A study of kinematics of adult pedestrian and head impact conditions in case of passenger car collisions based on real world accident data

Yong PENG[1,2], Caroline DECK[2], Jikuang YANG[1,3], Dietmar OTTE[4], Remy WILLINGER[2]

Abstract The aim of this study is to study the kinematics of adult pedestrians and assess head injury risks based on real-world accidents. A total of 43 passenger car versus pedestrian accidents were selected from accident databases for simulation study. According to real-world accident investigation, accident reconstructions were conducted using multi-body system (MBS) pedestrian and car models under MADYMO environment to calculate head impact conditions in terms of head impact velocity, head position and head orientation. Pedestrian head impact conditions from MADYMO simulation results were then used to set the initial conditions in a simulation of a head striking a windscreen using finite element (FE) approach. The results showed strong correlations between vehicle impact velocity and head contact time, throw distance and head impact velocity using a quadratic regression model. In the selected samples, the results indicated that AIS 2+ and AIS 3+ severe head injuries with probability of 50% are caused by head impact velocity at about 33 km/h and 49 km/h respectively. Further, the predicted head linear acceleration, HIC value, resultant angular velocity and resultant angular acceleration for 50% probability of AIS 2+ and AIS 3+ head injury risk are 116 g, 825, 40 rad/s, 11368 rad/s^2 and 162 g, 1442, 55 rad/s, 18775 rad/s^2 respectively, and the predicted value of 50% probability of skull fracture is 135 g.

Keywords Pedestrian, Accident reconstruction, Dynamic response, Head injury

I. INTRODUCTION

Pedestrians are considered to be the largest group of vulnerable road users. Every year thousands of pedestrians are killed in vehicle-to-pedestrian accidents. In China, more than 65,225 persons were killed in 2010, of which pedestrians accounted for 25%, the highest proportion of the total traffic fatalities [1]. In Germany, 440,000 road users were injured in 2004, half of these aged between 25 to 65 years old, and 5800 fatalities were registered in that year of which 14% were pedestrians [2]. According to the Institute for Traffic Accident Research and Data Analysis of Japan, the number of road accident fatalities was 4,863 in 2010 and pedestrians accounted for 35% [3]. Statistics from Europe showed that 7,491 pedestrians were killed in road traffic accidents, which is 20% of all fatalities in 2008 [4]. In vehicle-to-pedestrian accidents, head injuries are one of the most common injury types and can lead to lifelong disability or death. International Harmonized Research Activities (IHRA) investigated and analyzed 1,605 pedestrian accidents in Australia, Germany, Japan and the USA, and the results showed that head injuries accounted for 31% of 3,305 AIS 2+ (Abbreviated Injury Scale) injuries [5]. Neal-Sturgess et al. [6] reviewed the APROSYS European in-depth pedestrian database from 1997 to 2004 and found that the most frequently injured body regions were the head and lower limbs. A statistical analysis was undertaken by Fildes et al. [7] using real world crash data and the results showed that the head and face regions accounted for a sizeable proportion of serious injuries to children (29%) and to adults (28%) as per the University of Hannover data. Head injuries alone of AIS 4+ severity accounted for 20% of fatal injuries in Australia.

The automobile windscreen, which pedestrians strike frequently, has been identified as one of the main contact sources for pedestrian head injuries. Otte reported that the windscreen was the most frequent vehicle source of head injury in 543 accident cases [8] and Mizuno reported that windscreen glass was the leading source of head injury for adult pedestrians in the Summary Report of IHRA Pedestrian Safety Working Group activity [5].

Many studies on vehicle-to-pedestrian collisions have been conducted and pedestrian protection has

1 Research Center of Vehicle and Traffic Safety, State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, Hunan University, 410082, China; 2 Institute of Fluid and Solid Mechanics, University of Strasbourg, 67000, France; 3 Department of Applied Mechanics, Chalmers University of Technology, Sweden; 4 Accident Research Unit, Medical University of Hannover, 30625, Germany.

become an increasing concern in the world. In order to study injury biomechanics of pedestrians in vehicle impacts, a biofidelic model of the human body was developed by Yang under the MADYMO program [9]. Peng et al. investigated adult and child pedestrian head impact conditions in different types of vehicles and found that the head impact condition is affected by the vehicle type, impact speed and pedestrian gait [10]. Epidemiological studies were carried out to assess the typical characteristics of these accident scenarios. Real world databases [11, 12] have been established to understand injury mechanisms and tolerances of the living human body and to provide the operational framework for investigating real world pedestrian scenarios. Accident reconstructions based on real world data have also been conducted [13-15]. However, studies on the combination of simulation and real pedestrian accident patterns and the correlations of the calculated parameters with actual pedestrian head injuries are very rare. In MADYMO, the MBS model is realistic at simulating pedestrian kinematics and is computationally efficient; however, the MBS model cannot exactly calculate physical parameters to predict head injury, and defining the exact stiffness in MADYMO is always a difficult problem.

In this study, accident reconstructions were carried out using a combination of MBS and FE methods. A total of 43 passenger car versus pedestrian accidents were selected from the In-depth Investigation of Vehicle Accidents in Changsha (IVAC) and the German In-Depth Accident Study (GIDAS) databases for simulation study. MBS accident reconstructions were done using MBS pedestrian and car models under MADYMO environment, based on real-world accident investigation. The head impact conditions at the time of head impact with windscreen were obtained from MBS simulation results and these conditions were input into the Hybrid Ш head FE model to compute the head injury parameters. The objective of the current study is to analyse the load and impact conditions for the head and to assess the head injury risks of pedestrians based on reconstruction results.

II. METHODS

Source of Data

In this study, all data used are from the In-depth Investigation of Vehicle Accidents in Changsha (IVAC) [11] and the German In-Depth Accident Study (GIDAS) [12].

Since 2006, the IVAC has collected on-scene accident cases in Changsha that is the capital city of Hunan province located in the middle of China. The team consists of researchers from Hunan University, medical and traffic authority sectors. When an accident is reported, the researchers travel to the scene to collect onsite accident data together with traffic police. The final position of the pedestrian and the vehicle after the accident, skid marks, the pedestrian contact points on the vehicle and the condition of the road at the scene are recorded. Pedestrian data, such as age, gender, height, weight and injury details, are obtained from the emergency hospital. The severity of the pedestrian injuries is assessed using the Abbreviated Injury Scale 1998 revision.

The GIDAS has collected on-scene accident cases in the area of Hannover and Dresden since 1999. 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 behavior, trauma medicine, rescue services, road design, road conditions and victim injuries is collected. Furthermore, the injuries are classified in accordance with the Abbreviated Injury Scale version 1998.

A total of 43 pedestrian cases were selected from the IVAC and GIDAS databases, 15 cases from IVAC and 28 from GIDAS. These sampled cases met the following conditions: (1) pedestrian height between 150 cm and 185 cm and weight more than 50 kg; (2) the impact speed over 20 km/h; (3) clearly identified impact locations between pedestrian body segments and accident car to relate contact points and injuries. Details of these 43 cases are listed in the Appendix.

MBS Accident Reconstruction Examples

Two cases from the IVAC database illustrate the methodology of reconstruction. In the selected cases, one pedestrian struck the centerline of the vehicle and the other pedestrian struck the vehicle's side.

IVAC 7: A male pedestrian was hit by a Honda (2001 model). The traveling speed was estimated at about 60 km/h. The pedestrian was running across the street when the car was traveling near the middle line. The driver caught sight of the pedestrian and braked the car. The pedestrian's leg impacted the fender and his head impacted the windscreen. Throw distance was 12.4 m and Wrap Around Distance (WAD) was 2.3 m. The pedestrian was running cross the road from left to right at an initial speed of about 7 km/h. The injuries were scalp hematoma (AIS 1), right knee laceration into joint (AIS 3) and right tibia fracture (AIS 3).

IVAC 14: The car was traveling straight ahead and the pedestrian was attempting to cross the road from left to right. The driver claimed that he did not see the pedestrian until he felt the impact with the car body. He steered the car left instinctively and then steered right. The pedestrian was thrown about 18 m. The vehicle's traveling speed was estimated at about 60 km/h. The pedestrian's injuries included a cerebral contusion (AIS 3) and hematoma (AIS 2), fatal head injuries (multiple laceration) (AIS 6), and right tibia (AIS 3) and fibula (AIS 3) fractures.

As shown in Figure 1 and Figure 2, the pedestrian models and vehicle models are constructed in MADYMO. A validated MBS pedestrian model [16] developed by Yang et al. is used as the basic pedestrian model. In the reconstruction, the basic pedestrian model is scaled according to the real height and weight of the victim using the "GEBOD" code within MADYMO.

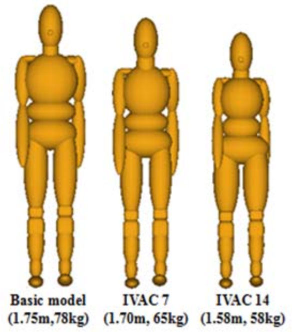


Figure 1 Basic and scaled pedestrian models for reconstruction

Figure 2 Car models for reconstruction

The vehicle geometry and stiffness determine the kinematics of the pedestrian in the accident. Therefore, facet car models were developed based on the drawings of production cars with the same model and year as the accident cars in order to get accurate definition of the front end geometry of the car. The contact stiffness of vehicle front components was obtained according to Martinez et al. [17].

Windscreen FE Model

Nowadays, the polyvinyl butyral (PVB) laminated windscreen is widely used in passenger cars. The PVB laminated glass is obtained by pressing together two pieces of glass plate and one piece of PVB film under high temperature condition. The function of the interlayer is to prevent the glass plies from shattering on impact, thus it greatly reduces the possibility of injury caused by sharp pieces of flying glass. The mechanical properties of windscreens are determined by both glass and PVB layers. In this study, a windscreen FE model was developed using two layer shell elements with tied element connection: a layer of shell element for glass and the other layer of shell element for PVB [18]. The glass layer was modeled by shell elements which fail when they reach a maximum stress. The PVB layer was modeled with membrane elements, using a hyper-elastic material.

The windscreen model was validated against impact test results. The headform used in the test was a standard EEVC adult headform impactor with a total weight about 4.8 kg. As shown in Figure 3, the headform was propelled to hit the centre and the side of the windshield at an angle perpendicular to the windscreen at a speed of 40 km/h [19]. In order to validate the windscreen FE model, simulations were conducted according to the test condition. The fracture pattern of the windscreen and the magnitude and pulse duration of the head linear acceleration in the simulation were compared with the corresponding impact test. As shown in Figure 4, the simulated windshield models have a similar crack pattern as in the test. Furthermore, the simulated linear accelerations have a similar shape and peak value as those in the test which indicates that the windscreen FE model is acceptable (Figure 5).

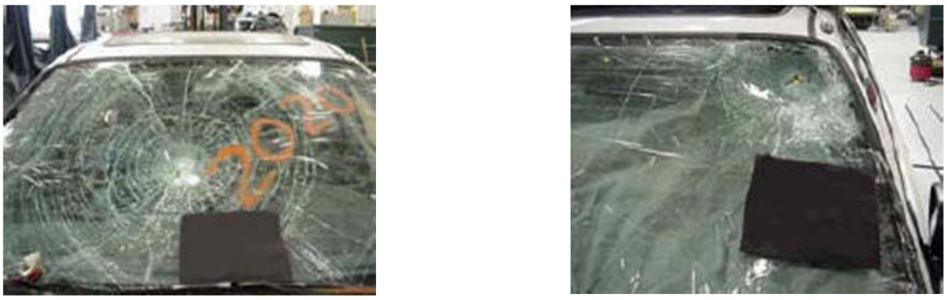


Figure 3 Fracture pattern of windscreen during headform impact tests

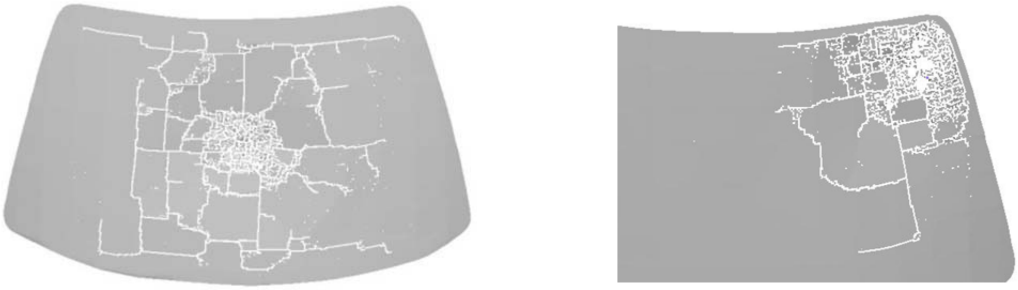


Figure 4 Fracture pattern of windscreen during simulations

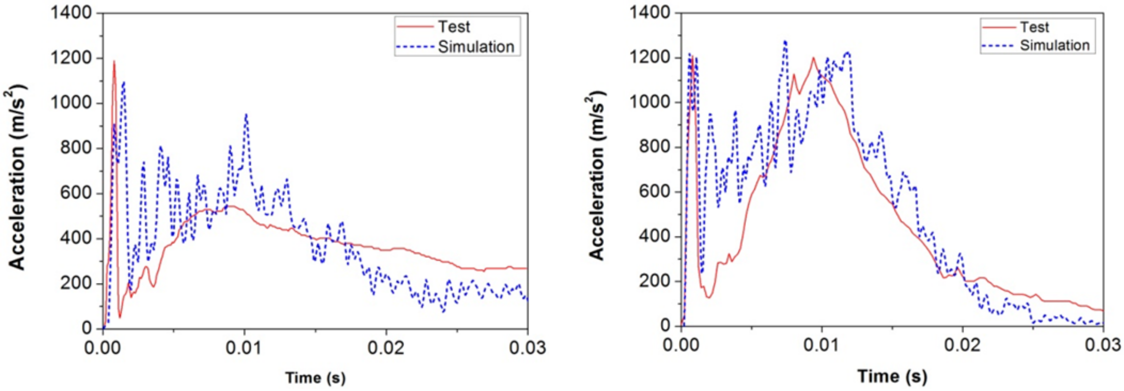
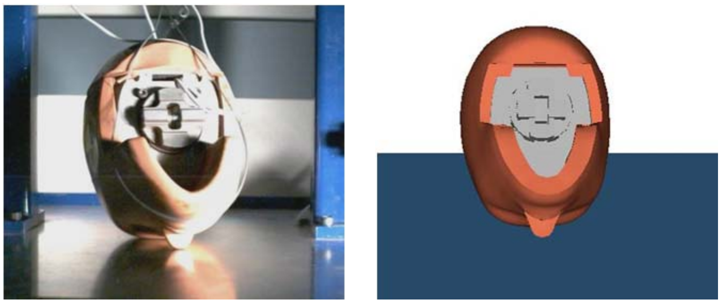


Figure 5 Comparison of headform accelerations during impact test versus simulation

Hybrid III Head FE model

The Hybrid Ⅲ 50th percentile head FE model was employed in this study. The head FE model was developed by NCAC (National Crash Analysis Center). The total headform includes 15492 nodes and 21917 elements and the effective mass is 4.65 kg (Figure. 6b). In order to validate the Hybrid Ⅲ head model, the experiment in which the headform was dropped from a height of 376 mm was simulated, as shown in Figure 6. Figure 7 shows that the magnitude and pulse duration of the headform linear acceleration versus time in the simulation agreed well with the corresponding experimental impact test.



a Test b Simulation

Figure 6 Headform drop test (left) and simulation (right)

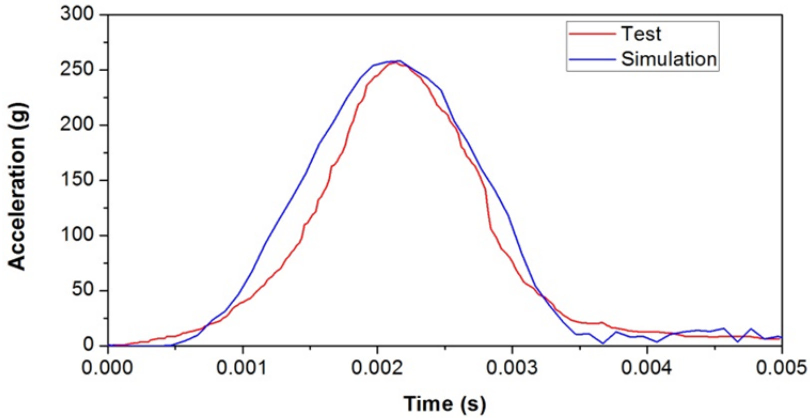


Figure 7 Comparison of headform accelerations in test and simulation

Setup of FE head impact reconstructions

The set up of the FE simulations were configured based on the output of MBS pedestrian head impact conditions before contact with the windscreen. The MBS computed head impact conditions include linear velocity, angular velocity, head position and head orientation relative to the windscreen (Figure 8). The friction coefficient between headform and windscreen was set as 0.2.

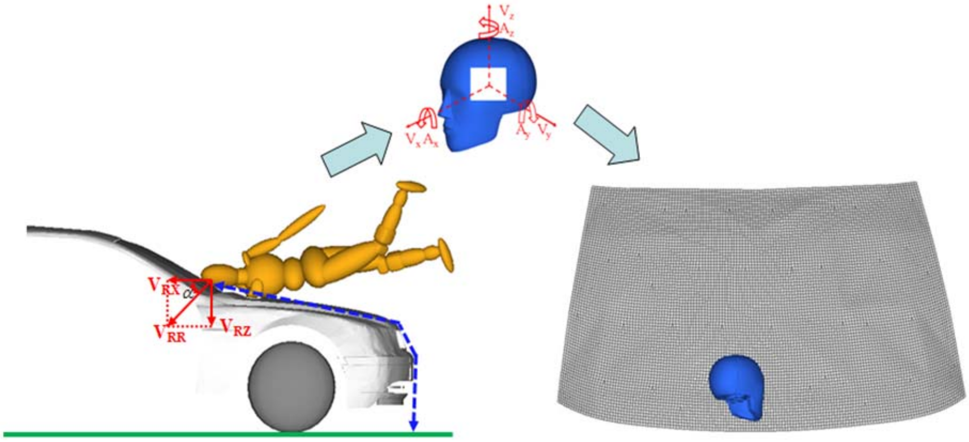


Figure 8 Setup of FE reconstruction

Statistical Methods

A quadratic polynomial regression model is employed to study the relationship between pedestrian kinematic responses and vehicle impact velocity. A quadratic equation has the following form:

$$y = Ax^2 + Bx + C$$

where C is the y intercept and A and B are constants. The calculated correlation coefficient R^2 is used to describe the strength of the relationship and the regression curves illustrate the relationship.

In this study, the single logistic regression analysis is applied to study the association between pedestrian head injury risks and the calculated injury parameters. S-shaped regression curves are generated to illustrate the relationship. The probability of severe injury P(x) is assumed to have the following form:

$$\mathrm{P(x)} = 1/(1 + \mathrm{e}^{\alpha-\beta x})$$

where x is the injury parameters and α, β are the coefficients to be determined using the maximum likelihood method to maximize the function's fit to the data [20]. The quality of the statistical model is examined by means of chi-squared χ^2 and associated probability value p. Therefore, the χ^2 and p values indicate whether or not the relationship between injury and predictor variables are statistically significant. The relationship between injury and predictor variables is statistically significant when the probability value is at the level of P ≤0.05. When $x = \alpha/\beta$, S-shaped regression curve has a bending point with a maximum or minimum value for the slope and the probability value p is equal to 50%. So the value of α/β gives the median of the distribution of predicted head injuries over values of x.

III. RESULTS

Cases Reconstruction

The results show that the kinematics of the pedestrian models in the MADYMO simulations were comparable to that in the real-world cases in terms of impact speed, impact location and throw distance.

Compared to the recorded contact position on the vehicle in the real-world accident, the simulation results coordinate well, as shown in Figure 9. The leg impacted on the bumper first, then the thigh impacted on the headlight and last the head impacted on the lower windscreen. The simulated throw distance and WAD is 11.3 m and 2.0 m, respectively, for a vehicle impact velocity of 54 km/h. In this simulation, the computed head velocity is 40 km/h before impact with the vehicle.

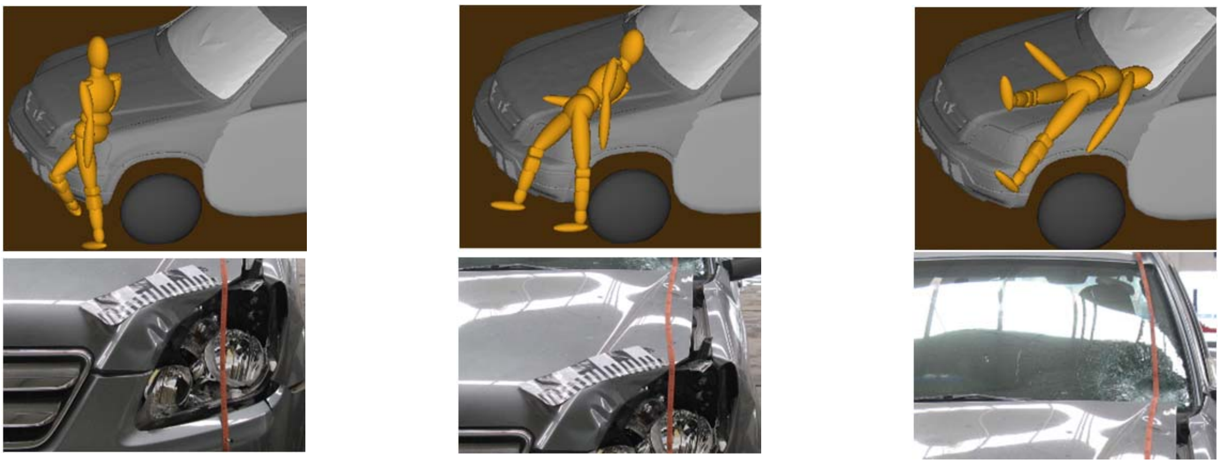


Figure 9 Illustration of the simulated pedestrian kinematics and comparison to real world observation for case IVAC 7

Figure 10 shows the simulation process of impact with the vehicle and pedestrian kinematics. The pedestrian was first hit by the bumper on the left knee, then the upper legs and hip struck against the bonnet edge, and finally the head impacted the lower windscreen. The simulation results show that the throw distance is 12.9 m and the WAD is 1.84 m, which is comparable to the real world situation. Before impact, the computed head velocity is 63 km/h in this simulation.

Figure 10 Illustration of the simulated pedestrian kinematics and comparison to real world observation for case IVAC 14

Accident Reconstruction Results Analysis

As shown in Figure 11, three types of collision are defined based on the relative position of the pedestrian and the vehicle front-end at the first contact. The pedestrian accident data show a higher frequency (40%) of the type 2 collision whereas both type 1 and type 3 show a frequency of 30%.

The pedestrian head is divided into six parts according to the distribution of the first head contact area. Figure 12 shows that the percentages of occurrence of first impact in areas of right and left side are 53% and 47%, respectively. Highest frequency (53%) of first contact was observed at occipital part (parts L1 and R1) compared to lateral (parts L2 and R2) and frontal parts (parts L3 and R3), which accounted for 26% and 21%, respectively.

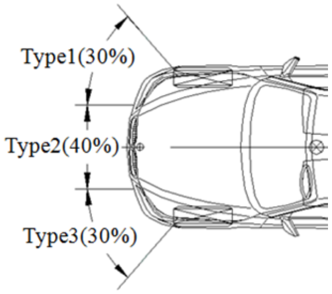


Figure 11 Types of collision based on position of first contact between pedestrian and vehicle

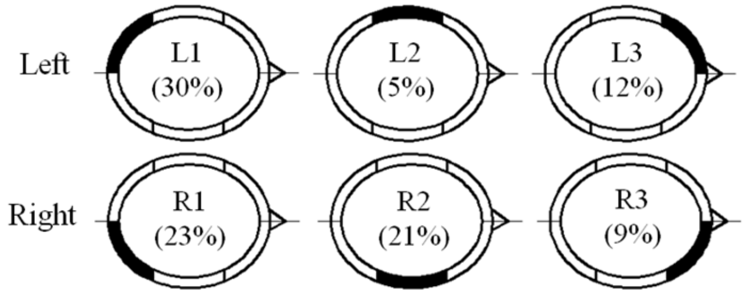


Figure 12 Distribution of the first head contact area

Figure13 shows the head impact angle for all of the cases. It can be found that head impact angles range between 22° and 83° and that the average of the pedestrian head impact angles are about 55°.

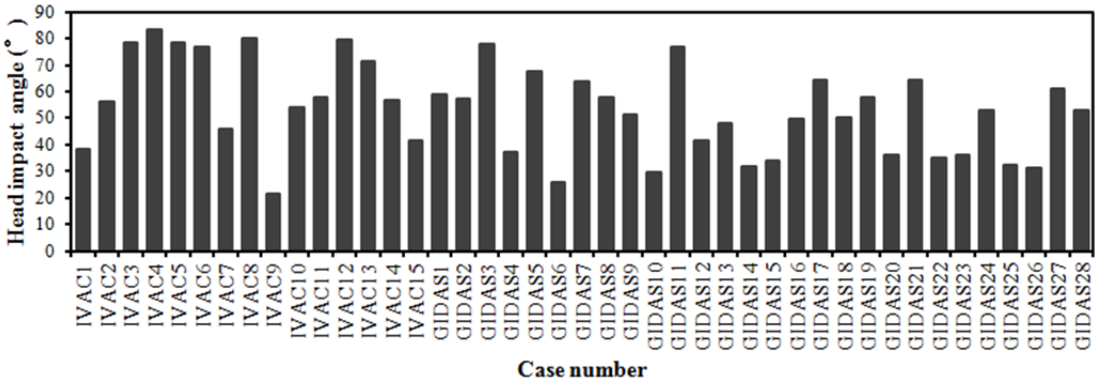


Figure 13 Head impact angle computed from the MBS simulations

Figure 14 provides a comparison of accidents and simulation results in terms of Wrap Around Distance (WAD) values. It appears that the simulation results are quite close to the accident data. From these values, it can be observed that the WAD varied from 1600 mm to 2517 mm, with an average of 2052 mm. As most of the cases present WAD values over 1900 mm, the head impact was typically located on the windscreen area.

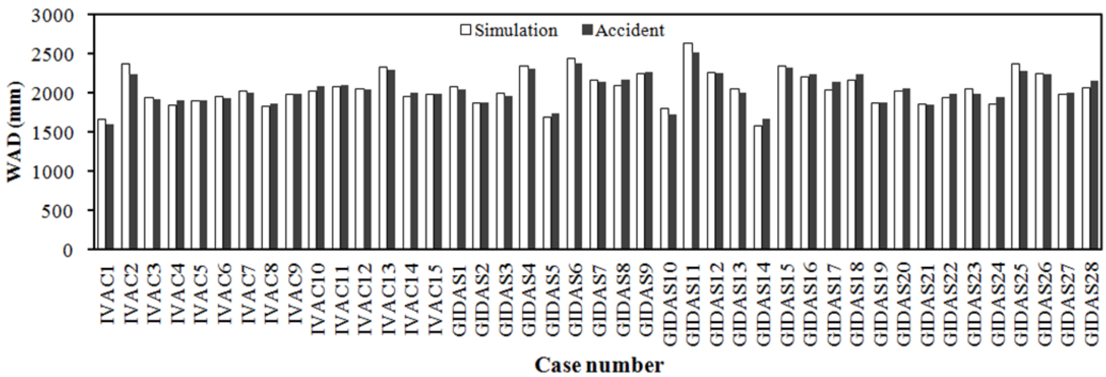


Figure 14 Comparison of computed and measured WAD values for all accident cases

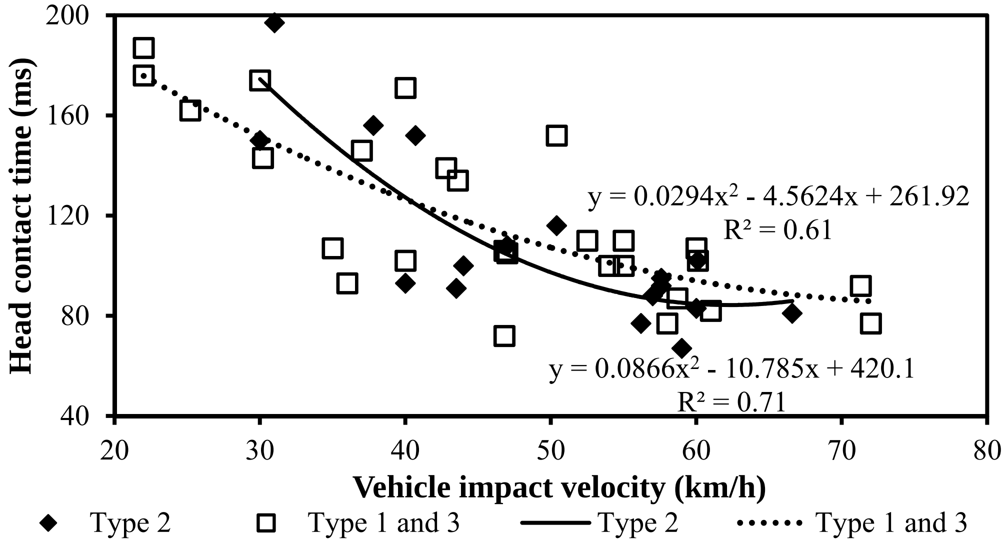


Figure 15 Relationship between head contact time and vehicle initial speed for three impact types (see Figure 11)

Polynomial regression curves and scatter of data points between car impact velocity and head contact time are plotted in Figure 15. Head contact time is defined as the time duration between the first contact of the human body and the head contact against the vehicle. Strong correlations are found with R^2=0.71 for impact type 2 and R^2=0.61 for types 1 and 3. It can be observed that the correlation is stronger for type 2 than for types 1 and 3. In the low-speed collisions (less than 40 km/h), head impact time is lower for types 1 and 3 than for type 2, while the time is higher for types 1 and 3 than for type 2 over 40 km/h. Head contact time decreases with increasing vehicle impact velocity when the initial point of impact is on the bumper, and the range of impact time varies from 67 ms to 197 ms. This parameter is of critical importance when activation time of active protection systems such as air bags or bonnet pop-up is concerned.

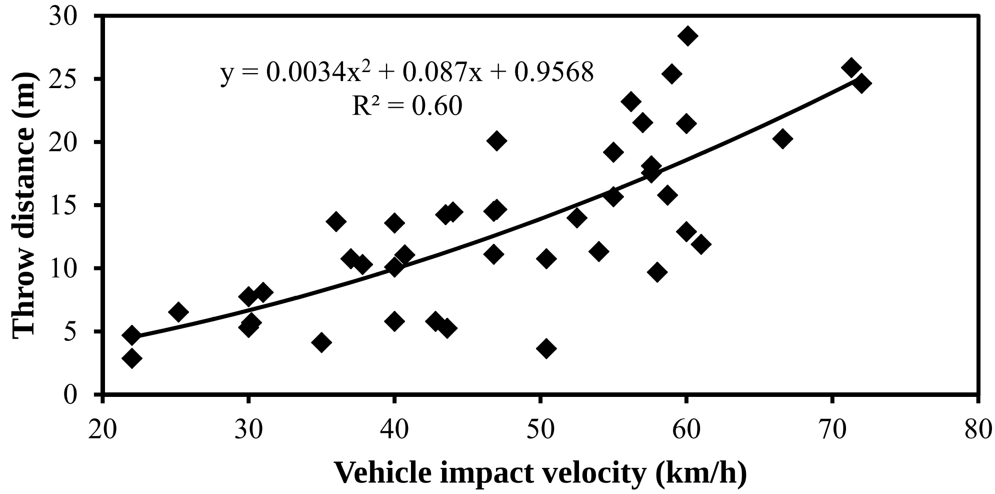


Figure 16 Relationship between throw distance and vehicle impact velocity

Figure 16 illustrates the relationship between throw distance and vehicle impact velocity. The definition of throw distance in the study is the distance between the position of initial collision and the pedestrian's final position, and it includes three parts: contact phase, flying phase and sliding phase. The throw distance of a pedestrian is used for estimating impact speed. The present result shows that strong correlation exists between these two parameters (R^2=0.60).

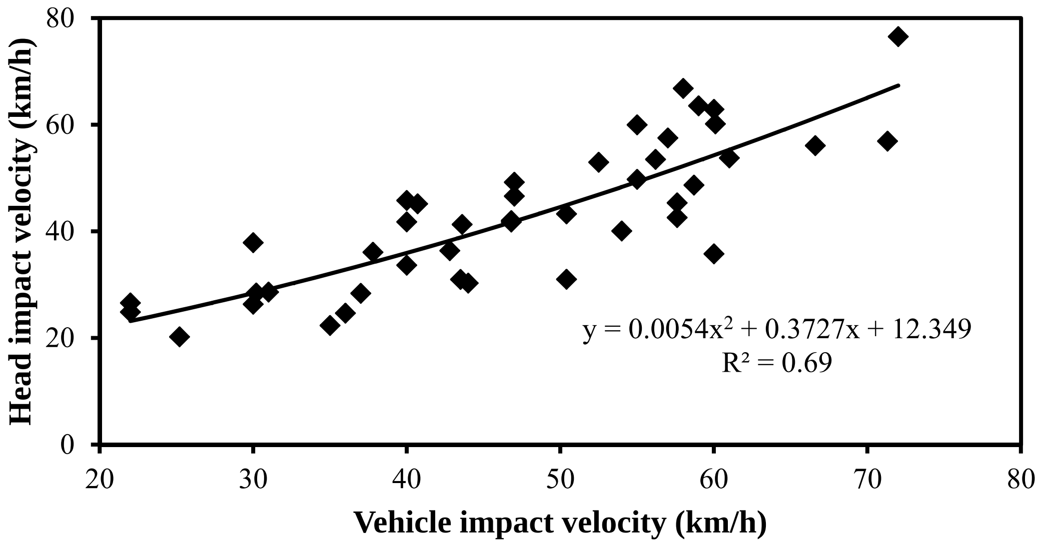


Figure 17 Relationship between computed head impact velocity and initial vehicle speed

The quadratic regression curves and scatter of data points between head impact velocity at the time of contact with the vehicle and initial vehicle impact speed are illustrated in Figure 17. The regression curve shows that the pedestrian head impact velocity trend increases with the increase of vehicle speed with a strong correlation (R^2=0.69).

Assessment of Head Injury Risks

In order to further investigate head injury risks, head impact velocity and angular velocity were derived from the MADYMO simulation. Peak linear acceleration, HIC value, Skull Fracture Correlate (SFC) and peak angular acceleration were then computed in the FE simulation. The correlations between output injury parameters and AIS 2+ and AIS 3+ head injury then were examined using a single logistic regression model. Table 2 summarizes the values of α, β, χ2, p and α/β of the regression model.

TABLE 2 LOGISTIC REGRESSION COEFFICIENTS AND STATISTICS FOR PROBABILITY OF HEAD INJURY

Predictor variables	Head injury code	α	β	χ^2	p	α/β
Vehicle impact velocity (km/h)	AIS 2+	3.7631	0.1129	12.8925	0.0003	33
	AIS 3+	4.1693	0.0850	10.0454	0.0015	49
Resultant angular velocity (rad/s)	AIS 2+	7.4188	0.1848	20.0731	0.0049	40
	AIS 3+	7.5838	0.1385	19.9145	0.0014	55
SFC(g)	Fracture	5.2097	0.0386	9.4318	0.0021	135
Head linear acceleration (g)	AIS 2+	6.6861	0.0579	16.0943	0.0063	116
	AIS 3+	5.6627	0.0350	15.2255	0.0039	162
HIC	AIS 2+	5.2778	0.0064	26.4277	0.0027	825
	AIS 3+	5.6212	0.0039	28.0291	0.0034	1442
Resultant angular acceleration (rad/s^2)	AIS 2+	5.6839	0.0005	19.5401	0.0033	11368
	AIS 3+	5.6324	0.0003	18.9403	0.0014	18775

Table 2 shows that the p values are 0.0003 and 0.0015 for the correlation between head impact velocity and AIS 2+ and AIS 3+ head injury risks, respectively, while the predicted values of 50% probability are 33 km/h and 49 km/h, respectively. The correlations between head resultant angular velocity, linear acceleration, HIC value and resultant angular acceleration and head injury risks are calculated, and the p values are 0.0049, 0.0063, 0.0027 and 0.0033 for AIS 2+, respectively, and the p values are 0.0014, 0.0039, 0.0034 and 0.0014 for AIS 3+, respectively. The predicted head resultant angular velocity, linear acceleration, HIC value and resultant angular acceleration values of 50% probability causing AIS 2+ head injury are 40 rad/s, 116 g, 825 and 11368 rad/s^2 respectively, and causing AIS 3+ head injury are 55 rad/s, 162 g, 1442 and 18775 rad/s^2 respectively. It can also be seen that the p value is 0.0021 for the correlation between SFC and head fracture risk and the predicted value of 50% probability is 135 g. Owing to the fact that the p values are less than 0.05, vehicle impact velocity, resultant angular velocity, SFC, head linear acceleration, HIC value and resultant angular acceleration exhibit a strong correlation with head injuries. In addition, S-shaped regression curves are plotted to illustrate these relationships for the six parameters under study in Figure 18. Based on this study, the two parameters which are the best correlated with head injury are head linear acceleration and head angular velocity.

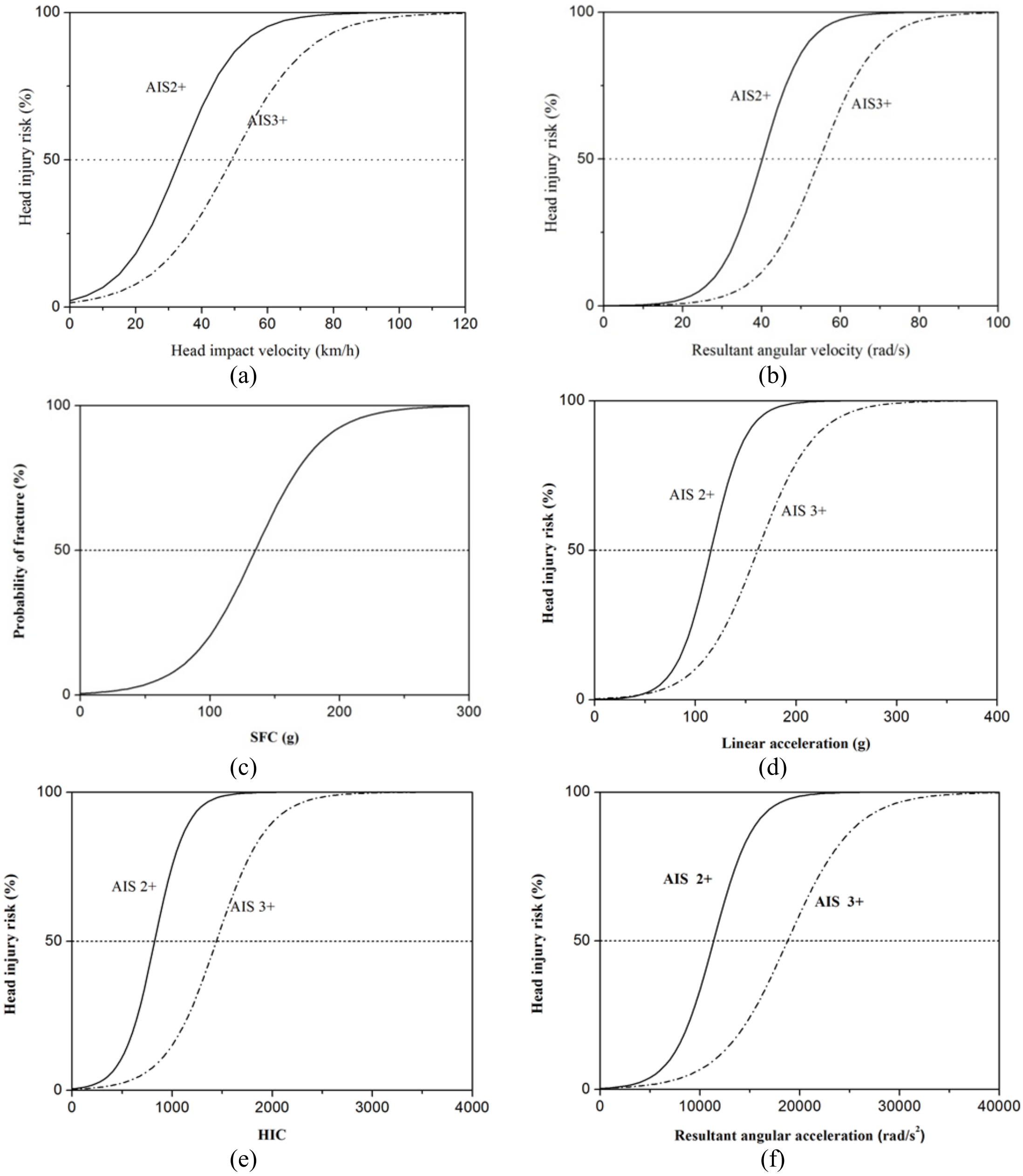


Figure 18 Logistic regression curves for head impact velocity, linear acceleration, angular velocity, angular acceleration, HIC value and SFC

IV. Discussion

In the current study, a sample of 43 real world pedestrian accident cases, 15 from the IVAC database and 28 from the GIDAS database, which were selected for general epidemiologic analysis were considered for head injury risk investigation. Accident reconstructions were carried out by using MADYMO programs with the aim focused on head responses, and two cases from the IVAC database were selected to illustrate the methodology of reconstruction. The overview of the simulated vehicle-to-pedestrian impact kinematics shows that there is a unique contact order, i.e. leg-hip-elbow-shoulder-head. Compared to crash scene data in terms of impact position on vehicle, WAD and throw distance, it is obvious that the simulation results reproduce the reality in a realistic way. Furthermore, computed pedestrian head impact conditions from MADYMO simulation were used to set the initial conditions in a simulation of a Hybrid ш head FE model striking a windscreen FE model.

In the current study, head impact time, throw distance, head impact angle, head impact velocity, head resultant angular velocity, peak linear acceleration, SFC, HIC value and peak angular acceleration are computed and considered either for the validation of the pedestrian kinematics or as potential head injury indicators.

Figure 13 shows that the average of the pedestrian head impact angles are about 55° which is 16% lower than 65° specified by EEVC for adults. A strong correlation was found between initial vehicle impact speed and head contact time, throw distance and head impact velocity by quadratic regression model. Figure 17 shows that higher vehicle impact speed produces higher head impact velocity. These results permitted the validation of the MBS simulation and are in agreement with results from the literature [21, 22]

The single logistical regression approach is employed to examine the correlation between output injury parameters and head injury risks. From the statistical results, it can be found that AIS 2+ and AIS 3+ severe head injuries with probability of 50% are caused by head impact velocity at about 33 km/h and 49 km/h, respectively. In this study, HIC 1000 corresponds to a 75.4 % and 15.2% possibility of AIS 2+ and AIS 3+ head injuries, respectively. The predicted head linear acceleration, HIC value, resultant angular velocity and resultant angular acceleration for 50% probability of AIS 2+ and AIS 3+ head injury risk are 116 g, 825, 40 rad/s, 11368 rad/s^2 and 162 g, 1442, 55 rad/s, 18775 rad/s^2 respectively, and the predicted values of 50% probability of skull fracture is 135g. These results agree well with other studies on head injuries. Prasad and Mertz reported that 16% risk of life-threatening brain injury is caused by HIC 1000 [23]. Fijalkowski et al indicated that angular rotational acceleration ranging from 11.5 krad/s^2 to 16.5 krad/s^2 applied in the coronal plane can induce mild-to-severe DAI for humans [24]. In addition, Zhang found that the mean HIC value, resultant linear acceleration and the peak resultant rotational acceleration for minor injury cases is 351 (±169), 103 (±30) g and 7,354 (±2,897) rad/s^2, respectively [25]. Vander et al found that 15% or less probability of skull fracture is obtained for SFC < 120g, with a 95% confidence band of 88 g < SFC < 135 g [26]. As a whole, the results obtained in this study demonstrate the quality of both the MBS and the FE analysis, providing valuable results for further investigation based on human head FE analysis.

However, there are several limitations of the current study. First, at accident data level, there are several uncertainties in the information, especially for the vehicle impact speed and initial posture of the pedestrian. Second, pedestrian models are scaled from a standard adult pedestrian model using the GEBOD program and characteristics of joints and stature could only be approximated. Third, the stiffness properties of each part of the MBS car model came from impactor tests of similar cars introducing some uncertainties due to simplification. Fourth, the circumstance parameters, such as contact friction coefficients, are set according to the literature. In order to overcome these difficulties which are inherent in real world accident simulation, a statistical approach is needed and thus consolidation of the present study would need more accident cases and more detailed injury records in order to get consistent data for further definition of head injury curves.

V. CONCLUSIONS

In this study, a total of 43 real world pedestrian accidents were reconstructed in order to compute the head impact conditions and to assess the head injury risk. A combination of multi-body simulation for the pedestrian kinematics and FE simulation for the Hybrid Ш head impact against the windscreen was conducted. After validation of the computation of the pedestrian kinematics against accident data, the head impact conditions were considered for the FE simulation of the head impact against the windscreen. The results indicated that the AIS 2+ and AIS 3+ severe head injuries with probability of 50% were caused by head impact velocity of about 33 km/h and 49 km/h, respectively. The average of the pedestrian head impact angles were about 55° which is 16% lower than 65° specified by EEVC for the adult. Parameters such as SFC, head linear acceleration, HIC value and resultant angular acceleration were calculated to predict brain injuries. The predicted head linear acceleration, HIC value, resultant angular velocity and resultant angular acceleration for 50% probability of AIS 2+ and AIS 3+ head injury risk are 116 g, 825, 40 rad/s, 11368 rad/s^2 and 162 g, 1442, 55 rad/s, 18775 rad/s^2 respectively, and the predicted value of 50% probability of skull fracture was 135 g for SFC.

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VIII. APPENDIX

TABLE 1 SUMMARY OF ACCIDENT DATA

Case NO	Model	Gender	Age	Height (cm)	Weight (kg)	Direction (O`clock)	Vehicle speed (km/h)	MAIS Head
IVAC1	Jinbei	Female	30	163	50	9	44.0	0
IVAC2	Hoda	Male	20	172	60	4	22.0	1
IVAC3	Fukang	Male	49	160	52	3	30.0	1
IVAC4	Chery A5	Female	16	150	50	2	35.0	1
IVAC5	JETTA	Male	26	162	50	10	30.2	1
IVAC6	JETTA	Female	50	174	70	10	22.0	1
IVAC7	Honda	Male	32	170	65	9	54.0	1
IVAC8	JETTA	Male	17	171	80	3	30.0	2
IVAC9	Wuling	Male	43	162	56	8	40.0	2
IVAC10	BUICK	Male	26	171	62	9	57.6	2
IVAC11	Siena	Female	18	163	50	10	43.5	2
IVAC12	Linshuai	Female	73	163	50	4	58.0	3
IVAC13	Mazda6	Male	48	173	72	4	43.6	3
IVAC14	BMW318	Female	49	158	58	2	60.0	6
IVAC15	JETTA	Male	22	167	60	2	61.0	6
GIDAS1	ASTRA	Male	57	175	80	2	31.0	0
GIDAS2	FIORION	Male	55	168	54	8	40.0	0
GIDAS3	Golf 4	male	63	173	68	8	46.8	0
GIDAS4	Golf 3 Kombi	Female	26	184	70	2	55.0	1
GIDAS5	GALAXY	Female	51	168	90	2	25.2	1
GIDAS6	GLOF	Male	68	175	85	4	42.8	2
GIDAS7	E220	Male	35	176	76	9	47.0	2
GIDAS8	Mondeo	Male	18	182	72	9	37.8	2
GIDAS9	CARISMA	Male	67	166	80	9	57.0	2
GIDAS10	Mercedes A140	Female	27	160	60	8	59.0	2
GIDAS11	Mazda6	Male	41	185	78	10	60.0	2
GIDAS12	Vectra A	Male	34	171	90	10	60.1	2
GIDAS13	BMW316i	Female	37	165	64	2	50.4	2
GIDAS14	sprinter	Female	49	160	55	9	36.0	2
GIDAS15	cordaoba	Male	19	180	65	4	66.6	2
GIDAS16	PASSAT	Male	54	170	60	9	57.60	3
GIDAS17	CORSA JOY	Male	57	180	77	2	37.00	3
GIDAS18	Peugeot307	Female	32	185	80	9	40.7	3
GIDAS19	ASTRA	Female	66	168	55	2	47.0	4
GIDAS20	CLIO	Male	54	170	70	9	55.0	4
GIDAS21	PASSAT	Female	89	153	61	4	58.70	4
GIDAS22	Smart	Male	43	162	62	9	46.8	5
GIDAS23	Corsa	Male	23	180	80	9	52.5	5
GIDAS24	Corolla Verso	Female	83	160	70	9	56.2	6
GIDAS25	PASSAT VDI	Male	51	175	90	9	71.3	6
GIDAS26	Fiesta	male	65	170	85	4	72.0	6
GIDAS27	BMW316	Female	64	168	60	3	50.4	6
GIDAS28	Audi C4	Male	65	176	72	8	40.0	6