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Influence of the front part of the vehicle and cyclist's sitting position on the severity of head injury in side collision

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An injury of cyclists during a collision with a car is currently a neglected topic. Most research projects evaluate in detail the injury of pedestrians, but with an increasing number of cyclists it will be necessary to devote more attention to their safety. This study is focused on the most common type of collision and offers insights into the biomechanics of cyclist's head injury without the use of bicycle helmet. Initial mechanical and kinematic conditions that affect Head Injury Criterion (HIC) after a car hits a cyclist were determined using simulation software MADYMO. In relation to HIC, three different shapes of the front part of the car and three basic cyclist's positions were compared.

Key words: *bicycle, biomechanics, head injury, multibody simulation*

1. Introduction

Interaction of a moving car with the human body is greatly biomechanically stressed topic that is studied in detail on a number of important sites around the world, both through real-world crash tests and modelling using computational methods. Traffic accidents are a global health problem, having some 1.2 million casualties per year [1]. Moreover, traffic accidents cause high fiscal damage (close to 2% of gross national product), and they have a negative effect on social area. Therefore, in 2000 the EU announced an ambitious plan of halving the number of people killed on European roads from 50 000 to 25 000 by 2010 [2].

In 2008, a total of 77 cyclists were killed on Czech roads, including 2 children under the age of 14 years. Other 431 cyclists were seriously injured and 2,516 suffered minor injuries. These data, however, refer only to accidents on the roads when the accident got reported to the police. The severity of accidents (number of deaths per 1000 accidents) caused by cyclists in 2008 was second highest after motorcycle drivers. In half of all cycling accidents, the rider's head was hit – either in a clash with the vehicle or with the ground. The most common locations of injury that occur after a fall from a bike is head – 44%, arm – 27%, lower limbs – 23% and abdomen – 6% [3]. The 60–90% of fatal cyclist injuries were due to head injury [4]–[7].

The 68 (88.3%) out of 77 cyclists killed at the time of an accident were not having a helmet equipped. In the case of severe injuries 80.7% (348 out of 431) and in the case of minor injuries 81.1% (2041 out of 2516) had no bicycle helmet equipped [3]. According to Maki, Kajzer [5], 92% of cyclists using helmets had

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no head injuries in traffic accidents, while 48% of cyclists without helmets had head injuries.

It was presented that shocks of car impacts to cyclists are similar to the car impact to a pedestrian [8]. Vehicle impact speed is the primary factor for the severity of injuries in collisions of cars with pedestrians [9]. If a pedestrian is struck at 50 km/h one is more than twice as likely to die than at 40 km/h and more than five times more likely than at 30 km/h [1]. Approximately 50% of fatal pedestrian accidents are at a speed of 50–80 km/h [1]. It has been shown that a place of head impact of a cyclist is more backward positioned than pedestrian's. This difference was explained by the different heights of the cyclist's and pedestrian's head from the ground [8], [10]. Cyclists are generally less involved in accidents leading to serious injury or death than pedestrians [6] and the risk of death or serious injury is also lower for cyclists than for pedestrians (in Japan) [5]. The relative speed between the cyclist and a car at the time of collision is higher than between the pedestrian and a car. One could therefore assume that cyclists will have a more serious injury than pedestrians, particularly in accidents involving smaller velocities. However, the results of analysis show the opposite trend (in the case of serious injury). Acceleration of cyclist's head is 50% lower than pedestrian's thanks to sliding on the hood of the car [6].

Analysis of accidents shows that cyclists suffer fewer fatal traumas during frontal impacts than during side impacts [11]. Most of the head impacts in an accident go from cyclist's side (57%) or from the front (27%) [4]. 66% of fatal accidents took place with the side impact to a cyclist, which means that side impacts are the most common configuration for the death of cyclists [5]. As the most common type of collision for the period 1.1.2007–30.6.2009 in the U.S., according to Olson [12] is the impact from the side (so-called Broadside).

2. Materials and methods

2.1. Head injury criterion (HIC)

To assess the severity of head injury Head Injury Criterion (HIC) was used, which is defined as

$$\mathrm{HIC} = \left\{ (t_2 - t_1) \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,dt \right)^{2.5} \right\}_{\max}$$

where $a(t)$ is the resultant acceleration of the head and t_1 and t_2 are variable initial and final time intervals during which HIC reaches its maximum value. For regulation purposes the maximum interval between t_1 and t_2 was set at 15 ms (HIC_{15}), or 36 ms (HIC_{36}). The use of HIC is based on proposal of the National Highway Traffic Safety Administration (NHTSA), 1972 [13].

For the direct impact it has been demonstrated that HIC is an acceptable discriminator between severe and less severe injuries [14]. It also correlates with the risk of fractures of the skull [15]. However, for the shock from different directions, a poor correlation between HIC and severity of injury was found. The explanation is that the rotation of the head, often the primary cause of various types of traumatic brain injury, was not taken into account [13]. HIC calculating head rotation has also been suggested but never thoroughly evaluated [16]. HIC predicts the risk of injury from external mechanical impact to the head, which can be measured directly from the crash test dummy, but does not take into account the internal mechanical response. Furthermore, there is no distinction between different types of traumatic brain injury. For research on the so-called "next generation wound" a computational model of the head was used [16]. More detailed description of the injury was achieved by using the calculated internal mechanical response, resulting from external mechanical impact to the dummy. Examples of such injury determination are SIMon, a simulated injury monitor [17], GAMBIT or Head Impact Power (HIP) [18].

2.2. Simulation of cyclist's being hit by a car

The MADYMO pedestrian model [19] consists of 52 rigid bodies. The outer surface is described by 64 ellipsoids and 2 planes. It is available in five body sizes: 3-year-old child, 6-year-old child, small female (5th‰), mid-size male (50th‰) and large male (95th‰), and may also be scaled using stature and mass. For this simulation a validated model was chosen of the mid-size male of 50th‰ of standing pedestrian "h_ped50el". Standing height is 1.74 m, knee height is 0.54 m and weight is 75.7 kg. In the ellipsoid pedestrian models, structural deformation of flexible components is lumped in kinematic joints in combination with dynamic restraint models. Deformation of soft tissues (flesh and skin) is represented by force-penetration based contact characteristics for the ellipsoids. These characteristics are used to describe contact interactions of the pedestrian model with itself and with its environment. Inertial properties of the pedestrian components are defined in the rigid bodies. All internal contacts within the human models are already included in the model include-files [19].

Many attempts have been made to validate pedestrian models in MADYMO by reconstructing the real collisions [20]. The human pedestrian model has been validated extensively. First, one series of leg shear and bending tests have been used [21]. The contact characteristics (stiffness, hysteresis, damping) with the various other body parts have been based on data found in literature. An extended description of the validation simulations and results can be found in [22]. From the extended validation of the pedestrian models it can be concluded that the models accurately predict the global kinematics, the models accurately predict the impact points on the vehicle, especially for the head, the models can reasonably predict the occurrence of fractures in the upper and lower legs during the impact between the pedestrian and the vehicle and the models can predict the shape and trends of the head, chest and pelvis accelerations and the bumper forces [19].

The model is mounted using the JOINT parameters on bicycle models (Fig. 1) with a geometry corresponding to a normal mountain bike, road bike and trekking bike. The bicycle models have been modelled using the Multibody modelling technique. Contact function between the rider and the bicycle was also set. Contact places are hands with handlebars and back with seat. The pedestrian model as the cyclist has been validated for lateral impacts up to 40 km/h by Hassel and Lange [23]. Pedestrian model was used as well for bicycle impacts by Rodarius, Mordaka [24]. Multibody modelling of cyclist impacts using MADYMO showed good ability of the model to reproduce cadaver kinematics for a 50 km/h side impact [25]. Multibody pedestrian and cyclist simulation models have the potential to provide similar information as a pedestrian dummy [25]. Currently the MADYMO pedestrian models are used in the EC project APROSYS, to reconstruct pedestrian–vehicle and cyclist–vehicle accidents [26].

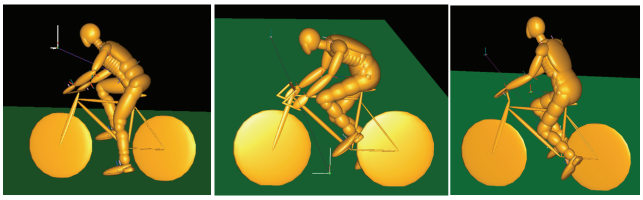

Fig. 1. Wheel models (left to right: mountain, road, trekking)

Three full body car pedestrian impact tests have been performed using PMHSs (post mortem human subject) [27]. These tests have been simulated for validation purposes of the pedestrian models. In the validation simulations, the pedestrian substitutes were each simulated with a scaled pedestrian model based on the height and weight of the unembalmed PMHSs. For each simulation the position and posture of the pedestrian model was adjusted in accordance to the position and posture of the PMHS in the simulated test [19].

For the validation the vehicle model represented a small family car and consisted of six ellipsoids. The bumper, the hood, the hood-edge and the windscreen

Table 1. Parameters of cars

	SEDAN	SUV	MPV	SEDAN – 0.2 m longer hood	SEDAN – 0.4 m longer hood
Impact edge height (m)	0.42	0.66	0.50	0.42	0.42
Beginning of the hood height (m)	0.63	0.90	0.70	0.63	0.63
End of the hood height (m)	0.83	1.12	1.00	0.89	0.95
Hood length (m)	0.70	0.77	0.60	0.90	1.10
Angle of the hood (Wed)	16.6	16.6	30.0	16.6	16.6
Length of the windscreen (m)	0.96	0.96	1.10	0.96	0.96
Height of windscreen upper edge (m)	1.36	1.65	1.60	1.36	1.36

were represented by one ellipsoid each, and the wheels by two ellipsoids. The geometry and dimensions of the car model were based on an existing car. The location of the centre of gravity and moments of inertia of the car model were approximated, based on the one-dimensional nature of the car motion in the tests. The dynamic characteristics of the bumper system (force-penetration for the contact) were based on results from legform to bumper impact tests by Schueler and Glasson [28]. The mechanical properties of the windscreen were based on the static data published by Yang, Lövsund [27].

According to validated model five types of vehicles were modelled in total with the characteristics of the front part listed in Table 1.

2.3. Simulation conditions

The simulation corresponds to the standard for crash tests ISO 13232 for motorcycles with configuration of objects marked as 143. The cyclist was moving at 15 km/h perpendicular to the direction of a car. The car crashed into the left side of the cyclist. Initial vehicle speed was 35 km/h, 40 km/h and 65 km/h (depending on the needs of the simulation) and in all the cases the slowdown of the car was 8.0 ms^{-2} which corresponds to an intense or panic braking. Braking deceleration begins when the contact between legs and car takes place. In simulation, explicit-implicit Euler method was used with fixed time step 1.00000E-05. Analysis type was dynamic with starting time 0.0000s and end time was 1.0000 s. Average time needed for the simulation was 25 minutes. We observed the primary and secondary body contact with the car, cyclist's trajectory in the air and on land, including the tertiary contact.

3. Results

3.1. Comparison of movement kinematics depending on car type

In the early after-impact phase the most important role is played by a high impact edge in relation to the biker's centre of gravity. The lower the impact edge is, the higher rotation the body gets. If the level of the impact edge is around the biker's centre of gravity, the biker gets carried by it. A shift in the original direction of movement is evident in all cases, because of cyclist's speed before the collision.

The vehicle type SEDAN (see Fig. 2) has the impact edge located below the cyclist's centre of gravity, therefore there is a rotational movement of the biker. After the primary contact, which is targeted on the lower limbs on the near side of the contact the body rolls over the front hood and windshield. The body is stretched into an upright position. The trunk retraction is apparent and is followed by contact of the head with the lateral part of the windscreen. The specific place of the impact of the head is determined by cyclist's height or length of individual segments of the body and hood length. The position of the body is the same for a vehicle type SEDAN with different front lengths (see Fig. 3). The body shape follows the hood and therefore the points of head impact are different. The longer hood makes the head hit to the windshield lower.

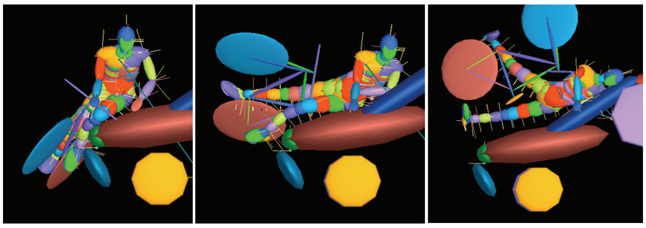

Fig. 2. Detail of movement: SEDAN – mountain bike at 40 km/h

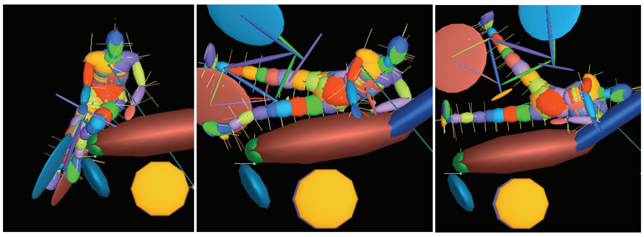

Fig. 3. Detail of the movement: SEDAN with the front longer by 0.4 m – mountain bike at 40 km/h

We see a significant difference in the SUV-type vehicles (see Fig. 4), where the impact edge is approximately at the same level as the biker's centre of gravity. This leads to carrying the biker and shaping his body according to the hood. The primary impact is directed into the hip and upper limb close to the collision. Body retraction is in opposite direction compared to collision with a vehicle type SEDAN. There is a significant shoulder rotation, due to hitting the upper limb and the head impacts frontally or frontal-laterally to the point where the front hood turns into the windshield.

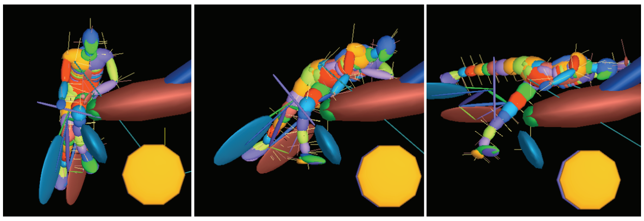

Fig. 4. Detail of movement: SUV – mountain bike at 40 km/h

The impact edge below cyclist's centre of gravity causes the rotation of the cyclist's body in the case of the MPV-type vehicles, however (see Fig. 5) the steeper front hood and closer position of the windshield stops the rotation soon and the body copies the hull shape without retraction. The head impacts the front window laterally.

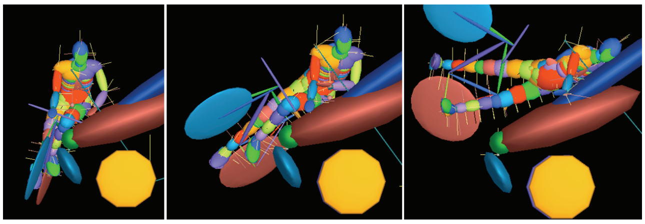

Fig. 5. Detail of movement: MPV – mountain bike at 40 km/h

3.2. Comparison of movement kinematics depending on cyclist's position

Cyclist's position, with different bending angles of the trunk, affects the kinematics of movement just after the primary impact especially by the height from which the head strikes the car hood. During the impact the head moves along different paths and thus acquires a different impact velocity. As documented in Fig. 6, in the "lying" position on the road bike the head hits from the smallest height. The opposite situation occurs in the upright position on the trekking bike, when the head falls from the greatest height (see Fig. 7).

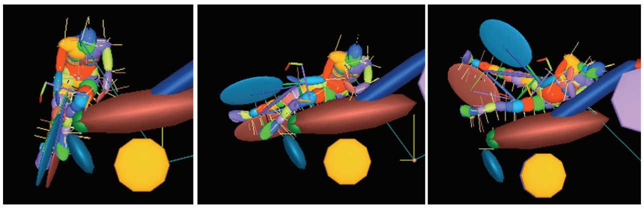

Fig. 6. Detail of movement: SEDAN – road bike at 40 km/h

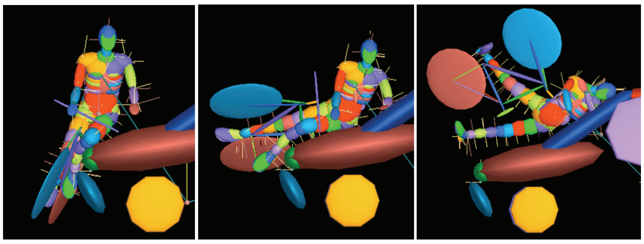

Fig. 7. Detail of movement: SEDAN – trekking bike at 40 km/h

3.3. Effect of the front of the car on HIC_{36} and influence of cyclist's position on the HIC_{36}

The average values of HIC_{36} in the contact phase (primary and secondary phase) for three different types of cars and tree different types of positions are summarized in Table 2. The difference between the values of HIC_{36} for individual positions is mainly due to different head height above the hood, which affects an impact speed of the head and accordingly also its acceleration.

Table 2. Average HIC_{36} for vehicle types by speed and for each position

HIC_{36}/vehicle speed	35 km/h	40 km/h	65 km/h
SEDAN	60	135	927
SUV	216	412	2353
MPV	100	211	1515
Mountain bike	119	180	1345
Road bike	24	46	1009
Trekking bike	234	532	2441

The shape of the front of the car will affect the speed of the head, the head acceleration respectively, which is indicated by a change of HIC_{36}. In detail the crash speed of the head is summarized in Table 3. The highest speed we measured for the SUV-type vehicles, the lowest for the SEDAN vehicle.

Table 3. Average speed of the impact of the head, depending on the type of car

Head impact speed (m/s)/ vehicle speed	35 km/h	40 km/h	65 km/h
SEDAN	4.6	5.7	10.6
SUV	7.1	8.2	13.5
MPV	5.4	6.2	11.1

4. Discussion

Limitation of this study is validation of bicycle–car impact. A model of standing pedestrian is even widely used for a simulation of cyclists' accidents by several highly cited researchers [5], [25], [29]–[31] as well as by well-known Netherlands Organisation for Applied Scientific Research (TNO) [23], [24]. It is possible to find the validation through the kinematic analysis using "throw distance" parameters. When we compare our model situations for "throw distance" with the other authors' published data from real accidents (lateral impacts) [32]–[34], the results are very similar (Fig. 8).

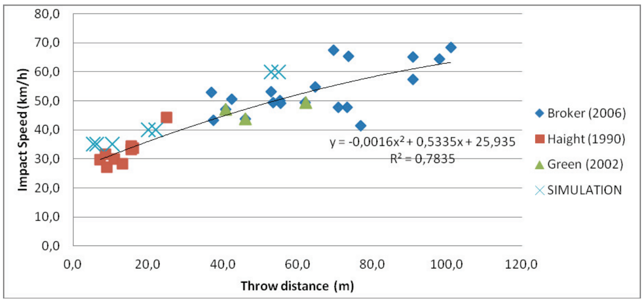

Fig. 8. Throw distances after bicycle–car impacts

In all the situations simulated the severity of head injuries grew with increasing speed of a car, which is consistent with the analysis of pedestrian impacts [35]. The place of the impact of the head from an analysis of movement kinematics corresponded to the impact point according to Maki, Kajzer [5], where during an impact to Bonnet-type vehicles (mini-car, sedan Small, Midsize sedan, coupe Large, Sports and specialties, Wagon) the biker's head hit either the windshield or roof, but did not hit the front hood. The trajectory of the head of a cyclist and pedestrian indicates increasing distance of the place of head impact to the hood for low-placed impact edges [6]. The results show that the friendliest type of the car is SEDAN, i.e., low impact edge and wedge-shaped front hood, the least friendly vehicle type is an SUV with a high-placed impact edge and a high nose. SEDAN forwards rotation to the cyclist and the final component of the impact velocity into the windshield is very high. SUV picks the cyclist and throws him forward. In the analogous experiment with pedestrians it was shown that SUVs, vans and pickup trucks were twice as likely to cause traumatic brain injury at low speeds as conventional SEDAN-type vehicles, this is not right at higher speed [35]. Whether the injury occurs in contact with the car or with the ground was not specified in this work. Compared with conventional SEDAN-type vehicles there was higher mortality in pedestrians hit by pickups and SUVs, but not by vans [35]. SUVs and pickups also showed a higher percentage of injuries of the lower limbs above the knee, but a lower percentage of injuries below the knee [35].

The MPV vehicle type does have a low-placed impact edge and wedge-shaped front part, but shorter and steeper hood and windshield go directly against the dynamic component of rotation, due to which they stop and throw the body forward. The difference between various types of cars deepens with increasing speed (see Fig. 9).

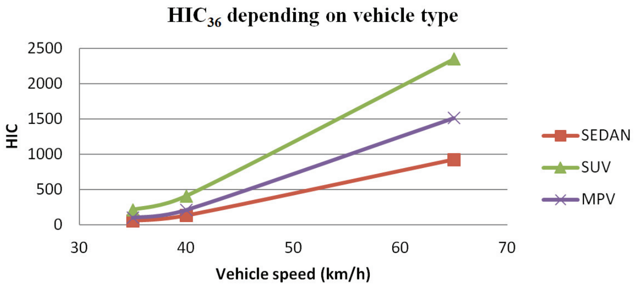

Fig. 9. Average values of HIC $_{36}$ for various types of vehicles by speed

In accordance with the results of the previous study [35] an influence of design of the front vehicle part is evident. Based on our results we can conclude that the HIC_{36} is the highest and also rises most steeply for a vehicle with the longest front part (see Fig. 10).

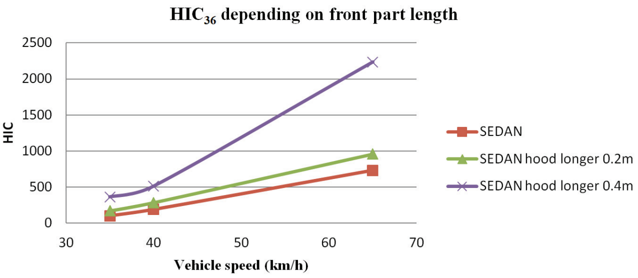

Fig. 10. HIC_{36} for mountain bike and various lengths of front part

The impact velocity and impact angle of the head are very important parameters for the cyclist's head injury [6]. The worst values of HIC_{36} were determined for trekking bikes, which means an upright position (see Fig. 11) because the head in upright position has the highest impact velocity.

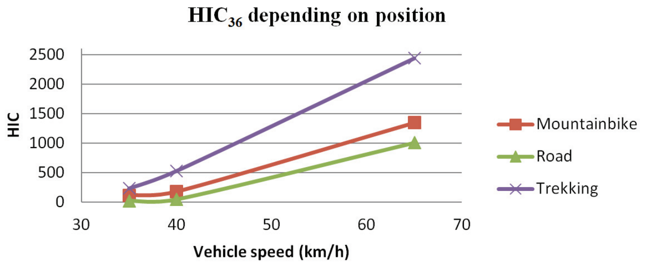

Fig. 11. HIC_{36} depending on the position

In terms of statistics the side impact is the most common type of cyclist accidents on the roads. The issue of head injury in general is a very complex topic; specifying a particular internal mechanical response to the external mechanical loading is only possible thanks to advanced simulations using finite element methods. However, in terms of time consumption of these methods the head injury criteria are used for safety testing. We used the most common criterion HIC_{36}, with the knowledge of all limits, particularly not taking rotation of the head into account. For a comprehensive evaluation of cyclist's head injury during a collision with a car, the rotation can occur and the overall consequences can be different. However, to assess the absolute influence of certain parameters in this type of collision HIC_{36} can be used as a benchmark for determining severity of injury.

The damage causing mechanisms during cycling and pedestrian accidents are similar. For cyclists we expect their higher speed before impact, which can cause a cyclist to fall obliquely on the front hood after the side impact and is subject to shear forces and the resulting motion can be composed of multiple components. As a positive factor of the cyclist's speed in a side impact we can pronounce the slip of the rider over the front fender and thus avoiding further contact with the car's windshield. According to the analysis of movement kinematics by Maki, Kajzer [5] on which our experimental work was based, a cyclist hit by a SEDAN glided over the hood and gradually fallen over and his head hit the windshield or roof. A cyclist hit by SUV was picked up and followed the shape of the front of the vehicle. Unlike our work, the Maki, Kajzer [5] did not distinguish between the types of vehicles and even did not take braking capabilities of the vehicle into account in the simulation analysis in the MADYMO software (wet or dry road, tire status or whether there was any braking immediately before impact) which undoubtedly affects results of the simulation as well as analysis of real situations. Due to our efforts of the most accurate model of real situations the vehicle deceleration of 8 m/s immediately before the collision was calculated in our analysis. At the same time, the results clearly show that it is necessary to distinguish between different types of cars or characteristics of their fronts, as these parameters dramatically affect the trajectory on which the head of the cyclist moves and thus the resulting HIC values or the severity of injury.

Another difference in comparison to a pedestrian is the position of centre of gravity. It is higher for a biker. In the cases where the impact edge of the car lies lower the head injuries appear to be less severe and therefore a higher centre of gravity of a cyclist will be more favourable in this respect.

5. Conclusion

This work summarizes the issues of injuries among cyclists and their specifics in collision with cars. By using the simulation program MADYMO a sensitivity analysis was performed and essential parameters affecting bicycle-related head injury in a side collision with a car were established.

During the simulations we calculated the exact data for the particular situations. We have demonstrated that the severity of head injury increases with the speed of the car at the moment of the impact. For the higher-positioned centre of gravity of a cyclist (trekking bike) the HIC_{36} is higher than for lower position (road bike). For SUV-type vehicles the HIC_{36} is higher than for the SEDAN type and the SEDAN type with a longer front hood will cause more severe head injuries than a SEDAN with a shorter front hood. These conclusions are of course only for specific vehicle parameters (Table 1) in a category and for specific morphological parameters of the human body of 50th‰ of standing pedestrian.

The present work could be the basis for more detailed and extensive analysis in the experimental area, which can be expected to refine the results for different types of human interaction with vehicle. The results of such studies are useful and interpretable in a number of industries related to construction of vehicles and safety equipment, and ultimately should help to reduce the frequency and severity of traffic injuries.

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