Analysis of Cyclist Kinematics in Car Impacts considering different Vehicle Fronts, Collision Speeds, Body Heights and Impact Constellations

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ABSTRACT

In order to analyse the kinematics of cyclists in car accidents a wide range of impact constellations has been simulated using the MADYMO multi-body solver. The study comprises six real passenger car fronts, all representing different vehicle classes, named Compact, Sedan, Van, Sports Car, SUV and OneBox [1]. Four cyclist heights are considered, a 6-year-old child, a 5 %-female and a 50 % as well as a 95 %-male. Each cyclist model consists of a size-specific bicycle model and the corresponding MADYMO Ellipsoid Pedestrian Model placed on top.

Parameter studies carried out in advance reveal that the pedal position has a decisive effect on the cyclist kinematics. Therefore four different pedal positions have been defined with the leg facing the vehicle backward, forward, up and down. Three representative impact scenarios have been derived from an accident analysis, including two perpendicular constellations with a lateral impact of the cyclist in the central and outboard area of the car front (crossing scenarios) as well as one oblique scenario.

While for the oblique scenario a constant vehicle speed of 25 km/h is defined, this parameter is varied for the crossing scenarios. Here the simulations are conducted with vehicle speeds of 40, 35, 30 and 20 km/h. The speed of the cyclists is not varied and always amounts to 15 km/h.

The simulation models and parameters have been validated by reconstruction of a real accident taken from the GIDAS database. The impact positions of hip and head as well as the final position of the cyclist could be reproduced with satisfying accuracy.

The simulation results reveal an increased head impact area, which can reach up to the roof leading edge and in case of sports cars even beyond. Furthermore, the study shows high values for head impact velocity as well as angle. Even the average values for the head impact velocity usually lie above the collision speed.

Keywords: cyclist kinematics, simulation, front shape, collision speed, pedal position, bicycle & cyclist sizes.

1 INTRODUCTION

Although the focus in the field of vulnerable road user (VRU) safety has been on pedestrian safety so far, accident data shows a high relevance for cyclist-passenger car collisions as well.

In 2010, almost 2000 cyclists were killed in road accidents in Europe (referred to EU-15 plus Poland, Romania, Slovenia, Czech Republic and Hungary), which makes up 6.8% of the total number of road accident fatalities [2].

A simulation study has been carried out in order to analyse the kinematics of cyclists in car accidents for a wide range of impact constellations. Three representative impact scenarios have been derived from an accident analysis, including two perpendicular constellations with a lateral impact of the cyclist in the central and outboard area of the car front (crossing scenarios) as well as one oblique scenario.

The goal of the study is to provide a comprehensive overview of head impact locations, velocities and angles by consideration of different vehicle front geometries, cyclist models, pedal positions, impact scenarios as well as vehicle speeds. The according simulations have been conducted with the MADYMO multi-body solver. In the following, the simulation models as well as boundary conditions used within the study are described. This also comprises a reconstruction of a real accident taken from the GIDAS (German In-Depth Accident Study) database in order to validate the simulation models and parameters.

2 SIMULATION

As a first step, the definition of representative vehicle as well as cyclist models is necessary, so that both the influence of the vehicle front geometry as well as the cyclist stature can be comprehensively addressed.

2.1 Simulation models & impact scenarios

The study comprises six real passenger car fronts, all representing different vehicle classes, named Compact, Sedan, Van, Sports Car, SUV and OneBox. Those classes are based upon a categorisation, which has been developed to consider the different front designs of modern cars and their impact on pedestrian accident kinematics [1]. For each class a representative real passenger car front has been defined and converted into MADYMO, i.e. facet surfaces have been generated based on the corresponding finite elements. Figure 1 shows the front geometries of those class representatives.

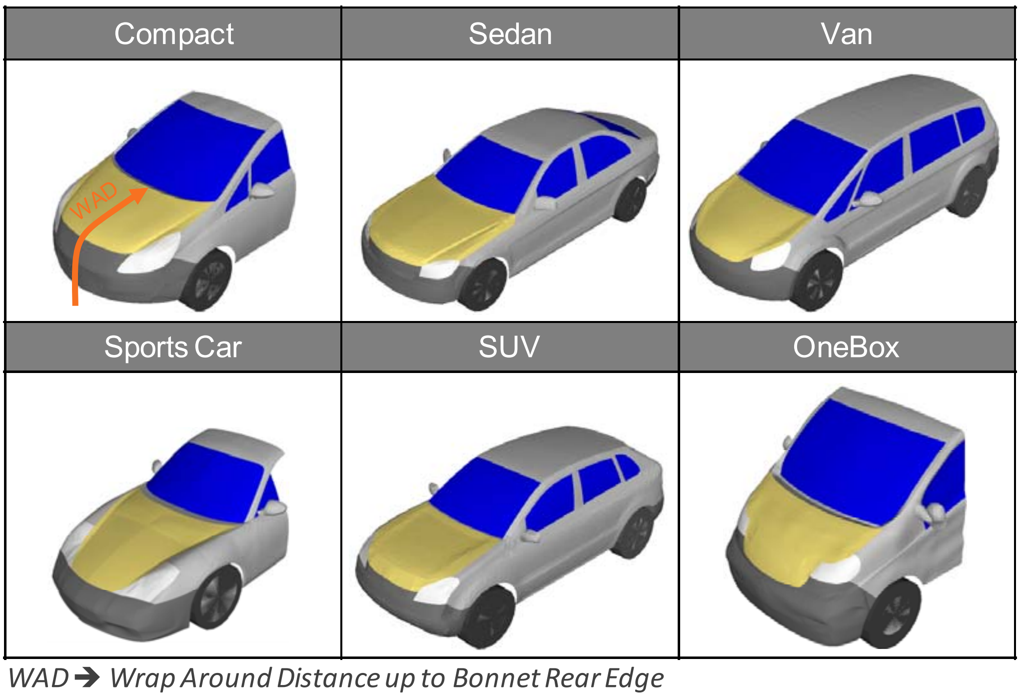


Figure 1. MADYMO models of vehicle class representatives.

The geometrical parameters of the vehicle class representatives are given in Table 1. These are the height of the bonnet leading edge (BLE), the wrap around distance (WAD) of the bonnet rear edge, the bonnet angle and the angle between bonnet and windscreen, measured at the corresponding intersection with the vehicle longitudinal centre plane. The height of the bonnet leading edge has significant influence on the accident kinematics while the WAD of the bonnet rear edge is relevant for the location of the primary head impact relative to the vehicle front, i.e. whether the VRU impacts on the bonnet or in the windscreen area.

Table 1. Geometrical parameters of vehicle class representatives.

Vehicle Model	BLE Height [mm]	Bonnet Angle [°]	Angle Bonnet-Windscreen [°]	WAD [mm]
Compact	777	18.5	173	1522
Sedan	763	11.3	161.3	1877
Van	775	21.8	172.2	1607
Sports Car	532	16.2	166.7	1812
SUV	955	13.4	163.9	1793
OneBox	1021	31.2	172.7	1550

The contact stiffness characteristics defined for the vehicle models are derived from the APROSYS-project and based on the stiffness corridors developed by Martinez et al [3]. For the study no deceleration is applied to the vehicle models prior to the primary head impact, which on the one hand reflects the large percentage of cyclist-passenger car accidents without braking and on the other hand guarantees uniform and reproducible boundary conditions for the analysis of the primary head impact. A brake dive of the vehicle is not considered in the simulations. Simulations are stopped right after the primary head impact.

The kinematics is determined by simulations with the MADYMO multi-body solver, taking collision speeds of 20, 30, 35 and 40 km/h into account. The collision speed corresponds to the vehicle speed at the time of the initial contact between cyclist and vehicle. The simulated scenarios are based on accident research data. There are two perpendicular constellations with a lateral impact of the cyclist in the central and outboard area of the car front, i.e. the cyclist models are configured facing sideways to the vehicle and with different overlap (Figure 2).

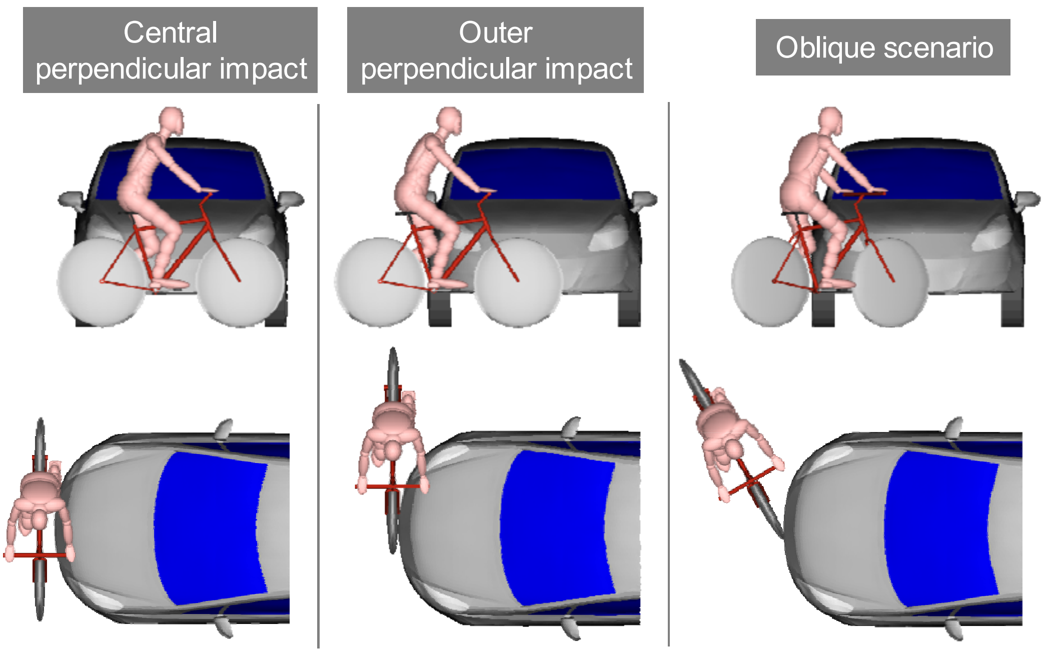
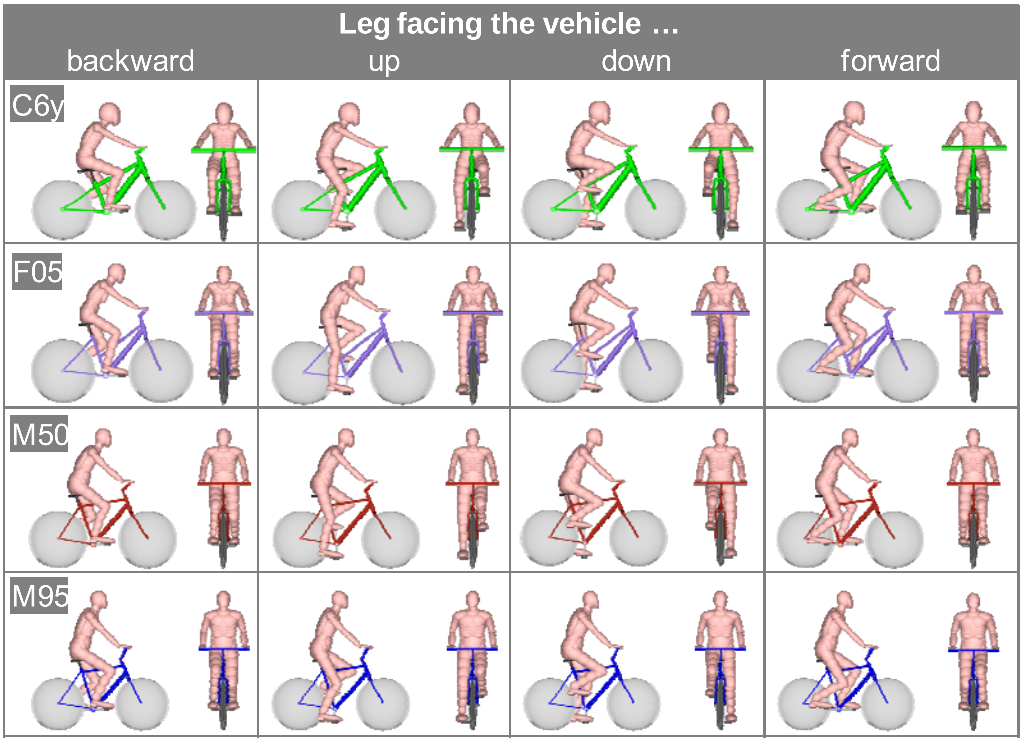


Figure 2. Impact scenarios.

Beside those crossing scenarios an oblique scenario is considered, which represents an impact constellation with a turning car. This scenario results from the outer impact constellation by rotating the bicycle by 30 degrees towards the vehicle. It addresses those turning accidents where the velocity vector of the cyclists points in direction of the oncoming car, which leads to a higher relative head velocity. Due to the turning manoeuvre of the car its speed is defined lower than for the two crossing scenarios. The value chosen is 25 km/h and it is not varied within the study. For all constellations the speed of the cyclist amounts to 15 km/h.

Beside different adult cyclist models (5th percentile female, 50th percentile and 95th percentile male) a 6-year-old child model is also considered. Those four models cover a wide spectrum of possible cyclist heights. Each cyclist model consists of a size-specific bicycle model and the corresponding MADYMO Ellipsoid Pedestrian Model placed on top, as illustrated in Figure 3. The saddle and steer heights are adapted according to the cyclist anthropometry. Due to the way contact is generated within the simulation the bicycle frame together with the front fork and pedals perform ideal stiff when they impact the vehicle. For the tyres and the saddle the hysteresis-contact-model of the cyclist's shoe soles is used.



	C6y	F05	M50	M95
Height cyclist [m]	1.17	1.53	1.74	1.91
Weight cyclist [kg]	23.0	49.77	75.7	101.1
Mass bicycle [kg]	12.6	15.1	16.8	17.3

Figure 3. Cyclist models & pedal positions.

Parameter studies carried out in advance reveal that the pedal position has a decisive effect on the cyclist kinematics. Therefore different pedal positions have been defined with the leg facing the vehicle backward, forward, up and down (Figure 3). The consideration of six vehicle fronts, four cyclist models, four pedal positions, three scenarios and four collision speeds (no speed variation for the oblique scenario) adds up to a total of 864 simulations within the study.

2.2 Model validation

The simulation models and parameters have been validated by reconstruction of a real accident taken from the GIDAS database. Both accident scenario as well as accident vehicle correspond well to the simulation boundary conditions described above. The vehicle is equivalent to the simulation model Compact (Figure 1). For the cyclist the 50th percentile male allows a sufficient representation within the simulation. But since the cyclist was riding a bicycle which was too big for his stature, a case specific bicycle model has to be built up. Furthermore, the geometry of the handlebar is not consistent with the straight one of the already generated bicycle models (Figure 3).

The impact locations of hip and head as well as the final position of the cyclist could be reproduced with satisfying accuracy, as Figure 4 illustrates. The collision speed is 35 km/h and the average braking deceleration amounts to 5 m/s^2. In order to consider the brake dive of the car the vehicle front is inclined by 1.5 degrees.

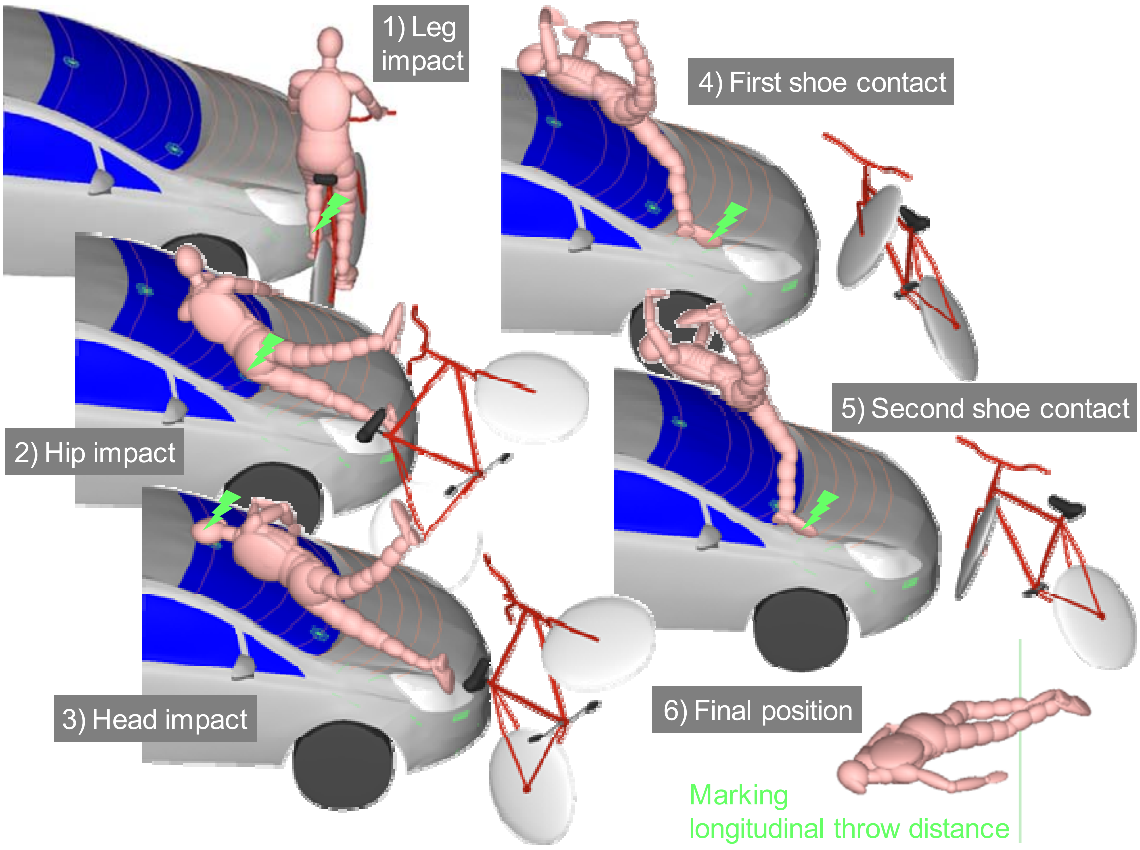


Figure 4. Accident reconstruction on the basis of vehicle contact points & throw distance.

The various simulations conducted within the accident reconstruction reveal a significant influence of the pedal position as well, both for the impact locations of the different body parts and the longitudinal throw distance.

3 SIMULATION RESULTS

In the following, the simulation results of the different cyclist and vehicle models are summarised with regard to head impact location, velocity and angle at the time of primary impact.

3.1 Head impact location

Figure 5 gives an overview of the head impact locations. For each vehicle model a differentiation is made between the particular impact scenarios (Figure 2). In case of the perpendicular scenarios the underlying collision speed for the head impact analysis is 35 km/h, which represents the upper end of the most relevant velocity spectrum for cyclist-passenger car collisions according to the conducted accident analysis prior to the simulation study. Since the oblique scenario represents an impact with a turning car there is a fixed collision speed of 25 km/h.

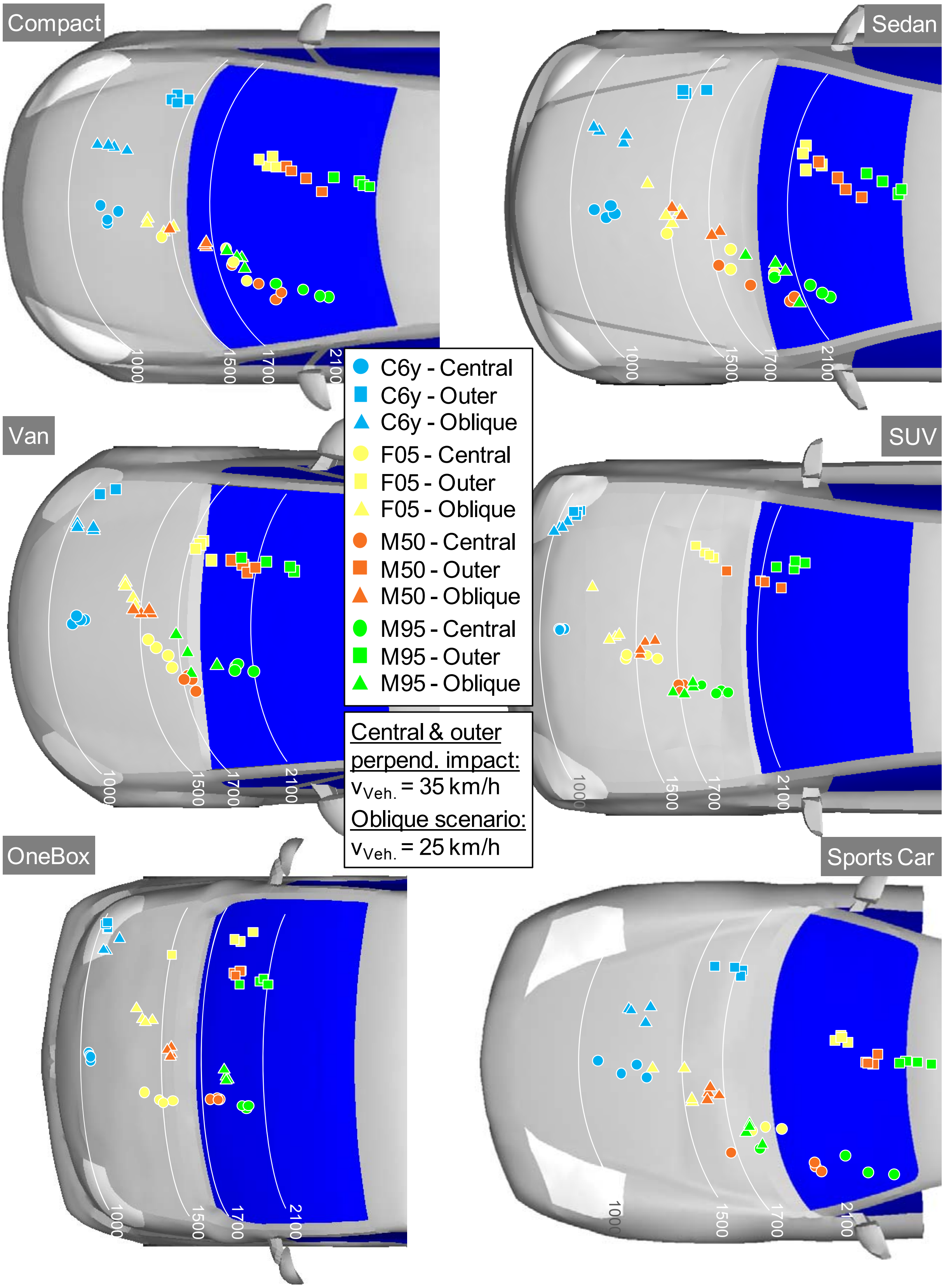


Figure 5. Head impact locations differentiated by impact scenario & cyclist model.

As a reference for the analysis of the head impact area serves the head test zone definition within the pedestrian protection assessment by Euro NCAP (European New Car Assessment Programme). It reaches from a WAD of 1000 mm to a WAD of 2100 mm, whereas the WADs of

1500 mm and 1700 mm respectively mark the transition from the child to the adult test zone. As long as the test point still lies on the bonnet, the child zone ends at the WAD of 1700 mm. The Euro NCAP tests are based on a scenario with a crossing pedestrian and a vehicle speed of 40 km/h. Safety measures related to the pedestrian's head concentrate on the defined test area between WAD 1000 and 2100 mm.

The simulation results in Figure 5 reveal an increased head impact area for cyclists. It can reach until the roof leading edge and in case of a sports car even beyond. For the vehicle models Sports Car, Sedan and Compact there is a significant share of head impact locations beyond the WAD 2100 line, even for the 5th percentile female. In general the outer perpendicular impact constellation leads to the highest WAD values. Furthermore, the bicycle speed of 15 km/h results in an offset between the point of initial contact and the head impact location, i.e. there is a clear diagonal motion of the dummy over the bonnet surface, with a head impact more forward than the leg impact.

3.2 Head impact velocity

The head impact velocity is defined as the relative velocity between the vehicle and the head centre of gravity at the moment of head impact. Due to the higher collision speed within the perpendicular scenarios, the analysis of the head impact velocities is done separately for the oblique scenario. Furthermore, a differentiation between the bonnet and windscreen area is made. Looking at the results for the perpendicular scenarios with a collision speed of 35 km/h in Figure 6, the broad spectrum of impact velocities for the different areas and vehicles becomes apparent. Especially the maximum values achieved in the simulations are conspicuous since they often lie far above the collision speed. Each vehicle model reaches values higher than 50 km/h and except for the SUV the velocities are even higher than 55 km/h. The highest value of 61.3 km/h results from a windscreen head impact in a simulation with the OneBox vehicle. Even the average values, apart from impacts on the bonnet of the OneBox vehicle, turn out to be higher than the collision speed.

One striking aspect regarding the cyclist kinematics observed in the simulations is the high share of primary head impacts or at least contacts with the arm facing the vehicle. In case of an impact on the cyclist's arm the head does not touch the vehicle surface while a contact with the arm prior to the head impact on the vehicle involves a deceleration of the head. The high number of head impacts influenced by the arm results from the posture of the cyclist on the bicycle, with the arms stretched and in a parallel position.

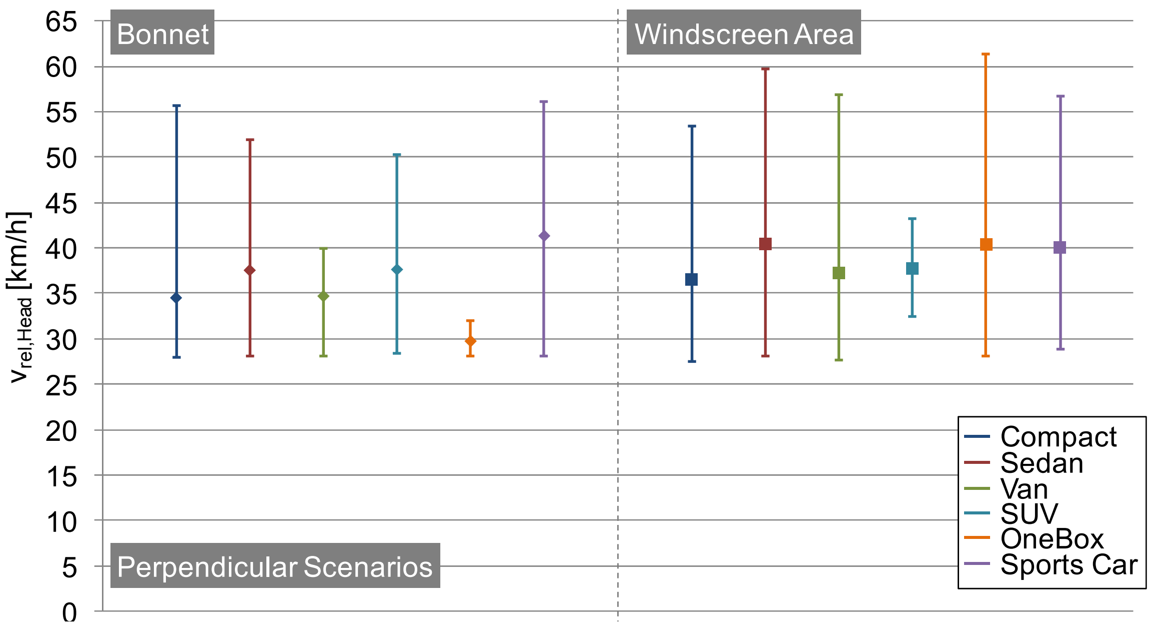


Figure 6. Head impact velocities for perpendicular impact scenarios ($v_{Collision}$ = 35 km/h).

For the oblique scenario with a collision speed of 25 km/h the head impact velocity level is again significantly higher than the collision speed (Figure 7). Contrary to the perpendicular scenarios the highest value of 46.1 km/h is achieved by the SUV. In case of the SUV there are no head impacts on the windscreen due to the long wrap around distance up to the bonnet rear edge. The same applies to the Sports Car.

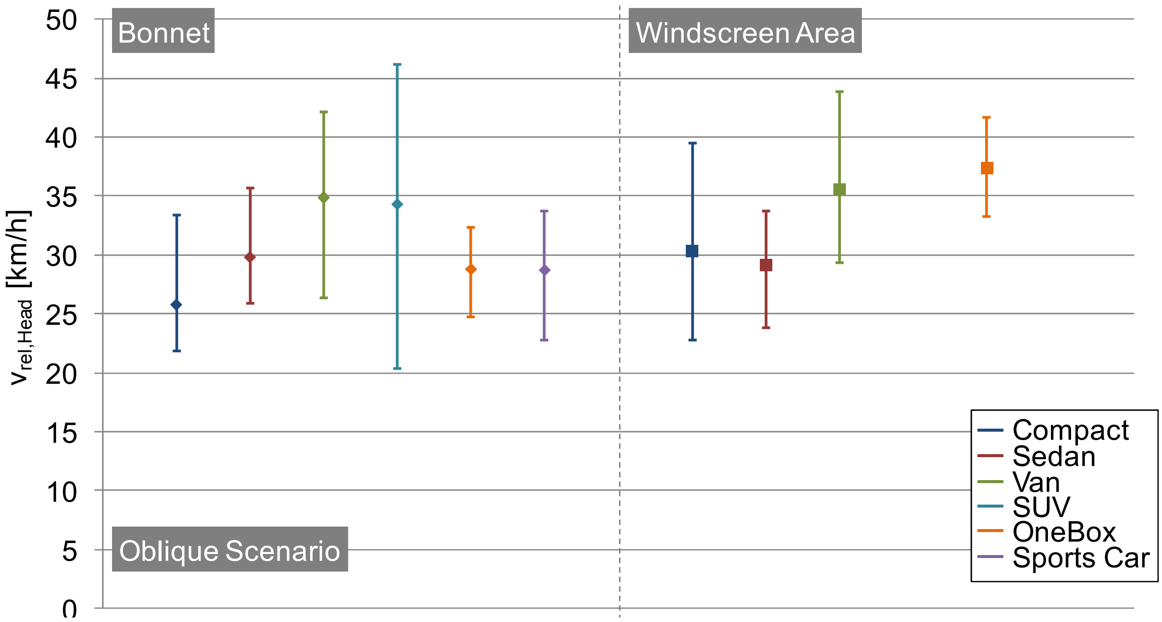


Figure 7. Head impact velocities for oblique impact scenario ($v_{Collision}$ = 25 km/h).

The simulations of the oblique scenario only show a few cases where the head impact is influenced by the arm. Because of the changed collision angle with the cyclist facing the vehicle the accident kinematics is totally different compared to the perpendicular scenarios.

3.3 Head impact angle

Due to the differences in the accident kinematics a differentiation between the perpendicular scenarios and the oblique one is made for the analysis of the head impact angles as well. The head impact angle results from the angle between the relative head velocity vector in x-z-direction and the horizontal (Figure 8). The calculation is done according to Equation (1).

$$\alpha_{Head} = \arctan\left(\frac{v_{Head,z}}{v_{Head,x} - v_{Veh,x}}\right) \quad (1)$$

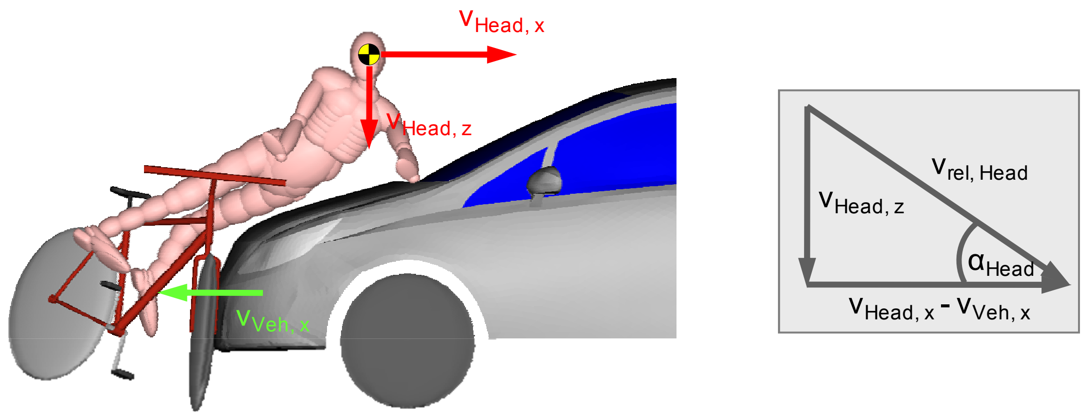


Figure 8. Calculation of the head impact angle.

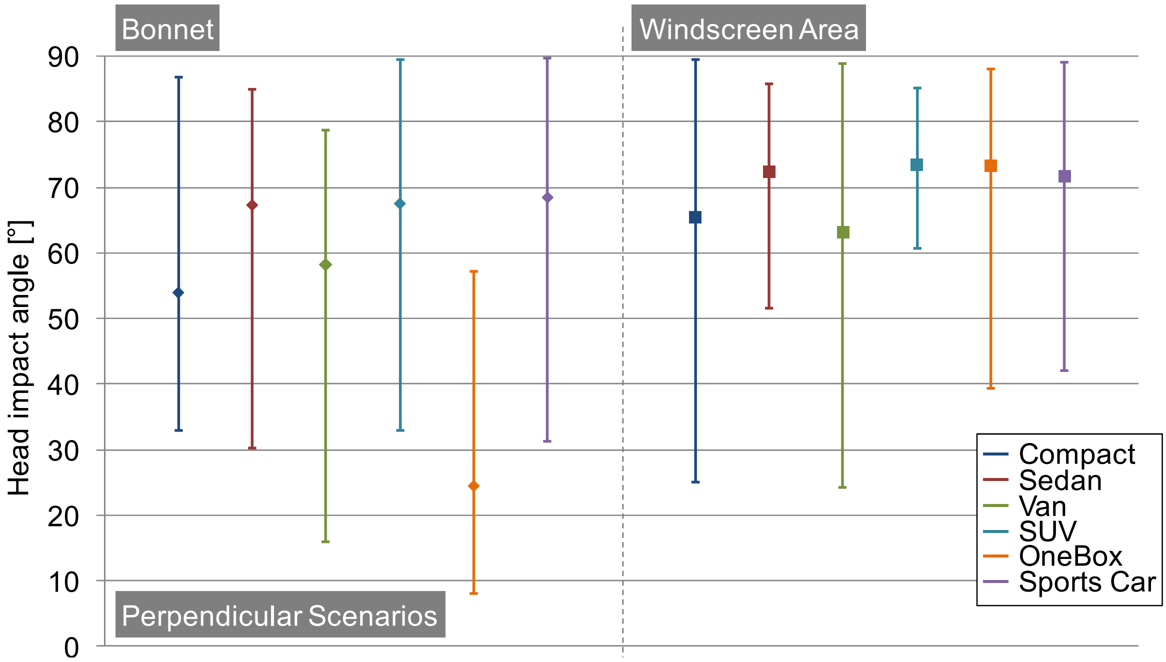


Figure 9. Head impact angles for perpendicular impact scenarios ($v_{Collision}$ = 35 km/h).

Figure 9 reveals for all vehicle models a wide range of impact angles within the perpendicular scenarios, reaching from values below 20 degree up to almost 90 degree. The vehicle models Sedan, SUV and Sports Car show average values about 70 degree for both bonnet and windscreen area. Conspicuous are the values of the OneBox vehicle. As a result of its steep front geometry it achieves the lowest average impact angle for the bonnet area (24.4°) and at the same time one of the highest average values for the windscreen area (73.3°).

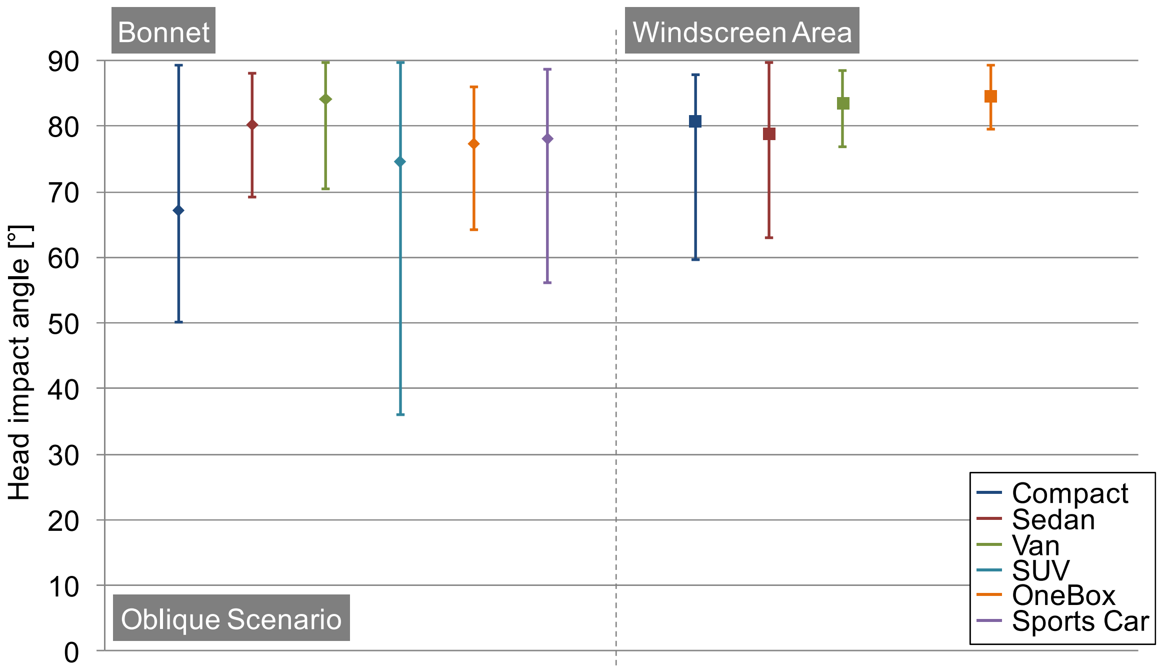


Figure 10. Head impact angles for oblique impact scenario ($v_{Collision}$ = 25 km/h).

For the oblique scenario the head impact angles are less scattered and higher (Figure 10). The average values in the windscreen area are all about 80 degree (SUV and Sports Car without head impacts on the windscreen). The same applies to the bonnet area, apart from the vehicle models Compact and SUV where the average angles are 67.2 and 74.6 degree respectively.

3.4 Influence of vehicle speed

In addition to the collision speed of 35 km/h considered for the perpendicular impact scenarios so far, further simulations with vehicle speeds of 20, 30 and 40 km/h are conducted, taking again all four pedal positions into account. As expected, a reduced collision speed leads for all vehicle models to a forward displacement of the head impact locations, i.e. the wrap around distances of the head impact locations are getting shorter with decreasing collision speed. This effect is less pronounced for front geometries with a high bonnet leading edge, as is the case for the SUV and OneBox vehicle.

Figure 11 illustrates the influence of the collision speed on the average head impact velocity for the different cyclist as well as vehicle models. It becomes apparent that for the bigger cyclist models, i.e. the 50th and 95th percentile male, the average head impact velocity always lies above the collision speed while for the smaller ones this depends on the vehicle front geometry.

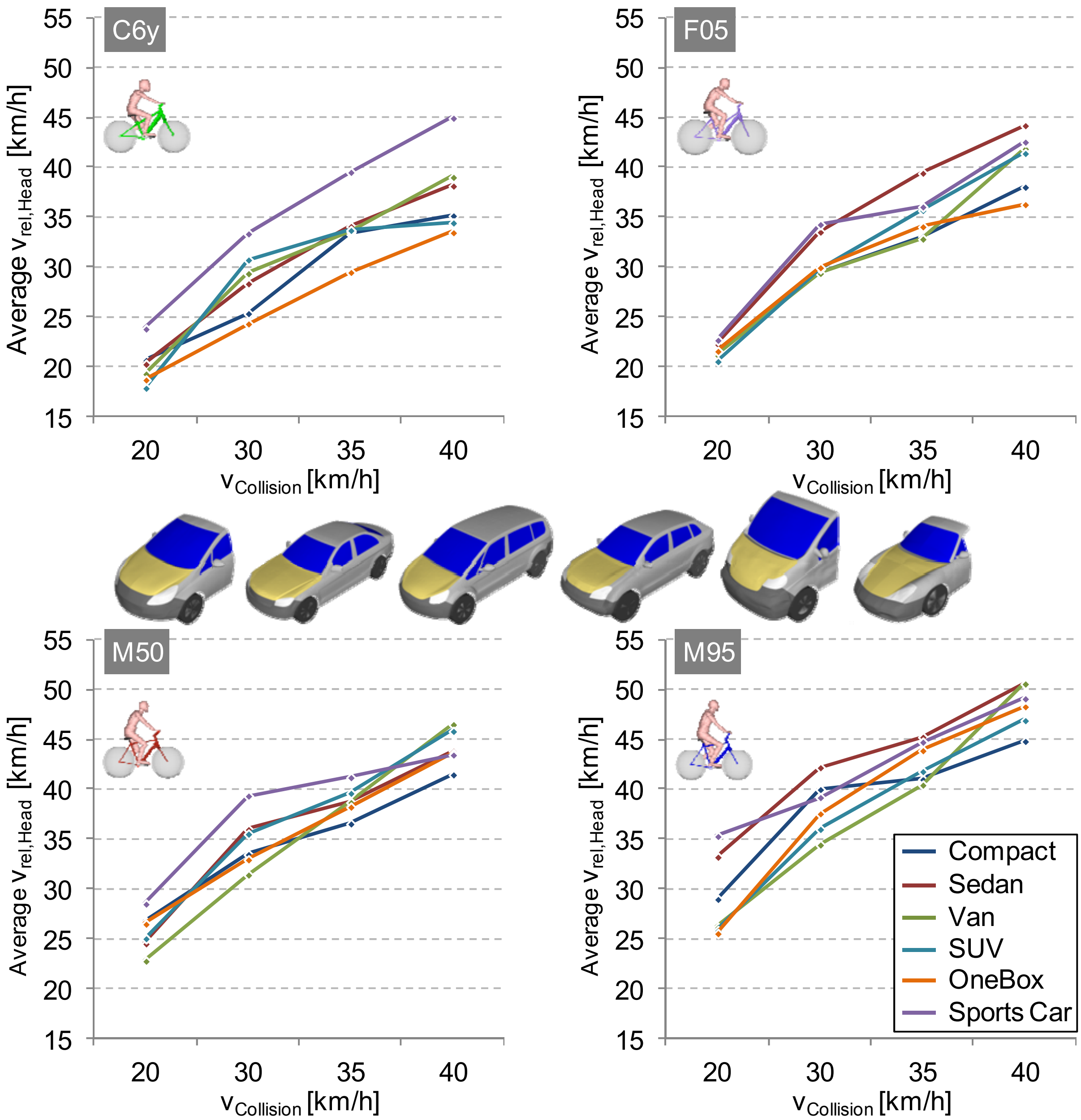


Figure 11. Average head impact velocity over collision speed for perpendicular impact scenarios.

In case of the 6-year-old child the Sports Car is the only vehicle where the average head impact velocity exceeds the collision speed for all simulations conducted. A reason for this is the low front height of the Sports Car which causes a high rotational velocity component of the cyclist due to the low vehicle-sided contact point. This results in high impact velocities for all cyclist models. The 5th percentile female shows average head impact values equal or above collision speed for 20 and 30 km/h. Looking at collision speeds of 35 and 40 km/h the Compact and OneBox vehicle models achieve lower average head impact velocities while the Sedan and Sports Car models lead for all simulations of the 5th percentile female to average head impact values above collision speed.

The simulations with collision speeds of 40 km/h, which is the speed level the Euro NCAP pedestrian head impact tests are based on, show very high average head impact velocities, especially for the 50th and 95th percentile male. A look at the maximum values stresses the difference in speed level compared to the boundary conditions for pedestrian protection. The maximum head impact velocities are achieved by the 95th percentile male. In a collision with the Van a value of 66.8 km/h is reached, followed by a value of 65.9 km/h in a collision with the Sedan. This demonstrates that the velocity level for a head impact of a cyclist can be considerably higher than the existing testing level for pedestrian protection.

4 CONCLUSIONS

In order to analyse the kinematics of cyclists in car accidents a wide range of impact constellations has been simulated using the MADYMO multi-body solver. Altogether, the study considers six real passenger car fronts, all representing different vehicle classes, four cyclist heights with corresponding bicycle models, four pedal positions, three impact scenarios as well as various collision speeds. The simulation models as well as the boundary conditions defined have been validated by reconstruction of a real accident case.

The simulation results reveal an increased head impact area, which can reach up to the roof leading edge and in case of sports cars even beyond. Furthermore, the study shows high values for head impact velocity as well as angle. Even the average values for the head impact velocity usually lie above the collision speed. These characteristics of cyclist-passenger car collisions have to be taken into account when developing vehicle related safety measures for cyclists. With regard to the high head impact velocities observed within the simulations, a reduction in collision speed by autonomous braking would be one of the most promising safety measures.

In a next step Polar-II dummy tests with an experimental vehicle will be performed in order to gain further insights into the kinematics of cyclists with regard to the different impact scenarios as well as collision speeds considered within the simulation study. Those tests will allow a further validation of the simulation models and an analysis of the cyclist crash loads for both primary impact and secondary impact, i.e. the impact of the cyclist on the ground.

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