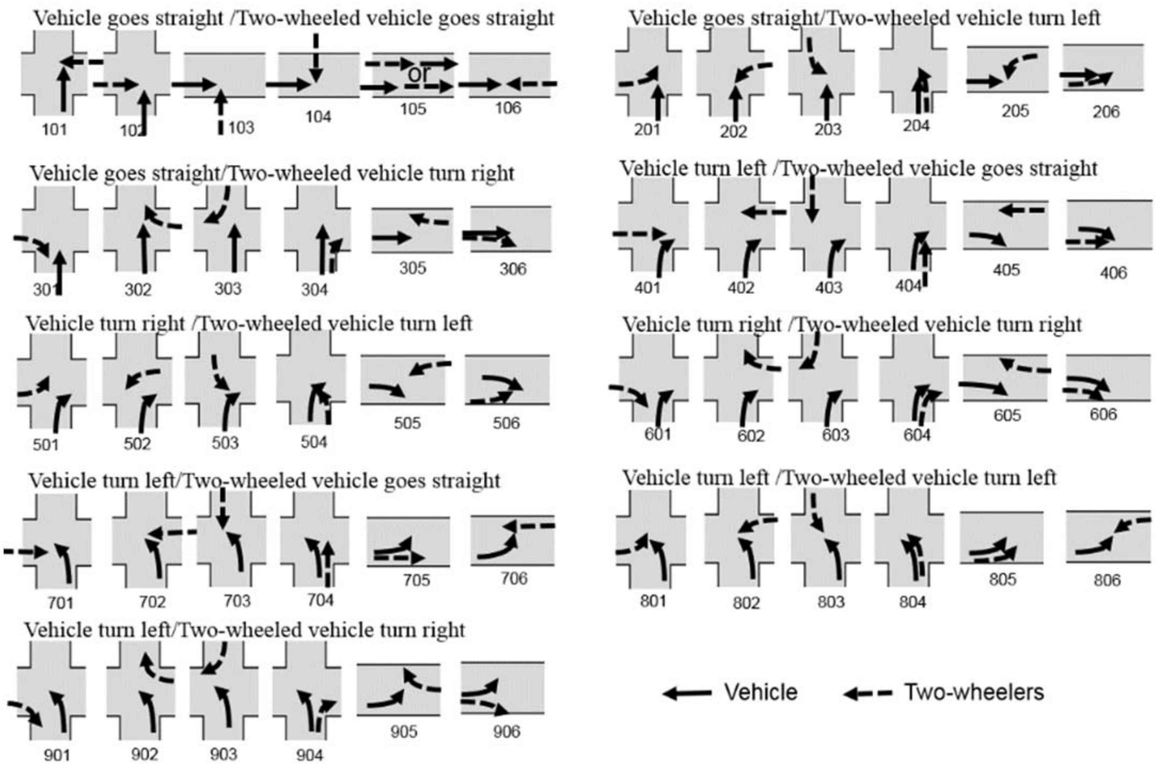

Fig. 2b. Definition of the Two-wheelers Accident Scenarios

X. APPENDIX III: DEFINITION OF THE VRU TRAJECTORY

Fig. 3a. Definition of the pedestrian kinematics and trajectory

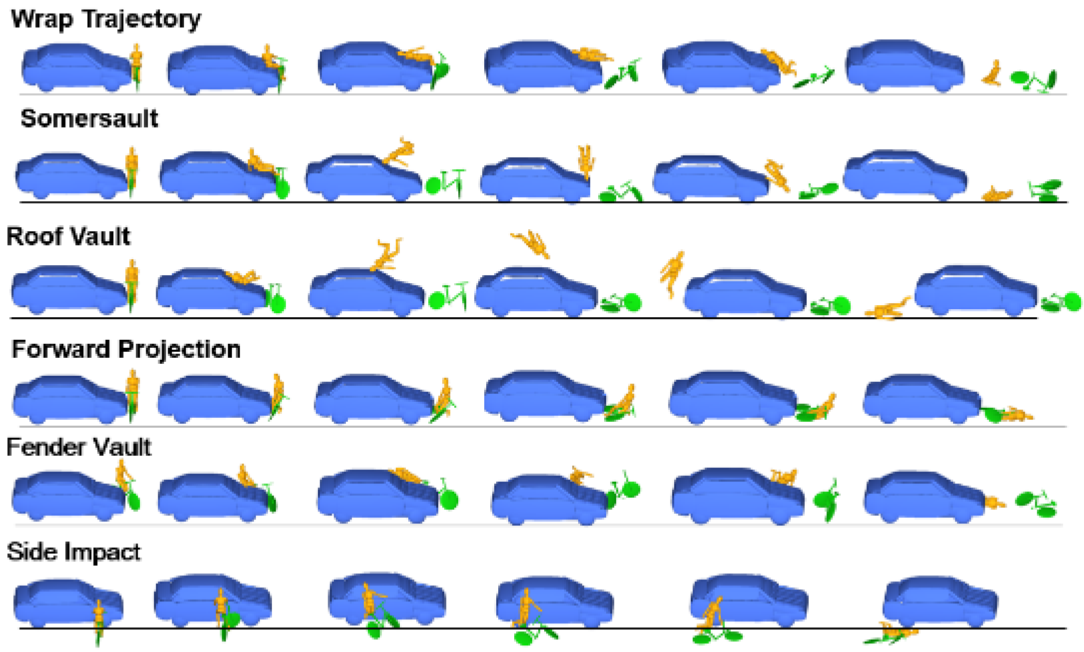

Fig. 3b. Definition of the rider kinematics and trajectory (the bicycle were only used to show the trajectories of the two-wheelers riders)