Simulation of car-pedestrian impacts. A new human-body mathematical model

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1 Introduction

In the European Union (EU) around 10,000 pedestrians are killed each year and 90,000 seriously injured, resulting in substantial economic losses due to fatalities and long-term consequences. The improvement of pedestrian safety is therefore considered a priority in traffic safety strategies (EEVC, 1985; ETSC, 1997a). The relative world-wide frequency of pedestrian fatalities varies approximately from 10 to 50 %. These differences are related to a number of factors such as road user behavior, legislation, education and training, social environment, road traffic environment, and vehicle safety. There are thus several different strategies which have to be undertaken to achieve acceptable safety for these road users and reduce the incidence and the severity of these accidents.

Since pedestrians are unprotected in vehicle impacts, they are considered a high risk population. It is extremely hard to find relevant vehicle designs to reduce the injury risks and severities. This paper gives a summarized description of a model which could serve as a useful tool for studying different countermeasures to reduce the severity of accidents.

Since the 1970's, many studies on injury mechanisms, tolerance levels, influences of the vehicle design on impact responses, safety countermeasures and assessment techniques have been carried out. Pedestrian substitutes such as biological specimens, mechanical dummies and mathematical models have been used in these studies. Data from real accidents as well as from simulations have served to analyze the influence of vehicle designs. The bumper, bonnet and windscreen have been shown to be the major injury-producing car structures.

During the past two decades significant reductions in pedestrian fatalities have been achieved in Europe (ACEA, 1992) and in the United States (NHTSA, 1992). This tendency is mainly due to improved traffic planning. However, new aerodynamic designs of cars may have contributed to the reduction of pedestrian injuries. So far, there is no statistical study to prove injury reduction by changes in car-front shape. However, the findings from experimental studies (EEVC, 1985; NHTSA, 1993) support the fact that the potential benefit may obtain from changes in front-end shape with rounded bonnet edges, smooth surface and low bumper, which is in accordance with the principle of the aerodynamic design of cars. ETSC (1997b) has recently estimated a potential reduction of fatalities by 7% if pedestrian-friendly car designs were to be introduced.

The growing use of small city cars in urban areas of European countries has entailed higher risks for pedestrians as small city cars have stiffer front regions than bigger cars to achieve acceptable compatibility in crashes with the latter (Hoffmann and Renner, 1994; Maurer et al., 1996). Therefore, there is an increasing concern about the city car designs also for pedestrian protection.

1.1 Injury epidemiology

Vehicle impacts have been confirmed to be the main cause of fatal and severe injuries (Ashton and Mackay, 1979). The secondary impact, the pedestrian-ground contact may of course also contribute to severe injuries, depending on which body area hits the ground first and at what velocity.

Pedestrians struck at impact speeds less than 25 km/h usually sustain only minor injuries. Serious injuries occur frequently at velocities between 25 and 55 km/h whilst at velocities greater than 55 km/h the pedestrians are most likely to be killed (Ashton, 1982) (fig. 1).

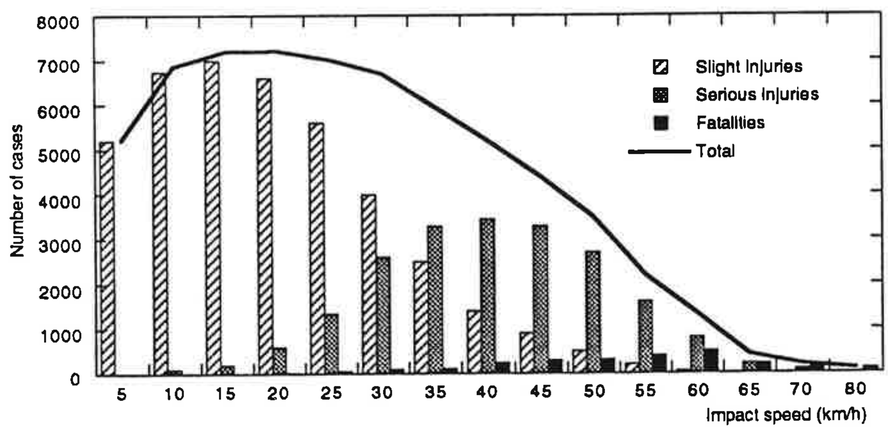


Figure 1.The injury severity distribution as a function of impact speed (based on Ashton, 1982).

The head and the lower extremities have been found to be the most frequently injured. At impact speeds less than 30 km/h, there is a high risk of modest leg/knee injuries (AIS 2-3) and these may result in long-term or permanent disabilities. The risk of fatal head injuries increases rapidly at impact speeds greater than 40 km/h.

1.2 Impact dynamics

The kinematics of the pedestrian and the distribution of injuries in car-pedestrian impacts are influenced by impact speed, car front shape and stiffness, bumper height, bonnet height and length, size of the pedestrian, and standing position of the pedestrian relative to the car (fig. 2).

When an adult is struck by a car front, the first contact occurs between the bumper and either the leg or knee-joint area, followed by the thigh contacting the bonnet edge. The lower extremity of the body is accelerated forwards, which causes the upper body to rotate relative to the car. Consequently, the pelvis and chest are impacted by the bonnet edge and top, respectively. The head may hit the bonnet or windscreen at a velocity estimated as a ratio of 0.7 - 0.9 to the car-travel speed for big cars (Pritz, 1983) and 1.1 - 1.4 for small cars (Cavallero et al., 1983). The victims then fall onto the ground. During the course of car-pedestrian contacts, the whole body wraps around the front of the car. The contact location of the upper body segments can be estimated by the wrap-around distance (WAD) along the car-front surface (fig. 2).

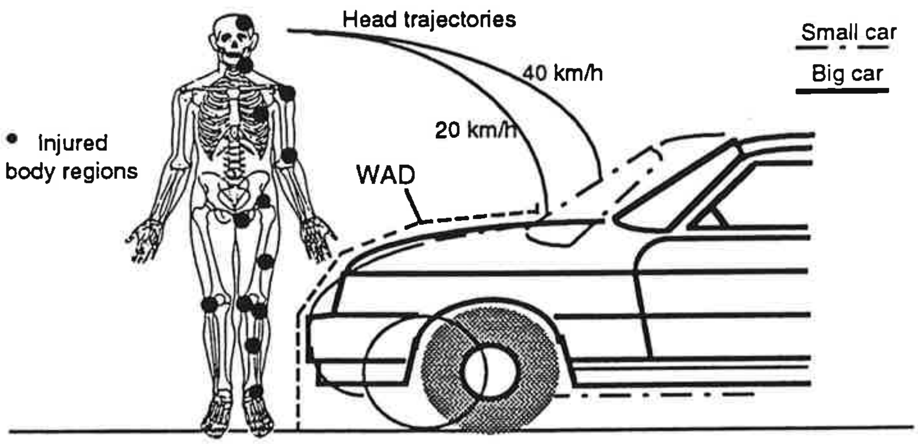


Figure 2. Distribution of injuries to an adult pedestrian in frontal car-pedestrian collisions, trajectories of the head with respect to small and big cars, changes of the locations of head impact at varying impact speeds, and the WAD (wrap around distance) (from Yang, 1997).

1.3 Injury and protection assessment techniques

To investigate the pedestrian impact response and injury mechanisms, and to assess car front aggressiveness, three different models can be used: human cadavers (biological models), mechanical or mathematical models. During the past decades, mainly biological and mechanical models have been used.

The use of cadavers in crash tests is mainly relevant for the study of the kinematics during an impact for different body segments, and to get insight into injury mechanisms.

Experiments with crash dummies are carried out to assess the interaction between the vehicle and the human body during the accident, and to evaluate the protective capacity of vehicles and safety devices. During the last decade, ongoing efforts have been oriented towards developing a new pedestrian dummy (Aldman et al., 1986).

A subsystem test method to assess the aggressiveness of passenger car-fronts to pedestrians has been proposed by EEVC (1994) and has been suggested as the European regulation. Lawrence et al. (1993) calculated a cost-benefit ratio of 7.5:1 if the EEVC subsystem test procedure were implemented, a result which today is widely discussed not least within the automotive industry. The configurations, requirements and thresholds for the subsystem tests are summarized in fig. 3.

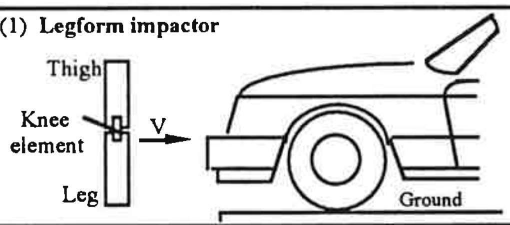
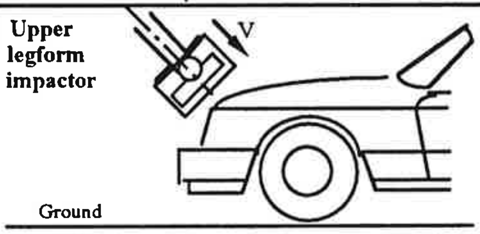
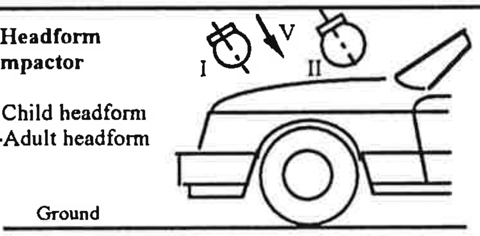
Configuration of subsystem tests	**Test requirement**	**Threshold (at 40 km/h)**
(1) **Legform impactor** 	- knee bending angle - knee shearing dislocation - acceleration at upper end of the tibia	< 15° < 6 mm < 150 g
(2) **Upper legform impactor** 	- impact force - bending moment	< 4 kN < 220 Nm
(3) **Headform impactor** I - Child headform II -Adult headform 	- Head Performance Criteria (*HPC*) - Nine tests shall be carried out with each headform impactor at positions judged to be the most likely to cause injury	< 1000

Figure 3. The EEVC impactors for pedestrian subsystem tests (based on EEVC, 1994)

1.4 Mathematical modeling of vehicle-pedestrian impacts

With the rapid development of computer hardware and software, mathematical models are increasingly being used as a complement to experimental methods, and play an important role in traffic safety research. Mathematical models can be used to analyse accidents, to design safety devices, to study crashworthiness and impact responses of the human body, as well as to assess injury risks in various types of accidents. Advantages of mathematical models are the exact repeatability of a simulation, and the possibility to easily conduct parameter studies. The mathematical models allow calculation of the detailed physical quantities within a biological structure. The results from validated mathematical models may supplement the data obtainable in crash tests.

Since the 1970's, a number of mathematical models have been developed for simulations of vehicle-pedestrian impacts. However, in these simulations, the impact responses of the models appeared excessively stiff, compared with the impact responses of a human subject since the models usually were based on crash dummies.

There is thus still a need to develop and validate a realistic human-body model. The knee joint and leg segment have to be adequately represented in the model so that it will allow the simulation of the knee responses associated with leg fracture, the investigation of the influence of car-front end on head responses to bonnet/windscreen impacts, and the prediction of the risk of pedestrian injury in car-pedestrian impacts. Well validated biofidelic mathematical models should be promising for the analysis of pedestrian impact responses and the study of the performance of the shape, stiffness, and design features of a vehicle, and the influence of the collision speed.

The aim of this study is to develop and validate a 3D mathematical model of the human-body to simulate car-pedestrian impacts. The model may be used to predict the risk of pedestrian injuries, to evaluate the performance of car fronts, and to study the influence of the collision speed.

2 Methods

A human body mathematical model was developed and used to simulate car-pedestrian impacts (fig. 4). The model uses the commercial software MADYMO 3D and consists of fifteen body segments connected by fourteen joints, including two human-like knee joints and two breakable leg segments. The characteristics of the body segments and the joints were based on available biomechanical data. The car-front model was based on that of Ishikawa et al. (1993). A detailed description of the model can be found in Yang and Lövsund (1997).

The validity of the model was evaluated by comparing results from computer simulations and published impact tests with cadavers. Available materials from tests include kinematics of pedestrian substitutes and measured injury-related parameters.

A parameter study has so far been performed by means of a factorial test with the following car-front parameters: bumper height, bumper stiffness, bumper lead distance, height of hood-edge, hood-edge stiffness, and impact speed. The results have been used to evaluate the effects of these parameters on impact force, knee rotation angle, knee ligament strain, head impact force, HIC value, and head angular acceleration.

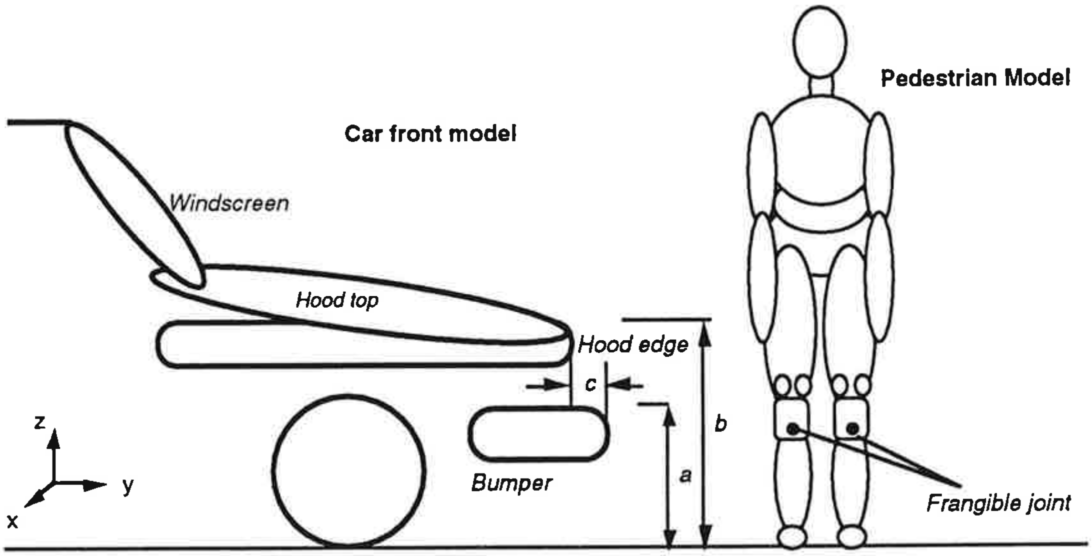


Figure 4. The simulation set-up for the car-pedestrian impact tests; a = bumper height, b = hood edge height, c = bumper lead distance.

3 Results

Two examples of the overall kinematics of pedestrian substitutes in the impact tests and simulations at impact speeds of 32 and 39 km/h are presented in fig. 5. The spatial motion of the pedestrian substitutes found in the impact tests is well predicted with the mathematical

4 Discussion

Pedestrian protection is one of the priority items in traffic safety strategies (EEVC, 1985; ETSC, 1997a,b) due to a high incidence of vehicle-pedestrian accidents and a high proportion of pedestrian fatalities among all killed road users. Furthermore there is a high risk of permanent disability. Effective countermeasures require knowledge about pedestrian injuries and injury mechanisms in accidents. Knowledge about injury mechanisms of pedestrians in car impacts has mainly been achieved from tests with cadavers. Cadaver tests, however, can not be used for extensive study of safety countermeasures due to ethical problems and high cost of such tests. Several types of dummies have therefore been developed to evaluate new countermeasures. So far none of them have been found appropriate to simulate responses of pedestrians in car impacts due to biofidelity and repeatability problems.

There exist several pedestrian mathematical models. The earlier pedestrian models show a limited biofidelity, and only allow for the prediction of the kinematic behavior. None of the previous models were used in the evaluation and development of countermeasures. Consequently, there is an increasing need for pedestrian mathematical models with improved biofidelity which are suitable for the prediction of the kinematic behavior and injury risks of pedestrians as well as for the evaluation of safety concepts in the early stages of car designs.

The developed human-body 3D mathematical model is able to simulate the responses of pedestrians in car impacts. The model provided valid results for car-pedestrian impacts at speeds of 25 to 39 km/h, which are the most common in real world accidents.

Important injury-related parameters can be calculated by means of the model, including impact forces, accelerations for different body segments, HIC, transverse dislocation and contact forces between articular surfaces, knee-ligament strain, and knee-bending angle. It is therefore considered a valuable tool to predict the risk of pedestrian injuries in accidents.

The pedestrian model is sensitive to changes in car-front parameters and impact speeds, and is thus also a useful tool for analyzing pedestrian responses, especially to the lower extremities, in different impact conditions and for studying the performance of the vehicle exterior as it relates to pedestrian protection.

Acknowledgement

This study was partly sponsored by the Swedish Transport and Communication Research Board (KFB).

model. It shows good flexibility in the lateral rotation of the body segments. The time history and the location of the head impact to the windscreen are correctly simulated.

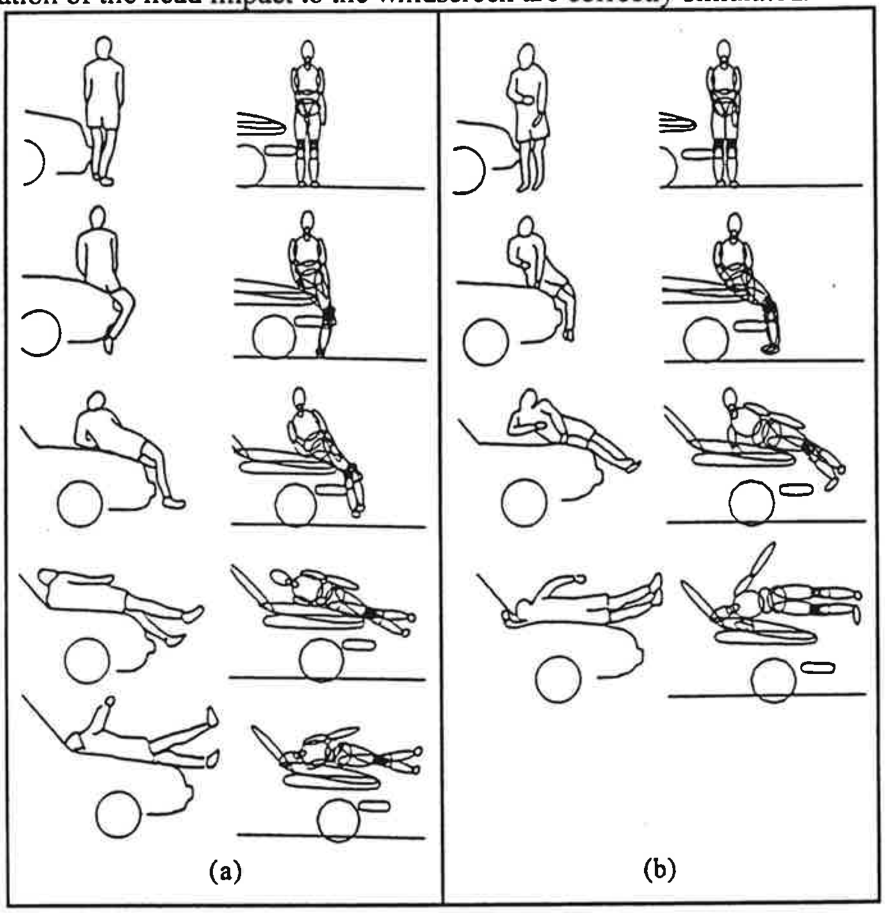


Figure 5. Comparison between the tests and corresponding simulations for kinematics of the pedestrian substitutes at impact speeds of (a) 32 km/h, and (b) 39 km/h; time step $\Delta t = 50$ ms.

A comparison between test and simulation at 32 km/h for the accelerations of the leg, pelvis and head indicated that the accelerations of the leg and head measured in the test are well predicted in the simulations in terms of the peak values and the curve wave shapes. The pelvis acceleration was underestimated in the simulation. A comparison between test and simulation at 39 km/h for the accelerations of the thorax, pelvis and head indicated that pelvis and head accelerations from the test were very similar with the corresponding results from the simulation regarding the peak values and curve wave shapes. The peak values of the thorax acceleration were underestimated in the simulation.

The model is sensitive to impact speed for almost all injury-related parameters. The lower extremity in the model is sensitive to the changes in bumper stiffness, bumper height, bumper lead distance, hood-edge height. The parameter study indicate significant effects of bumper height, bumper stiffness, bumper lead distance, and hood-edge height on responses of the knee-leg complex in a lateral impact to the leg. The head responses appear to be dependent primarily on hood-edge height.

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