Simulation on the form and kinematics law of contacting process for car/pedestrian collision

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ABSTRACT

Pedestrian protection project is presently the key aim in the fields of traffic safety and vehicle passive safety, which is attached to great importance by numerous researchers at home and abroad. Based on PC-Crash program for simulation and reconstruction of road accident and in-line MADYMO program for multi-body system dynamics analysis, the kinematics law and characteristics of pedestrian in the contact process for vehicle-pedestrian collision are analyzed with modeling. By modeling vehicle and pedestrian, and selecting main factors influencing on contact phase for vehicle-pedestrian collision as independent variables for simulation tests, which include the shape and geometry of vehicle front-end, motion conditions of vehicle in collision process (constant speed, accelerating, decelerating etc), as well as size and initial motion conditions of pedestrian at the moment of pre-impact (standing, walking, jogging, running etc), the form characteristics and kinematics law of pedestrian as well as corresponding vehicle impact speed threshold in the contact phase of vehicle-pedestrian under different collision circumstances are in depth researched. The comparisons of simulation results with real world vehicle-pedestrian collisions under observation as well as crash tests results have shown that a perfect harmony and consistency of kinematics law of pedestrian. Kinematics law of pedestrian in the contact process for vehicle-pedestrian collision is in depth mined by applying simulation technique, which can not only offer fully and accurately basic data to analyze kinematics law and kinetics law of pedestrian under different collision forms, but also provide powerful theoretical and technical support for technology appraisal of traffic accidents. The results in this paper will be of an important value in China.

INTRODUCTION

Pedestrian protection project is presently the key aim in the fields of traffic safety and vehicle collision safety, the issue on pedestrian protection in traffic accidents has already become an important project which is paid attention by researchers in vehicle and traffic safety all over the world. A great deal of bankroll was invested in researching on collision safety for vehicle-pedestrian in the developed countries such as U.S., EEC, Japan etc., where, by using various crash tests including vehicle crash involving cadaver or pedestrian dummy, limb-form or head-form impactor and computer simulation technique, the grouping research has been developed [Andrew Happer, 2000; Amrit Toor, 2002; Mark Meissner, 2004], and moreover, some achievements have been already obtained. At present, the test methods, standards and regulations relating to collision safety for vehicle/pedestrian have been already drawn up and promulgated by the developed countries according to a large number of the results of crash tests [EEVC WG10, 1994; EEVC WG17, 1998], which will facilitate to normalize vehicle construction, and effectively improve collision safety for vehicle/pedestrian.

China is one of typical countries on the world in which the road traffic is mainly grade intersection and mixed, the total amount of pedestrian injuries caused by vehicle is much more than that in the developed countries. According to the national statistics data, in the recent years, the proportion of mortality of pedestrian to the total involved in road accidents has been annually beyond 20 percent in China [Traffic Management Bureau of Public Security Ministry, 2001-2006]. Hence, pedestrian traffic safety has become much noticeable, there will be of great practical significance to develop the research on collision safety for pedestrian protection in China.

In recent years, the groping studies mostly on kinematics and kinetics analyses for vehicle-pedestrian collision as well as evaluation for pedestrian injuries have been conducted by some organizations and colleges in China [CHENG Xiu-sheng, 2003; LI Li, 2003], however, which is limited much to theoretical one, and furthermore, no effective achievements have been yet applied and put in practice. So, comparing with that in the developed countries, the research conducted by China in the field make much more slowly progress, and still in the primary phase of referring and learning, which is urgently demanded for correlative research institutes to completely, in depth develop the study on collision safety for vehicle-pedestrian as soon as possible.

Due to the advantages of expeditious, economical, avoidable influence of random factors in the test and restriction by test condition, easily simulating different collision forms and comparing, and also obtaining some parameters data which are very difficultly got through crash tests, computer simulation method has been of great application value and advantage in the research on collision safety for vehicle-pedestrian.

By using PC-Crash program for simulation of road accident and in-line MADYMO program for multi-body system dynamics analysis, the form characteristics and kinematics law of contacting process for vehicle-pedestrian under different collision circumstances are analyzed through modeling and simulation. The author would have expected that research results in the paper can not only provide referenced value and guidance meaning to a certain degree for study on kinematics law and kinetics law of pedestrian under different collision forms, as well as increasingly developing technology appraisal of traffic accidents, but also advance technologists to completely, in depth develop the research on collision safety for vehicle-pedestrian in China.

MODELING AND VALIDATION

MODELING

PC-Crash is the widely used worldwide program for simulation and reconstruction of road accident. MADYMO is based on the multi-body system dynamics, which nowadays is the very widely applied program for multi-body system dynamics analysis in the field of vehicle crash safety. The pedestrian model in the project is developed by using MADYMO model, vehicle model is given by applying PC-Crash model, and furthermore, simulation tests are performed on PC-Crash software platform [Dr. Steffan, 2006].

The pedestrian model is a multi-body system consisting of 16 rigid bodies interconnected by 15 joints, as shown in fig. 1. The different bodies, which represent different parts of human body respectively (head, torso, pelvis, femur etc.), are ellipsoidal; the different joints respectively represent different arthroses of human body. For each body, the different properties such as geometry, mass and moments of inertia, stiffness coefficient, hysteresis coefficient, friction coefficients etc., can be specified independently; synchronously, the characteristics of joint used to connect two bodies, ellipsoid to ellipsoid contacts as well as ellipsoid to vehicle contacts are defined. The data including major property parameters and mechanical characteristics etc. of different parts of human body are all derived from real human body statistics. The height and weight for the pedestrian multi-body as a whole can be specified based on China 50th percentile adult male; synchronously, the initial conditions such as position, orientation etc. for corresponding bodies of the multi-body system can be specified, then pedestrian models under different initial motion conditions (standing, walking or running) at the moment of pre-impact can be established, as shown in fig.2.

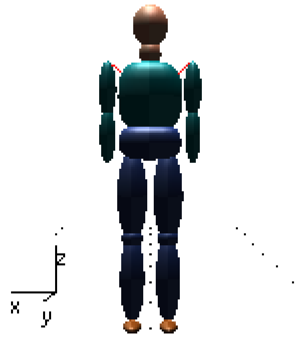
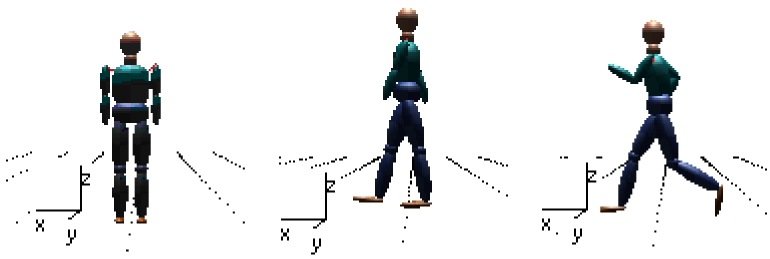


Fig.1 Pedestrian Model



Standing Walking Running

Fig. 2 Different initial motion conditions of pedestrian

Vehicle model is also a multi-body system consisting of a series of rigid bodies (ellipsoids) respectively representing different parts of vehicle body, the definition method is similar to that of the pedestrian multi-body model.

The vehicle/pedestrian model introduced into the simulation tests is shown in fig.3. For vehicle type VW Passat 1.8 CL and Toyota Hiace are typically selected.

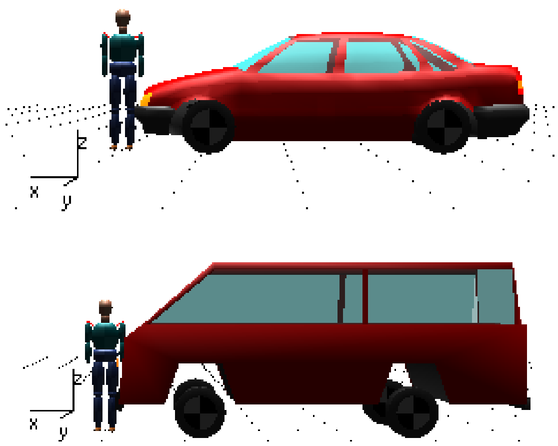


Fig. 3 Vehicle/Pedestrian Impact Model

VALIDATION

As there are a good many input parameters, which have to be specified, especially, in establishing the pedestrian multi-body model, and furthermore, the vehicle/pedestrian model themselves have been of a certain limits, the validation of the vehicle/pedestrian model has to be conducted.

Based on the staged crash tests in which pedestrian dummies were hit with different vehicle types and vehicle shapes, the verification of validity of pedestrian model done by some scholars [Andreas Moser, 2000] has shown that a better convergence and consistency between the crash test data and simulation results, thus the validity of car/pedestrian impact model has been validated.

As the crash tests involving pedestrian dummies may assume some deviations from real world for both mathematical models and crash tests themselves, the whole process for vehicle/pedestrian collision can not be completely, really reconstructed by the crash tests.

So, the pedestrian model in PC-Crash has to be continually revised and validated by using real world vehicle/pedestrian collisions data, which makes it possibly simulate and reconstruct the process for vehicle/pedestrian collision much completely and really.

TEST SCHEME

Real world vehicle/pedestrian collisions under observation and crash tests results have shown that the motion conditions of pedestrian in the contact phase for vehicle to pedestrian collision are noticeably influenced by a good many factors, which mainly include shape and geometry of vehicle front-end, motion conditions of vehicle in collision process (constant speed, accelerating, decelerating etc), size and initial motion conditions of pedestrian at the moment of pre-impact (standing, walking, jogging, running etc), collision forms of vehicle-pedestrian (including contact position and impact angle), as well as the interaction between them [XU Hong-guo, 2004]. So, the post-impact kinematics process and conditions of pedestrian will be much more complicated than that of car occupants, and be of greater uncertainties, which will increase enormous difficulties to the analysis on them.

Since the influencing factors on the contact phase for vehicle/pedestrian collision are extraordinarily complicated, for the convenience of simulation, 5 different parameters, which include the geometrical relationship between vehicle front-end and pedestrian body (*R*), typical collision forms (*F*), vehicle impact speed (V_V) and braking intensity (*Z*), pedestrian speed (V_P), will be selected from main influencing factors as independent variables for simulation tests. For each parameter (i.e. independent variable) the background and the level of value are respectively different.

1. Parameter *R*

The parameter *R* is composed of three components, i.e. the ratio of the height of the center of gravity (C.G.) of pedestrian to the height of impact point on vehicle front-end above ground h_v/h_p, the ratio of the size of pedestrian to the height of upper edge of vehicle front-end above ground s_v/s_p, and the ratio of the height of pedestrian knees to the height of impact point on vehicle front-end above ground h_v/h_j. So the parameter *R* can be expressed as:

$$R = \{h_v/h_p,\ s_v/s_p,\ h_v/h_j\}.$$

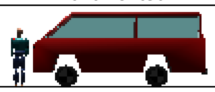
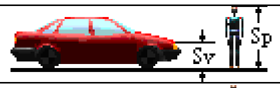
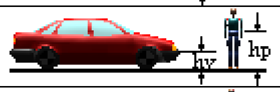
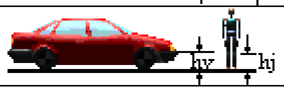
Vehicle Classification		Category A Low-fronted	Category B High-fronted	Category C Blunt-fronted
Vehicle Shape & Geometry Pedestrian Stature				
	s_v/s_p	<1/2	≤1/2	>1/2
	h_v/h_p	<1	≤1	>1
	h_v/h_j	≤1	>1	>1

Fig. 4 Relationship between vehicle shape, geometry and pedestrian stature

The meanings and value (range) of different components have been shown in fig.4, where the vehicle types are categorized into three different categories according to the front profiles of current vehicles, i.e. low-fronted, high-fronted and blunt-fronted; for the pedestrian China 50th percentile standing adult male is applied. In addition, the categories A and B being merged, the vehicle category A will be really applied to the simulation tests, which can meet the requirement of the analysis on tests (the correlative study [Andrew Happer, 2000] has shown that the post-impact motion form of pedestrian in the category A vehicle/pedestrian collision is extremely similar to that of the category B vehicle/pedestrian collision under the same other condition).

2. Parameter F

Two parameters, i.e. impact position P and impact angle Θ, will be applied to describe collision form, where P describes the location of pedestrian relative to vehicle at the moment of pre-impact; for the parameter Θ, the angle of motion direction between vehicle and pedestrian, which is measured according to the longitudinal axis of vehicle, and moreover, direction of positive angle is clockwise, is adopted to describe the direction of pedestrian motion relative to the vehicle at the moment of pre-impact.

Based on the analyses of statistics of vehicle/pedestrian collisions done by scholars [B. Wördenweber, 2004], for the simulation tests, the center and its left/right-sided sections of vehicle front-end, which is respectively distributed by the 1/3 of vehicle width, are selected as the first contact locations in vehicle-pedestrian collisions, thus the parameter P can be expressed as:

$$P = \{L_F, C_F, R_F\}.$$

Where, C_F, L_F and R_F respectively denote the center and its left/right-sided sections of vehicle front-end.

Based on mathematical analysis, if theoretically assuming that the pedestrian post-impact trajectory is the curve form of generalized continuous function with respect to any influencing factor (independent variable), for the parameter Θ, the following expression selected without proving can meet the requirement of the analyses, i.e.:

$$\Theta = \{\theta \square\ \theta = (n \square 1)\ 45°,\ n \square N,\ n < 8\}.$$

Where, N represents a set of positive integers.

Summing up the above analyses, the value of typical collision forms of vehicle/pedestrian can be described as the following expression:

$$F = \{(L_F, \Theta), (C_F, \Theta), (R_F, \Theta)\}.$$

3. Parameter V_V

In the view of the influence of test error, the value of impact speed of vehicle to pedestrian can be described following as:

$$V_V = \{v_v \square\ v_v = 10m,\ v_v \le V_V^{max},\ m \square N\},\ (\text{km/h}).$$

Where, N represents a set of positive integers, V_V^{max} denotes the maximum vehicle design speed.

4. Parameter Z

The two braking conditions, i.e. fully braking before vehicle-pedestrian collision and non-braking in the contact phase for vehicle/pedestrian collision, are only discussed in the simulation analysis, thus parameter Z can be described in the expression, i.e. $Z = \{0, \varphi\}$, where φ denotes the adhesion coefficient for longitudinal slip between vehicle tire and roadway.

5. Parameter V_P

As pedestrian speed is relative to a good many factors, such as pedestrian's age, sex, constitution, mood and travel purpose, as well as environment, conditions of traffic flow etc., and moreover, most pedestrians will take an emergency measures to avoid collision out of the instinct of self-protection, which makes the motion state of pedestrian at the moment of pre-impact more complicated and changeful (including standing, walking, fast walking, jogging, running). According to the results of correlative research on pedestrian traffic characteristics conducted by some scholars at home and abroad [Rodney Vaughan, 2000; FENG Shu-min, 2004; CHEN Ran, 2005; WU Jian-ping, 2004], the mean speed of pedestrian under different motion conditions (standing, walking, jogging, running) are selected to carry through simulation. The value of mean speed of pedestrian under different motion conditions can be described in the following form:

$$V_P = \{0, 5, 13, 20\},\ (\text{km/h}).$$

Summing up the above analyses and discussion, the simulation test conducted in the project is actually a complicated multi-factors test. For the convenience of analysis on the influencing law of single-factor and comparison, the multi-factors should be transformed to single-factor to carry through simulation. In the simulation tests of single-factor, the factor V_V is selected as variable, and moreover, the factors *R*, *F*, *Z* and V_P are, time and again, specified as constant. The simulation test scheme of single-factor has been shown in tab. 1.

R, F, Z, V_P = Const.		
Test ID Num.	V_V / km/h	V_P / km/h
1	10	5
2	20	5
□	□	□
n	V_V^{max}	5

Tab.1 Simulation test scheme of single-factor

TEST RESULTS AND ANALYSIS

BLUNT-FRONTED VEHICLE TO PEDESTRIAN COLLISION

When the front of blunt-fronted vehicle (such as bus, flat-fronted truck etc.) hits pedestrian, pedestrian's torso, even head or the whole body is directly contacted by the vehicle front-end, and instantaneously, the pedestrian is accelerated in the direction of vehicle's motion. As the height of impact point on vehicle front-end is higher than the pedestrian's C.G., the pedestrian will likely be vaulted forward at the extremely small projection angle, or be thrown directly ahead of the vehicle in the approximately horizontal direction (the projection angle is nearly zero) at the moment of post-impact (i.e. horizontal projection trajectory). In the whole contact process of vehicle/pedestrian, there will be only one contact between the pedestrian body and the vehicle, and moreover, the pedestrian's C.G. does not shift backwards with respect to the vehicle, always remaining ahead of the vehicle.

The results of simulation tests have shown that the influence of various factors, such as impact speed, braking intensity, pedestrian speed and collision forms, on the motion state and posture of pedestrian in the contact process for blunt-fronted vehicle to pedestrian collision is no noticeable. The case of high/low-fronted vehicle to child collision is the same as the above analyses.

HIGH/LOW-FRONTED VEHICLE TO PEDESTRIAN COLLISION

When the front of high/low-fronted vehicle hits adult pedestrian (the vehicle's upper leading edge/impact point is at or below the pedestrian's C.G.), pedestrian's lower limbs (lower leg/knee/femur) is initially contacted by the corresponding locations on the front bumper, and instantaneously, the femur/hip contacted by the vehicle front-end (leading edge of hood/fender, radiator grill etc.). The pedestrian is accelerated forward under the tremendous impact force of the vehicle, and simultaneously, will rotate about the upper leading edge of the front with respect to the transverse axis of the vehicle. As the vehicle continues forward, the pedestrian's C.G. will shift rearward (behind the impact point) with respect to vehicle, but continue to accelerate forward with respect to ground. If the pedestrian has not moved off the side of vehicle front, then there will be secondary contact between the pedestrian and the vehicle (typically including head/torso contact with the hood/windshield/A-pillar/roof). As the vehicle is decelerating, the pedestrian will start to separate from the vehicle after the secondary contact, and be vaulted forward at some projection angle, or be launched ahead of the vehicle in the approximately horizontal direction. After overturning through the air, the pedestrian falls to impact the ground and then tumbles/slides to rest.

The results of simulation tests have shown that the kinematics and characteristics of pedestrian struck by high/low-fronted vehicle are much more complicated than that of blunt-fronted vehicle to pedestrian collision, and moreover, the influence degree and laws of various factors (such as impact speed, braking intensity, pedestrian speed as well as collision forms etc.) on the pedestrian post-impact motion state and posture are respectively different.

Tab. 2 Contact times/impact speed threshold vs. influencing factors with fully braking

Impact Location	Impact Angle (°)	Pedestrian Speed V_P (km/h)	Impact Speed V_V (km/h)	Contact Times
1/2*W* (*W*: Vehicle Body Width)	0	0	<10	1
			>10	2
	45	5	<15	1
			>15	2
		13	<25	1
			>25	2
		20	<35	1
			>35	2
	90	0	<10	1
			>10	2
		5	<15	1
			>15	2
		13	<35	1
			>35	2
		20	<45	1
			>45	2
	135	5	<5	1
			>5	2
		13	<2.5	1
			>2.5	2
		20	<7.5	1
			>7.5	2
	180	0	<10	1
			>10	2
1/6*W* off Right Side of Vehicle Body	270	5	<45	1
			>45	2
		13	<80	1
			>80	2
		20	<140	1
			>140	2

1 Contact Times/Vehicle Impact Speed Threshold

When the front of high/low-fronted vehicle strikes pedestrian, there will be at least one contact between the pedestrian body and the vehicle, and furthermore, contact times and contact locations are relative to these factors such as braking intensity, impact speed, pedestrian speed as well as collision forms etc., which is obviously different from that of blunt-fronted vehicle/pedestrian collision (only one contact). The following two conditions will be analyzed.

Fully Braking Before High/Low-fronted Vehicle to Pedestrian Collision – If fully braking applied before high/low-fronted vehicle to pedestrian collision, then there will be one or two contacts between them, and moreover, the different vehicle impact speed threshold will correspond to the different collision circumstances.

When vehicle impact speed is below the impact speed threshold, there will be only one contact, namely after pedestrian's lower limbs/hip be struck, the pedestrian will be thrown directly ahead of the vehicle, or be vaulted forward flashing across the hood and front fender. When vehicle impact speed is beyond the threshold, two contacts will occur, namely, pedestrian's lower limbs/hip be struck initially by the front of vehicle, then, while rotating about the upper leading edge of the front with respect to the transverse axis of vehicle due to moment of rotation applied by the vehicle, the pedestrian will make secondary contact with the hood or windshield/A-pillar. The corresponding results of simulation tests are shown in tab. 2.

Non-braking in the Contact Process for High/Low-fronted Vehicle to Pedestrian Collision – If non-braking applied in the contact phase for high/low-fronted vehicle to pedestrian collision, then there will be at least two contacts between them, and moreover, the different vehicle impact speed threshold will also correspond to the different collision circumstances.

When impact speed is below the threshold, some contacts will occur (beyond twice), i.e. firstly be contacted by the vehicle front-end, secondly by the hood or windshield/A-pillar, and then, while sliding/tumbling over the vehicle body surface, or overturning as well as falling through the air, the pedestrian will make contact with the corresponding locations on the vehicle again. The contact times will be of greater randomicity, and the influence laws on it will be also more complicated. When impact speed is beyond the threshold, only two contacts will occur, namely, after two successive contacts with the front of the vehicle, the pedestrian will overturn and flash across the roof of the vehicle before falling to impact the ground.

The collision circumstance, which involving impact location (center section of the front-end, distributed by the 1/2 of VW Passat body width) and impact angle (θ = 90°), has been researched in this paper. The corresponding results of simulation tests are shown in tab.3.

Tab.3 Contact times/Impact speed threshold vs. influencing factors with non-braking

Impact Location	Impact Angle (°)	Pedestrian Speed V_P (km/h)	Impact Speed V_V (km/h)	Contact Times
1/2*W* (*W*: Vehicle Body Width)	90	0	<60	>2
			>60	2
		5	<35	>2
			>35	2

2 Rotation Angle of Pedestrian

When the front of high/low-fronted vehicle strikes pedestrian, as the vehicle's upper leading edge (i.e. impact point) is at or below the pedestrian's C.G., the vehicle will apply tremendous moment of rotation to the pedestrian body at the moment of impact, and the pedestrian body will make heavy rotation motion about the upper leading edge of the front with respect to the transverse axis of the vehicle. The rotation angle is mainly influenced by the front profiles and structure parameters, as well as the geometrical relationship between vehicle front-end and pedestrian body, while the influence of these factors such as impact speed, braking intensity, pedestrian speed as well as collision forms on it will be no noticeable. The corresponding results of simulation tests are shown in fig.5. Thereinto, for VW Passat at the impact speed of 60 and 120 km/h, the maximum rotation angles of pedestrian's torso (only contact phase of collision be considered) will respectively correspond to 126.0° (at 190 ms) and 152.5° (at 105 ms), while for Toyota Hiace at 50 and 100 km/h, the maximum rotation angles of pedestrian's torso will respectively correspond to 37.8° (at 65 ms) and 41.1° (at 50 ms). Obviously, the rotation motion of pedestrian body hit by the front of high/low-fronted vehicle will be much heavier than that of the blunt-fronted vehicle to pedestrian collision.

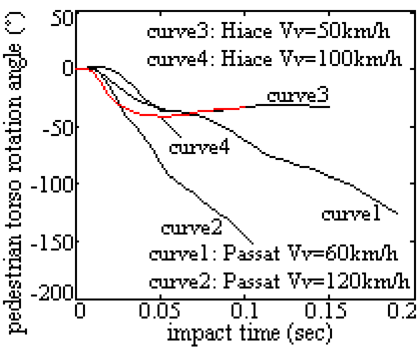


Fig.5 Comparison of rotation angle of pedestrian torso

CONCLUSIONS

Based on PC-Crash/MADYMO, the vehicle/pedestrian model is given and validated, the simulation test is constructed, and furthermore, the contact process for vehicle/pedestrian collision is simulated and reconstructed on PC-Crash platform, which can make it possibly analyze the kinematics of pedestrian in the contact phase of vehicle/pedestrian under different collision circumstances through modeling and simulation. The research results have shown that the modeling and simulation methods can be applied to perfectly conduct the simulation on pedestrian kinematics in vehicle/pedestrian collisions, which has been of practical application value in the research on collision safety for vehicle/pedestrian.

The results of simulation tests have shown that the kinematics and characteristics of pedestrian in the contact phase for blunt-fronted vehicle/pedestrian collision are evidently different from that of high/low-fronted vehicle/pedestrian collision, and moreover, the influence degree and laws of various factors such as vehicle's front profiles and structure parameters, the geometrical relationship between vehicle front-end and pedestrian body, impact speed, braking intensity, pedestrian speed as well as collision forms etc., on the pedestrian post-impact motion state and posture are respectively different. The comparisons between simulation results and real world vehicle/pedestrian collisions under observation as well as crash tests results have shown that a perfect harmony and consistency of kinematics of the pedestrian, which can provide a certain guidance meaning for analysis on kinematics and kinetics of the pedestrian in vehicle/pedestrian collisions as well as increasingly developing technology appraisal of road accident.

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