Load and Impact Conditions for Head Injuries in Car-to-Pedestrian and Car-to-Cyclist Accidents – A Comparison of Real Accidents and Simulations

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Abstract: Pedestrian and cyclist are the most vulnerable road users in traffic crashes. One important aspect of this study was the comparable analysis of the exact impact configuration and the resulting injury patterns of pedestrians and cyclists in view of epidemiology. The secondary aim was assessment of head injury risks and kinematics of adult pedestrian and cyclists in primary and secondary impacts and to correlate the injuries related to physical parameters like HIC value, 3ms linear acceleration, and discuss the technical parameter with injuries observed in real-world accidents based documented real accidents of GIDAS and explains the head injuries by simulated load and impact conditions based on PC-Crash and MADYMO. A subsample of n=402 pedestrians and n=940 bicyclists from GIDAS database, Germany was used for pre-selection, from which 22 pedestrian and 18 cyclist accidents were selected for reconstruction by initially using PC-Crash to calculate impact conditions, such as vehicle impact velocity, vehicle kinematic sequence and throw out distance. The impact conditions then were employed to identify the initial conditions in simulation of MADYMO reconstruction. The results show that cyclists always suffer lower injury outcomes for the same accident severity. Differences in HIC, head relative impact velocity, 3ms linear contiguous acceleration, maximum angular velocity and acceleration, contact force, throwing distance and head contact timing are shown. The differences of landing conditions in secondary impacts of pedestrians and cyclists are also identified. Injury risk curves were generated by logistic regression model for each predicting physical parameters.

Keywords: Pedestrian and cyclist; Accident reconstruction; Head kinematics and injury; Comparison study

INTRODUCTION

In the European Union (EU) 8,000 unprotected traffic participants, pedestrians and cyclists die annually, 300,000 are severely injured and 1.4 million are slightly injured annually in the course of traffic accidents [1]. Within the EU countries, the relative frequency of the pedestrian fatalities varies remarkably from 14% in Sweden to 32% in UK. The pedestrian fatalities in USA are about 5,000 and 3,000 in Japan each year. In China about 25,000 pedestrians are killed in the traffic accidents each year [2]. According to the statistical data, of total the traffic fatalities about 60% were pedestrians, cyclists and motorcyclists during the year 2000 to 2005[3] in China. The vulnerable road users expose a high risk in traffic accidents [4] due to that they participate in public traffic as unprotected persons.

During the last 20 years pedestrian safety has been widely studied and pedestrian protection becomes of increasing concern of the world, especially in the EU. Component subsystem tests for cars proposed by the European Enhanced Vehicle-safety Committee (EEVC/WG10 and WG17) were approved to assess pedestrian protection. The question is now to what extent results for the injury situation based on data of pedestrian accidents also apply to bicyclists, who also are to be protected by this directive. The latter are, however, by using self-protection measures such as a bicycle helmet and the proper motion relative to the motorcar as well as because of the coupled mass system driver-bicycle on the one hand rather similar to vehicle /vehicle collisions, on the other hand also comparable as far as the occurring kinematics are concerned. Thus the question arises whether in consideration of the injury situation and the severity of the accident the demands on the test conditions can also be valued analogously.

Bicycles generally do not have a standardized structure and there is no conformity criterion for the material used, design and construction methods. Hence generic safety standard for bicycle riders have been very difficult to formulate and are not standardized yet. In-depth accident investigation and accidents reconstruction is regarded as one of the efficient means to understand the injury mechanisms in pedestrian and cyclist accidents. Previous studies about pedestrian and cyclist accidents were mainly focused on the relationship between injury descriptions, impact velocities, points of impact et al and for cyclists thrown distances were taken into consideration [5-9] and simulation work has been done very often [10-12]. Furthermore, some statistical and configuration analysis on cyclist accidents in different areas were investigated [13-15].But studies dealing with the combination of simulation and real accident pattern are very rare. Also differences of head injury risks and kinematics of pedestrians versus cyclists were not adequately investigated. Suitable protective strategies would be distinct for pedestrian and cyclist because of the different nature of the two kinds of accidents.

The objective of this study is to identify the load and impact conditions for head kinematics and injury risks of pedestrian and cyclist in both primary and secondary crashes based on in-depth accident investigation and reconstruction results. The knowledge from this study is a prerequisite for developing guidelines to improve safety of vulnerable road users and with this perhaps the conceptual investigation for regular test procedures for cyclist head protection.

METHODOLOGY AND MATERIALS

Accident data collection

Since 1999, the GIDAS (German In-Depth Accident Study) project has collected on-scene accident cases in the area of Hannover and Dresden. Specialist teams go directly to the scene of the accident to collect the necessary information to complete detailed accident reconstructions as well as the medical data about how the involved people were injured and treated. In this way, extensive information about a wide range of fields of research such as " vehicle design for passive and active safety", " biomechanics", "driver behaviors ", "trauma medicine", " rescue services", " road design" and " road conditions" can be collected [16]. Per year in every investigation region approximate 1 000 traffic accidents are documented and per accident 1 000 to 2 000 individual data are collected in a special database. The injuries were classified in accordance with the Abbreviated Injury Scale AIS.

For accident analysis comparing pedestrians and bicyclists the following sampling criterion were employed: (1) solely head-on collisions of motorcars were regarded; (2) solely bonnet type front end passenger cars have been taken into account, accordingly so-called vans and SUVs had been excluded; (3) only collisions had been selected in which the pedestrian and/or bicyclists entered the scene at more or less right angles in relation to the direction of motion of the motorcar (clock system 2.00 to 4.00 o'clock and 8.00 to 10.00 o'clock, Fig.1); (4) to enable a comparison also solely persons taller than 150 cm were regarded. Ultimately n=402 pedestrians as well as n=940 bicyclists remained for a detailed analysis. From the sampled cases, a total of 40 accidents, of which 22 were pedestrians and 18 were cyclists, were selected for reconstruction as following requirements: (1) the impact speed should be greater than 30km/h; (2) the impact locations between pedestrian body segments and accident car should be clearly identified; (3) the injury causations could be easily indentified if the injuries were suffered from during the primary vehicle impact or the secondary road impact; (4) the bicyclists were without helmets protection.

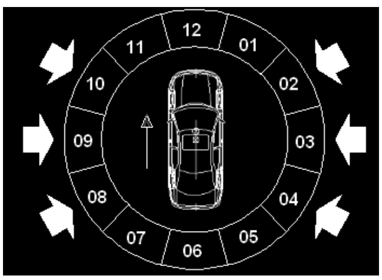


Fig. 1 Impact direction recorded in clock system in GIDAS

Accident reconstruction

Reconstructions in this study included two parts: PC-Crash simulation and MADYMO simulation. Fig.2 shows the schematic illustration of reconstruction combining the two programs. A scaled on-site sketch of the accident scene is important for PC-Crash simulation. Estimated initial impact location, rest positions of accident vehicle and victim, brake traces (if available) and some other marks are involved on the sketch. Vehicle information contains the damages of accident car, type, model and manufacture and so on. Victim information mainly includes the height, weight, year, injury parts and severity. Witness statements may include information about initial stance of victims at the moment of impact; however, not all cases can be witnesses available.

The initial setup of car velocity and dynamics in MADYMO reconstructions were based on the PC-Crash simulation results. The pedestrian orientations and positions in MADYMO simulation are approximated by associating the pedestrian injuries with the car impact points. Parametric studies concerning the velocity of accident car and stance of the pedestrian, pitch angle during the braking were performed in refine iterations to find the best correlations with all indications of in-depth on-site investigations. The final configuration which reproduced the same impact points on the car, the same injuries and throw out distance to the real accident was retained.

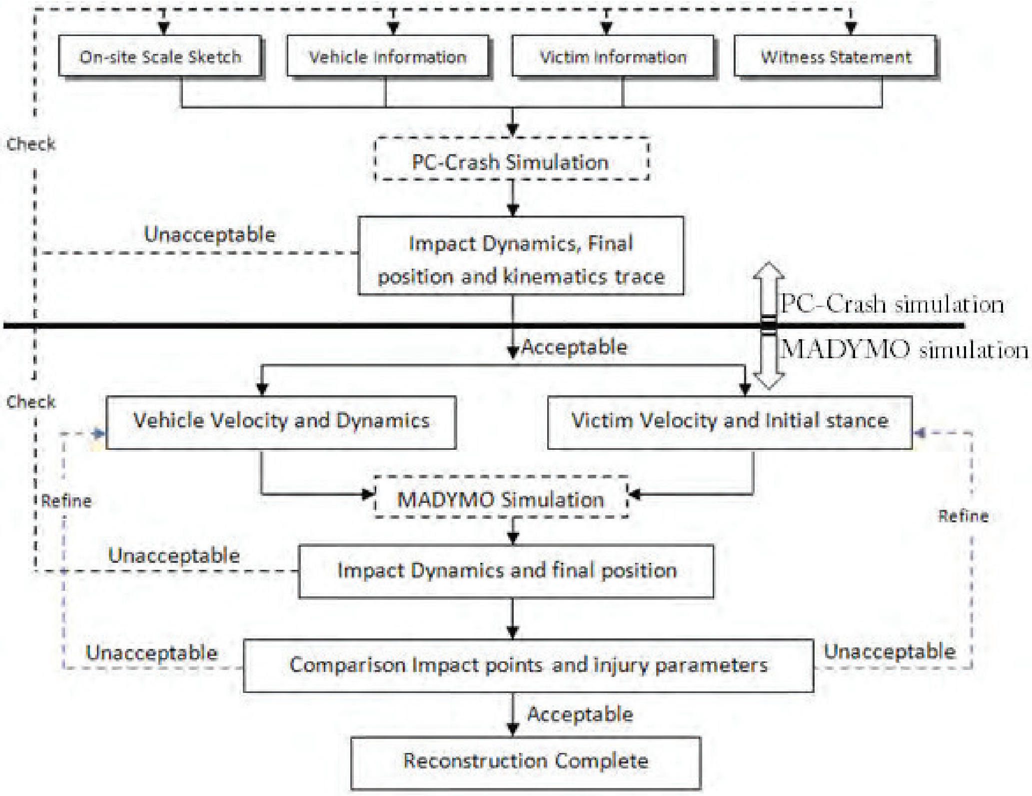


Fig.2 Schematic illustration of accident reconstruction combining PC-Crash and MADYMO

Pedestrian and cyclist simulation model and collision poses

In current study, the MADYMO 50th percentile male pedestrian model [17] was employed as reference dummy, from which the computed models were scaled based on victims` real height and weight. Using the scaling module MADYSCALE, models can be produced of any anthropometry and of any age according to 35 characteristic anthropometric parameters from GEBOD population. The advanced non-linear scaling methods allowed for the scaling of all mechanical parameters, including stiffness and damping. The model consists of 52 rigid bodies and with an outer surface described by 64 ellipsoids and 2 planes. The results from post mortem human subject (PMHS) tests [18-23] were used to evaluate the validity of the model. Additionally, this model was used in previous studies of vehicle-to-pedestrian and vehicle-to-cyclist reconstructions [24].

According to various walking speed, pedestrian walking poses (WP) can be sorted into four types as shown in Fig.3, which represents standing (WP1), normal walking (WP2), fast walking (WP3) and running (WP4). Cycling pose mostly decided by bicycle type. Three cycling poses (CP) were defined base on the angle back angle α. The angle more than 12degree, 5~12degree and 0~5degree correspond to CP1, CP3 and CP3 respectively (Fig.4).

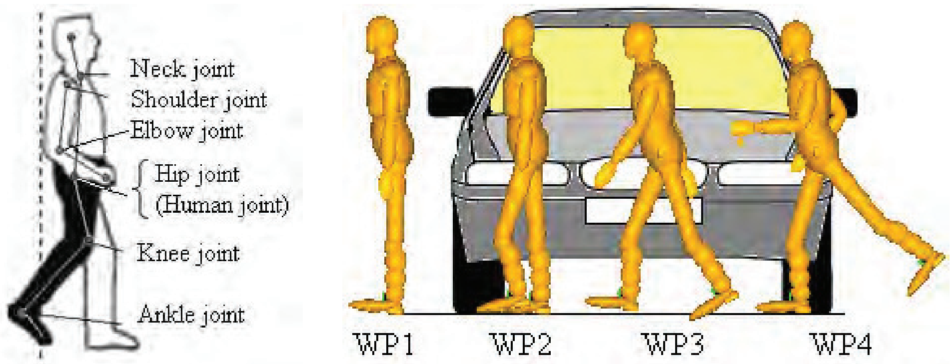


Fig.3 Definition joints and walking pose

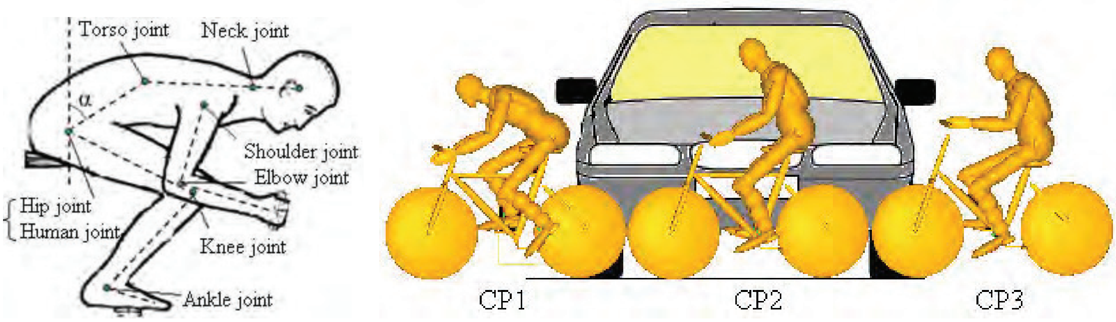


Fig.4 Definition joints and cycling pose

RESULTS

Comparison of epidemiologic data

The distributions of vehicle mass and vehicle were nearly identical for both pedestrian and cyclist accidents. It turned out that approximately 45% of accident vehicles had a crash weight of 1000 to 1300 kg, approximately 30% weighted less than 1000 kg, about 20% had a weight between 1300 and 1600 kg and 4% were heavier than 1600 kg.

As shown in Table 1, the distributions of impact direction in clock system are also nearly the identical for the both populations. Collisions at 9 O`clock and 3 O`clock are the most prevalent. Entering directions of 2 O`clock account for 25.9% for cyclist, this applied to 11.6% for the pedestrian accidents.

Table 1 Impact direction of pedestrian and cyclist

	8 O`clock	9 O`clock	10 O`clock	2 O`clock	3 O`clock	4 O`clock
Pedestrian (%)	2.0	32.9	4.0	11.6	46.2	3.2
Cyclist (%)	5.3	19.6	7.2	25.2	38.0	4.0

70% of bicycle accidents occurred at the impact velocity of up to 20 km/h, whereas only 35% pedestrian accidents happened in this speed range. For cyclist, only 1.4% of the cases occurred at velocities of more than50km/h, and 5% for pedestrians in this range (Fig.5). The collisions with bicyclists were significantly at lower impact speed.

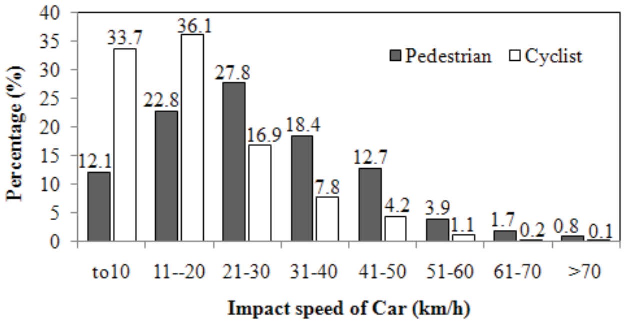


Fig .5 Distribution of car impact speed

Fig. 6 shows that the age distribution of pedestrians and cyclists is nearly with the identical trend, people age 18 to 64 accounts for 57.6% of all pedestrian cases and70.3% of all cyclists. It also shows that pedestrian in the elder group (65 or more) are almost doubled versus cyclist of such age.

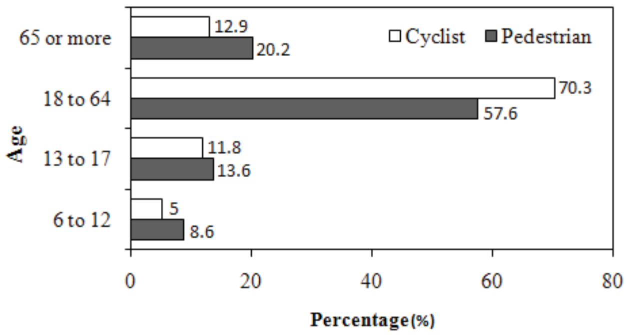


Fig.6 Pedestrian and cyclist age distribution

Fig. 7 indicates that 80.5% of bicyclists were injured slightly with MAIS 1, in comparison to only 57.8% of the pedestrians. Pedestrians have the higher frequency of suffering MAIS 2 injuries at 29.3% of all the cases than for cyclist at 16.2%. Additionally, only 2% of the bicyclists were severely injured (MAIS 3+) in comparison to 10% of the pedestrians. Therefore, we can conclude that the injury severity of the pedestrians is significantly higher than for bicyclists.

The injury distribution per body region denotes in Fig. 8 clearly shows that the percentages of slight injuries (AIS 1-2) at the analyzed body regions of cyclists are all higher than of pedestrians. Accordingly, the risks of sustain serious (AIS 3-6) injuries at head, neck, thorax, pelvis and lower extremities of pedestrians are times higher than cyclists.

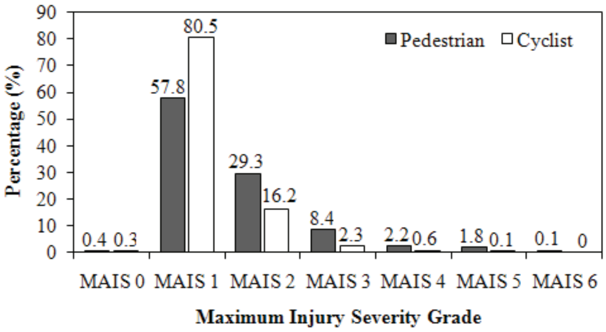


Fig. 7 Pedestrian and cyclist MAIS distribution

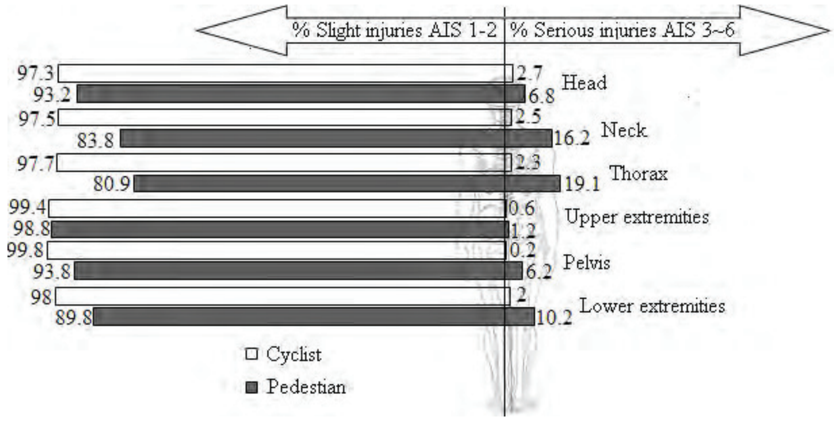


Fig. 8 Pedestrian and cyclist injury severity Grades of body regions

The causes of all impacts and head impacts only to pedestrians and cyclist were compared as shown in Fig. 9. The bumper was the most frequent cause of injuries in accident, 42.7% of pedestrian injuries and 23.4% of cyclist injuries were caused by it. Less frequent causes for pedestrian injuries were followed by windscreen, bonnet edge and bonnet, which in 30.7%, 30% and 24.5% of all impact respectively. For bicycle accidents the injuries caused by windscreen only in 14.7% followed after bonnet (20%) and bonnet edge (19.7%). The road surface generally causes fewer injuries of cyclists at the incidence rate of 59.5% in comparison to 70.3% for pedestrians. Contact with windscreen and bonnet accounts for the main causes of head injuries for both cyclist and pedestrian. Beyond that, the road is responsible for pedestrian and cyclist head injuries at the same rate of 26%.

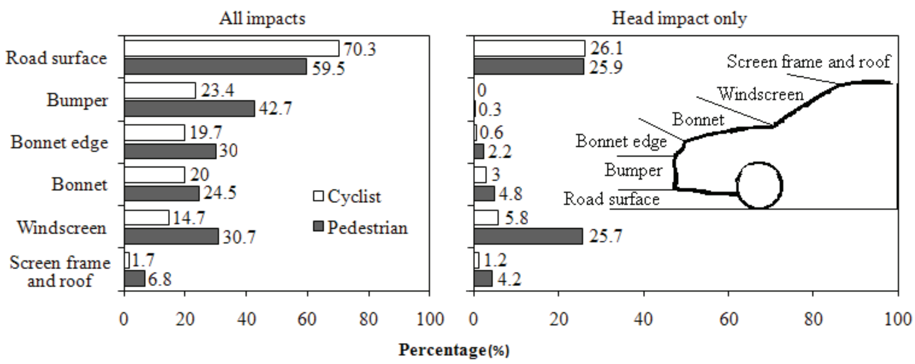


Fig. 9 Cause of injuries (100% all person)

Accident reconstruction results analysis

Detailed information about reconstructed cases is presented in appendix Table 2 and Table 3. The mean values along with stature, weight, center of gravity (C.G) height, car impact speed, pedestrian/cyclist moving speed and relative impact speed are summarized in Table 4. It can be seen that pedestrians and cyclists have nearly the same average stature. Cyclists have 4 cm higher C.G height and 2.7 km/h lower collision speed in average than pedestrians, whereas, the average moving speed of cyclist is nearly trebled versus pedestrians, thus pedestrian/cyclist relative impact speeds, as illustrated in Fig. 10, are at the same level about 50 km/h.

Table 4 Average of basic data for accident reconstruction

	Height (cm)	Weight (kg)	C.G height (cm)	Impact speed (km/h)	Moving speed (km/h)	Relative impact speed(km/h)
Pedestrian	172.5	71	95	50.9	4.2	51.1
Cyclist	169.3	68.2	99	48.2	11.8	49.6

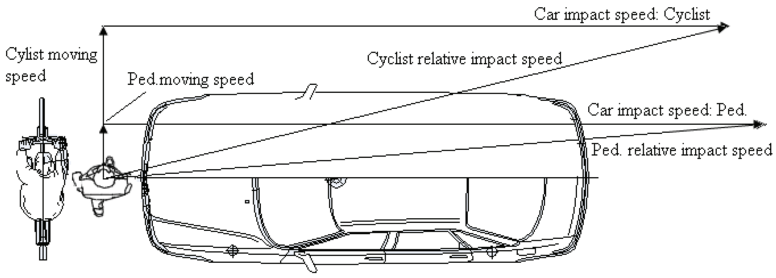


Fig. 10 Pedestrian and cyclist relative impact speed

Head contact points against windscreen, screen frame and roof are plotted schematically on one standard vehicle (Fig .11), similar to the representation found in Otte [15]. For pedestrians, the head struck the windscreen or the screen frame, but did not strike the roof; however, four cyclist heads struck the roof. Apparently, head collisions with windscreen frame and locations close to frame are more likely to result in serious injuries (AIS 3+).

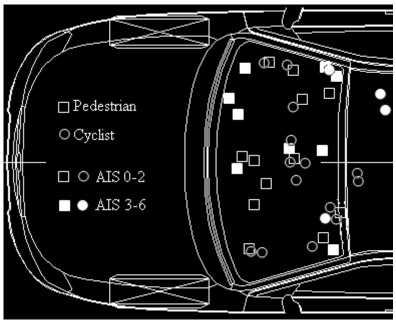


Fig. 11 Distribution of head impact locations

Fig 12 shows the comparison of head relative impact velocity and vehicle impact velocity of pedestrian and cyclist accidents. For pedestrian cases, head impact velocities either higher or lower than the vehicle impact velocities but the head impact velocity level is close to the vehicle impact velocity level. For cyclist cases, an obvious discrepancy shows that all of the head impact velocities are lower than the vehicle impact velocities. The head relative impact velocity averaged 49.7 (± 10.6) km/h in pedestrian cases and 32.5 (± 12.2) km/h in cyclists. Head impact angles occurred between 64.5 and 30 degrees, with a mean value of 47.7 (±10.6) for pedestrians, and between 74 and 11degrees, with a mean value of 39.3 (±20.5) degrees for cyclists.

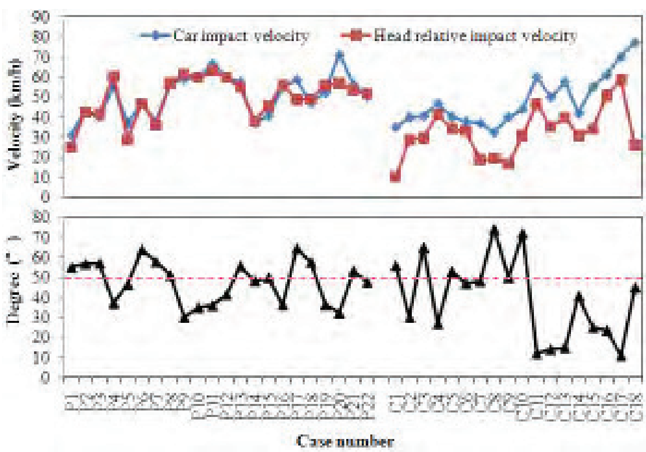


Fig. 12 Head impact angle & head relative impact velocity versus car impact velocity

Head contact time is defined as the time duration between the first contact of human body and the head contact against vehicle. Polynomial regression curves and scatter of data points between car impact velocity and head contact time are compared in Fig. 13. Strong correlations, R^2 = 0.78 for pedestrian and R^2 = 0.63 for cyclist, were found. The average pedestrian head contact time is 107.8 ms with a standard deviation of 27.5 ms, and 146.7 (± 24.2) ms for cyclists. It is considered that pedestrian head contact time is apt to be earlier than cyclists.

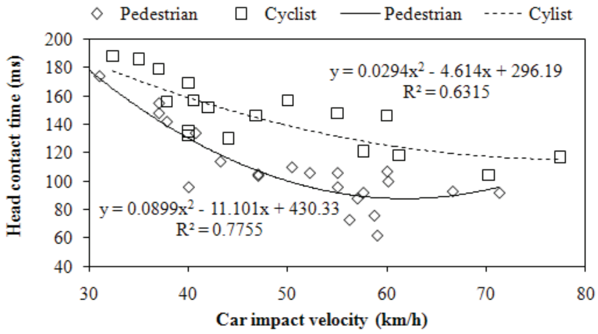


Fig .13 Comparison of pedestrian and cyclist head contact time

The definition of thrown distance in this study is that the distance from the collision position to the body final position, it include three parts: contact phase, flying phase and sliding phase. For both populations, strong correlations are found with R^2=0.83 and 0.81 for pedestrians and cyclist respectively. It is obvious that the longitudinal trajectory functions shows a higher increase when the polynomial regression is depicted for pedestrians than for cyclists (Fig.14). Similar point scatters along the vehicle travelling direction are shown for pedestrians and cyclists, although the cyclist moving speeds are normally higher than pedestrians. One of probable causes is that the transversal thrown distances are influenced a lot by the distance between the first contact points and the vehicle longitudinal axis.

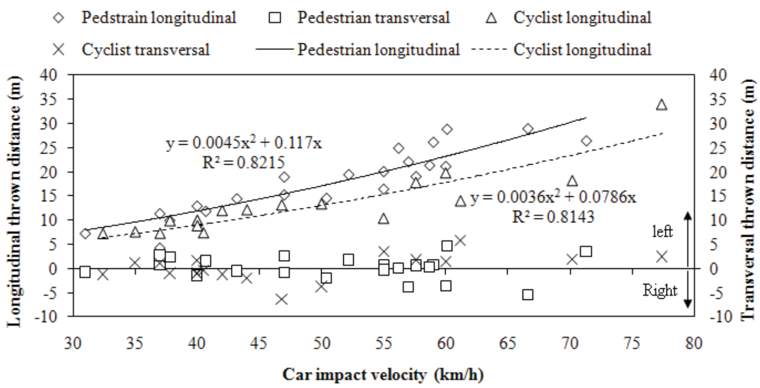


Fig .14 Longitudinal and transversal thrown distances of pedestrian and cyclist

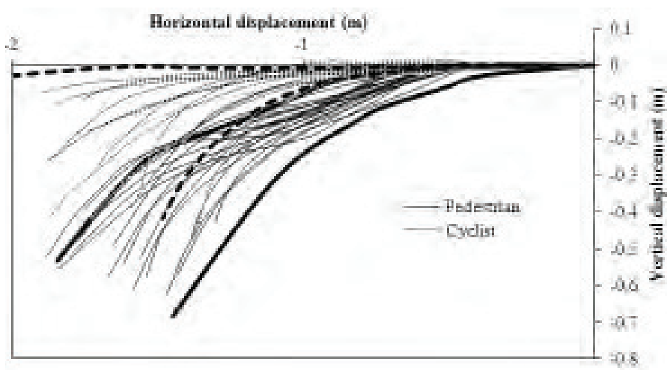


Fig .15 Comparison of pedestrian and cyclist head kinematics

Pedestrian and cyclist head kinematics are denoted by horizontal and vertical head displacements as shown in Fig.15. The trajectory regions are marked by the boundary trajectories with broad format. Compare to cyclists, pedestrians have larger vertical displacements because of the slides of cyclist over the bonnet before the head contact.

Assessment of head injury risks in primary and secondary impacts

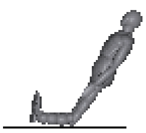
The calculated correlation coefficients (R^2) for polynomial regression models between car impact velocity and head responses are listed in Table 5. The highest coefficient was found between HIC value caused by primary contact (P) of head and car impact velocity for both pedestrian (R^2=0.741) and cyclist (R^2=0.654). The cyclist HIC produced in secondary (S) impact has a stronger correlation (R^2 =0.526) than pedestrians. Weak correlations between contact force and peak linear acceleration in both primary and secondary impacts with impact velocity are shown. Peak angular acceleration in pedestrian and cyclist primary impacts appears to have very low correlation with car impact velocity.

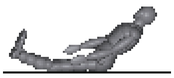
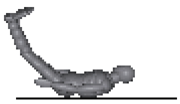
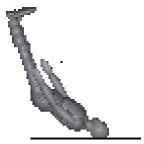
Table 5 Summary of correlation coefficients (R^2) between car impact velocity and head response from polynomial regression analyses

	HIC		Contact force (kN)		Peak linear Acc.(g)		Peak angular Acc.(rad/s^2)		Peak angular Vel.(rad/s)	
	P	S	P	S	P	S	P	S	P	S
Pedestrian	0.741	0.059	0.240	0.222	0.379	0.169	0.009	0.167	0.370	0.223
Cyclist	0.654	0.526	0.325	0.325	0.410	0.266	0.005	0.309	0.097	0.261

In order to investigate the head response in primary and secondary impacts, four landing types were defined based on different first landing parts according to simulation results as shown in Table 6. The averaged secondary HIC values from type 1 and type 4 were higher than that of type 2 and type 3. The mean HIC values in primary contact from type 2 and 3 were less than the values caused by the secondary contact, inverse results show for types 1 and 4. The first landing parts in 83% cyclist cases can be classified into type 2 and type 3, this applied to 45% of the pedestrian cases. The highest average contact force in secondary collision occurred in landing type 4 followed by type 2 and type 1. The average peak values of linear and angular accelerations caused in secondary contacts appeared to be higher than in primary contacts for all four landing types. Landing types 2 and 3 were likely to sustain higher peak angular accelerations but lower peak linear accelerations than type 1 and type 4. For landing type 2 and 3, the mean peak angular velocities in primary and secondary contacts were almost in the same level.

Table 6 Head responses in primary (P) and secondary (S) impacts classified by landing type

Landing type	Case No.	HIC		Contact force (kn)		Peak linear Acc.(g)		Peak angular Acc.(rad/s^2)		Peak angular Vel.(rad/s)	
		P	S	P	S	P	S	P	S	P	S
Type 1  First landing: Tibia and feet	P1	286	139	3.4	0	64.3	68.3	3943	4761	15.5	18.9
	P2	676	244	6.4	6.2	208	122	10236	7578	31	23
	P4	1807	1692	9.13	11.5	133	240	2634	8442	29.8	28
	P5	835	664	6.6	11.4	163	175	17533	9788	31	35
	P9	3554	5192	6.7	11.3	156	279	10150	2090	68	70
	P14	1254	2144	6.7	11.3	119	220	14607	14907	31	33
	P17	3064	2267	6.2	11.5	179	249	26296	2373	46.4	31.2
	P18	1854	1688	6.2	11.3	155	237	677	26403	39.2	59.6
	C12	1071	1482	4.7	11.3	128	261	6606	23633	41.1	40.4
	C16	980	2346	7.5	12.1	176	279	4969	34702	37.3	48.5

	Mean	1538.1	1785.8	6.4	9.8	148.1	213.0	9765.1	13467.7	37.03	38.76
Type 2  First landing: Femur and pelvis	P3	557	693	6.3	11.3	139	173	14418	7020	29.5	57
	P8	2883	751	4.6	11.1	142	184	6699	8445	54.8	35.3
	P12	1841	713	10.1	10.8	148	242	9129	15501	44.2	27.9
	P13	1906	1531	6.8	11.5	158	232	9876	17680	34	28
	P15	1948	1885	9.4	11.3	193	220	22545	9545	39.1	38.8
	P19	2659	1875	12.9	11.5	216	222	10412	23097	29.7	50.5
	P20	7924	71	9.7	5.5	325	33	16933	4274	42	15.8
	C3	341	690	5.1	11.1	70	148	3526	17042	31.4	23
	C6	720	852	5.3	10	87.7	211	5474	12902	26.2	18
	C7	502	906	4.2	11.3	82.7	202.9	5302	18612	35.5	38.5
	C9	482	53	3.2	3.4	94.7	77.1	3834	8619	19.6	18.9
	C13	709	236	3.9	5.7	103	93	7023	72531	38.1	47.7
	C15	784	1226	8.8	12.1	116.8	217.6	6210	32420	28	47.3
	C17	924	2495	4.9	11.3	85.7	267	10140	19003	36.7	54.6
	Mean	1727.1	998.4	6.8	9.9	140.1	180.2	9394.4	19049.4	34.9	35.8
Type 3  First landing: back and thorax	P11	4247	11.2	13.1	10.8	235	214	19069	13844	41.5	49
	P21	2267	4666	4.5	11.3	154	254	2877	17183	58.4	60.1
	P22	2778	3233	10.8	10.8	191	289	42662	24662	31.5	42.4
	C1	269	78	4.3	0.35	63.3	31.8	2733	3445	9.9	8.9
	C2	529	120	4.6	4.7	85	90	4450	6118	85	90
	C4	755	1396	6.8	11.3	109	233	16982	30991	31.9	50.3
	C5	692	153	6.3	0	155.4	54	13406	3634	28.2	22.8
	C8	321	758	3.7	10.2	74	198	13221	21163	11.1	26.5
	C10	635	132	4.9	3.7	87.7	66.6	5866	6459	30.9	24
	C14	792	145	3.9	4.7	105	90	7811	20670	36.6	42
	C18	2701	1791	7.24	11.3	194.3	208	6606	23633	41.1	40.4
	Mean	1453.3	1134.8	6.4	7.2	132.2	157.1	12334.8	15618.4	36.9	41.5
Type 4  First landing: Head	P6	2779	1656	5.9	12	158	224	8976	17260	34.6	38.7
	P7	1072	1423	5.9	11.3	90	206	5684	15020	30	41
	P10	1904	1665	12.3	11.1	148	47	7899	26292	29	56.6
	P16	1452	3206	12.3	12.7	214	259	21410	1835	40.2	74.5
	C11	802	2344	9.3	11.3	119	243	9546	16856	34.5	60.6
	Mean	1601.8	2058.8	9.1	11.7	145.8	195.8	10703.0	15452.6	33.7	54.3

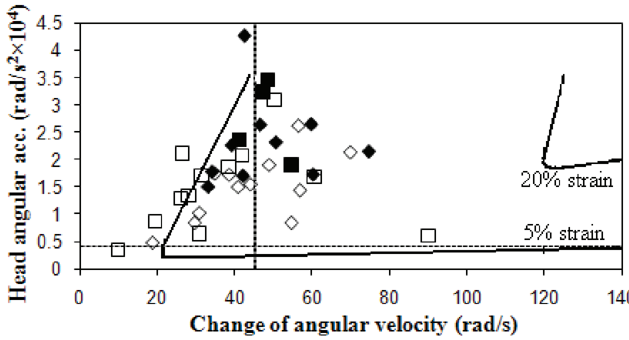


Fig. 16 Threshold corridor for angular velocity and acceleration

Löwenhielm suggested that bridging veins started to rupture from 4500 rad/s^2 angular acceleration or a change of angular velocity from 50 rad/s [18]. A criterion for diffuse axonal injury (DAI) that critical strain for moderate to severe DIS ranged from 5 to 10% was proposed by Margulies and Thibault [19]. The calculated injury parameters of all the cases are illustrated in Fig.16, all of the cases with severe (AIS 3-6) are within the area exceeded the 5% strain level, which correspond well with the injury code (AIS) occurred in the accidents.

Correlation of head injury risk and calculated physical parameters

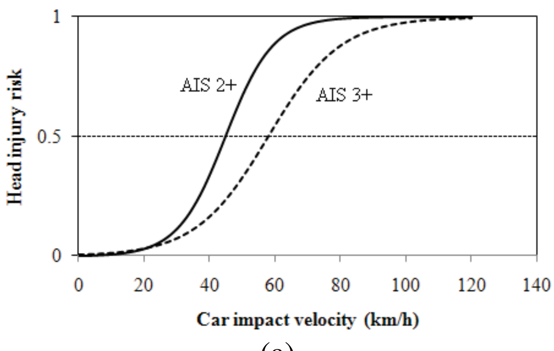
Logistic regression is a form of regression which is used when the outcome (response) variable is binary and the predictor variables are continuous, categorical, or both. S-shaped regression curves were generated to illustrate the relationship. In this study, the examination of brain injury risks p(x) relative to the calculated injury parameters x was performed with the logistic function:

$$p(x) = 1/\left(1+e^{(\alpha-\beta x)}\right)$$

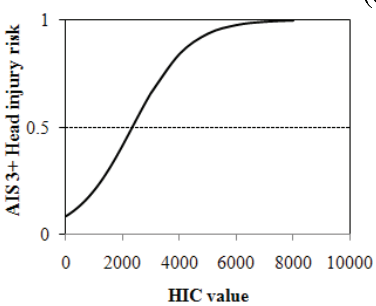
Where α is the intercept and β is the regression coefficients of x. Parameters α and β are determined using maximum likelihood method to maximize the function's fit to the data. Goodness-of-fit of the statistical model was examined by means of chi-square χ^2. The probability value P is associated with χ^2. The relationship between injury and predictor variables is statistically significant when the probability value is at the level of $P \le 0.05$. When $x = \alpha/\beta$, p(x) has a bending point with a maximum or minimum value for the slope and p(x) = 50% level. So the value of α/β gives the median of the distribution of predicted head injuries over values of x.

Table 7 Logistic regression coefficients and statistics for probability of head injury

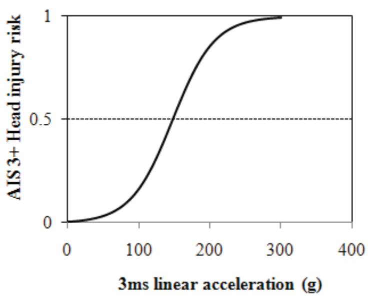
Predictor variables	Head injury code	α	β	χ2	p	α/β
Car impact velocity (km/h)	AIS 2+	6.1698	0.1377	14.154	0.0023	44.8
Car impact velocity (km/h)	AIS 3+	5.2422	0.0906	7.9471	0.012	57.9
HIC value	AIS 3+	2.3269	0.001	9.8931	0.0109	2327
3ms linear acceleration (g)	AIS 3+	5.0404	0.0341	14.226	0.0036	147.8
Resultant angular acceleration (rad/s^2)	AIS 3+	1.7988	0.0001	3.9177	0.0907	17988
Resultant angular velocity (rad/s)	AIS 3+	1.9434	0.0298	1.8537	0.1880	65.2



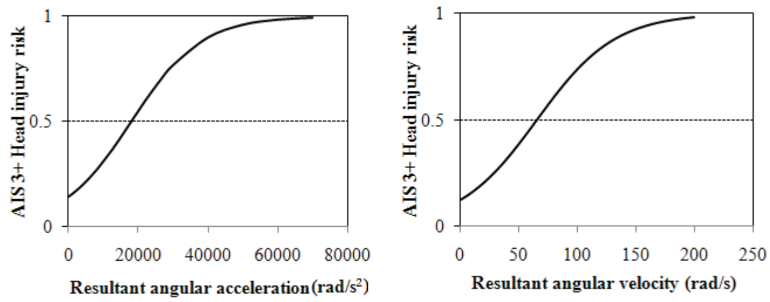
(a)



(b)



(c)



(d) (e)

Fig. 17 Logistic regression curves for car impact velocity, HIC value, 3 ms acceleration, angular acceleration and angular velocity

In this study, a logistic regression analysis was conducted to identify the correlations of head injury risks and calculated physical parameters. The predictor variables investigated were: vehicle impact velocity, head impact velocity, primary HIC value, 3 ms contiguous linear acceleration, maximum head angular acceleration and maximum head angular velocity. In Table 7, the values of α, β, χ2, p and α/β were listed. The logistic regression plots for observed injury outcomes and predictor variables are presented from Fig. 17 (a) to Fig. 17 (e).

Fig.17 (a) shows the correlation between AIS 2+ and AIS 3+ head injury risks and vehicle impact velocity, which correspond to the p values of 0.0023 and 0.012 respectively that are less than the significant probability value of 0.05. As shown in Fig.17 (a), 50% probability of vehicle impact velocity to cause AIS 2+ and AIS 3+ head injuries correspond to 44.8 km/h and 57.9 km/h respectively. The correlations between HIC value, 3ms contiguous linear acceleration, resultant head angular acceleration and resultant angular velocity and AIS 3+ head injury risks are with calculated p value 0.0109, 0.0036 , 0.0907 and 0.188 respectively. The predicted values of 50% probability to cause AIS 3+ head injuries are 2327, 147.8g, 17988 rad/s^2 and 65.2 rad/s respectively.

DISCUSSION

In this study, a subsample of n=402 pedestrians and n=940 bicyclists from GIDAS database, Germany was used for pre-selection, on which general epidemiologic analysis was performed. n=22 pedestrian and n=18 cyclist cases that the impact conditions, such as the height of person, impact direction, impact location on car and car front shape were mostly the same were sampled to reconstruct and to make a comparison study on load and impact conditions for head injuries of the two groups. Accident analysis show that vulnerable road users were most frequently struck from the lateral direction, this is comparable with the findings of Mclean et al. [25]. Car impact speed distribution in Fig. 5 shows bicyclists exposed to significantly lower impact speeds than pedestrians. Identical trends of age distribution and vehicle crash weight were shared by both populations. Upon injury, the risk of severe injuries for pedestrians is significantly higher than for bicyclists. The bumper was the most frequent cause of injuries in both pedestrian and cyclist accidents; this followed by windscreen, bonnet edge and bonnet. The road is responsible for pedestrian and cyclist head injuries at the same rate of 26%.

In this paper, accident reconstructions were carried out by using PC-Crash and MADYMO programs with the aim focus on head responses. It could be observed that in general, the kinematics of pedestrian and cyclist in PC-Crash and MADYMO program were similar and corresponded well with crash scene data in terms of impact location, throw out distance and resting location. From the data listed in Table 4, we can found that the mean relative impact velocities of the two group cases were at the same level about 50 km/h. Pedestrian head impact velocities either higher or lower than the vehicle impact velocities but the two are at the close level, however, an obvious discrepancy appears for cyclists that all of the head impact velocities are lower than the vehicle impact velocities (Fig.12). By investigating the relationships between vehicle impact velocity and throw out distance and head contact time with quadratic regression model, it can be found that there are lots of differences in kinematics between pedestrian and cyclist. Differences also exist in head trajectories as shown in Fig.15.

Strong correlations were found between HIC value caused by primary contact for both pedestrian and cyclist, this applied to the cyclist secondary HIC value. As we can see from Table 6 that the secondary head injury parameters affected a lot by landing type. Secondary contacts in landing type 1 and type 4 are likely to cause more serious injuries to head than type 2 and 3. 83% cyclists involve in landing type 2 and type 3 in comparison to 45% of the pedestrians.

Logistical regression approach was employed to relate vehicle impact velocity to AIS 2+ and AIS 3+ head injury risks as well as primary HIC value, 3ms contiguous linear acceleration, resultant angular acceleration and resultant angular velocity to AIS 3+ head injury risk. From the statistic results, it could be suggest that in urban areas the traffic speed should be lower than 45 km/h for the protection of vulnerable road users. Impact speed at about 58 km/h could cause AIS 3+ severe head injuries with probability of 50%. The regulatory limit of HIC value 1000 is widely accepted as the head injury criterion, which represented a 16% risk of life-threatening brain injury [26]. According to Zhang [27], the mean HIC value, resultant linear acceleration and the peak resultant rotational acceleration for minor injury cases was 351 (±169), 103 (±30) g and 7,354 (±2,897) rad/s^2 respectively. In the present study, HIC 1000 correspond to a 20.9% possibility of AIS 3+ head injuries and the predicted HIC value, 3ms linear acceleration and resultant angular acceleration for 50% probability of AIS 3+ head injury risk are 2327, 147.8g, 17988 rad/s^2 and 65.2 rad/s respectively, which are comparable to previous studies.

It was often difficult to identify the injuries causation by primary and secondary impact; only in case of comprehensive description of the kind of injuries a high correlation of assignment of an injury to the right subject was possible. Reconstruction car models were developed based on experienced methods. More accident cases are needed to get more persuasive conclusions.

CONCLUSION

There is a comparability of these two kinds of accidents. Identical trends of age distribution, stature (height and weight), vehicle crash weight and relative impact velocity were shared by both populations. However, due to the different structure of the collision mass systems and initial impact postures, bicyclists exposed to significantly lower impact speeds and they are injured less frequently and less severely than pedestrians in particular at the head and legs.

From the results of reconstruction, head collisions with windscreen frame and locations close to frame are more likely to result in serious injuries; cyclists sustain obvious lower head impact velocities and also more fluctuant head impact angle than pedestrians. Additionally, cyclist have a shorter longitudinal thrown distance and longer head contact time. Compare to pedestrians, cyclists have larger horizontal displacements because of the slides of cyclist over the bonnet before the head contact. Injuries from the secondary contact are affected significantly by landing type. Various suitable protective measures should be taken to gain effective protections for pedestrian and cyclist. The results of this study give the answers for directives currently applied to vehicle design for pedestrian protection to a large extent cover the requirements for the protection of cyclists.

Vehicle impact velocity that could result in a probability of vulnerable road users 50% AIS 2+ and AIS 3+ head injuries are 44.8 km/h and 57.9 km/h. Critical values of HIC value, 3ms linear acceleration, angular acceleration and resultant angular velocity for predicting AIS 3+ head injuries are 2327, 147.8g, 17988 rad/s^2 and 65.2 rad/s respectively.

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APPENDIX

Table 2 Summary of Pedestrian Information

Case NO.	Model	Age	Height (cm)	Weight (kg)	Direction (O`clock)	Speed(km/h) Vehicle	Speed(km/h) Ped.	MAIS head
P1	Opel ASTRA	57	175	80	3	31	0	0
P2	VW Golf4	63	173	68	9	43.2	5	0
P3	FIAT FIORION	55	168	54	8	40	5	0
P4	VW Golf 3	26	184	70	3	55	6.1	1
P5	BMW 3ER	37	165	66	3	37	0	2
P6	Mercedes E220	35	176	76	3	47	7	2
P7	Ford Mondeo	18	182	72	9	37.8	10	2
P8	Mitsubishi CA.	67	166	80	9	57	3	2
P9	Mercedes A 140	27	160	60	2	59	4.7	2
P10	Mazda 6	41	186	78	9	60	0	2
P11	Seat 0	19	180	65	3	66.6	9	2
P12	Opel Vectra A	34	171	90	9	60.1	10	2
P13	VW PASSAT	54	170	60	3	57.6	5.8	3
P14	Opel CORSA	57	180	77	2	37	1.5	3
P15	Peugeot 307	32	185	80	9	40.7	10	3
P16	Renualt CLIO	54	170	70	9	55	4.7	4
P17	VW PASSAT	89	153	61	3	58.7	3.2	4
P18	Opel ASTRA	66	168	55	9	47	0	4
P19	Opel Corsa city	23	180	80	9	52.2	0	5
P20	VW PASSAT	51	175	90	10	71.3	3.6	6
P21	Toyota Corolla	83	160	70	9	56.2	2	6
P22	BMW 316i	64	168	60	4	50.4	0	6

Table 3 Summary of Cyclist Information

Case NO.	Model	Age	Height (cm)	Weight (kg)	Direction (O`clock)	Speed(km/h) Vehicle	Speed(km/h) Cyclist	MAIS head
C1	VW Golf v1.9	67	178	78	9	35	9	0
C2	Renault CLIO	14	165	51	2	40	13	0
C3	MAZDA 626	44	179	74	2	40.5	20	0
C4	Opel OMEGA	25	185	72	2	46.8	25	0
C5	Opel ASTRA	11	153	54	9	40	10	1
C6	Opel ASTRA	56	152	54	10	37.8	10	1
C7	FIAT PUNTO	36	173	110	9	37	10	1
C8	VW PASSAT	47	168	50	9	32.4	5.4	1
C9	Ford KA	14	160	45	2	40	10	1
C10	AUDI A3	28	164	57	4	44	15	1
C11	Mercedes E220	37	177	72	2	60	5.4	1
C12	VW Golf variant	80	156	53	3	50	14.8	1
C13	Ford Fiesta CLX	32	176	82	9	57.6	7.2	2
C14	Peugeot 206	57	159	88	9	42	5	2
C15	Opel OMEGA	38	179	74	10	55	16.2	3
C16	Opel Astra	59	170	60	3	61.2	6.2	3
C17	Opel Astra	77	168	72	10	70.2	15.2	4
C18	FIAT PUNTO	63	185	82	3	77.4	15.5	5