Pedestrian and bicyclists head impact conditions against small electric vehicle

Nicolas Bourdet, Peter Luttenberger, Andreas Teibinger, Christian Mayer, Remy Willinger

Abstract The use of small electric vehicles (SEV) will increase significantly in urban areas over the next twenty years. The shape and mass of these SEVs show distinctive differences compared to the traditional car. The approach of the present study which is part of the SafeEV project is to simulate a large number of pedestrian and bicyclist accident scenarios involving SEVs, using multi-body system and considering four SEV front-end geometries at various speeds. A first idea coming from the project workgroup is to select three car shapes and to introduce two head impact speeds into the test methods (low travelling speed 30 km/h and higher travelling speed 50 km/h). The head impact conditions have been extracted in these accident scenarios with head impact velocities between 22 to 27 km/h at 30 km/h and 40 to 48 km/h at 50 km/h. The surface most often impacted is the windscreen with an impact velocity angle of about 30 deg at low speed. The results from both the project workgroup and the kinematic study should be considered in future standard test procedures when it comes to the definition of head impact conditions for SEV.

Keywords Bicyclist, Head impact conditions, Pedestrian, Multibody simulations, Small electrical vehicle, Virtual accident.

I. INTRODUCTION

Pedestrian head injuries are the most common severe and fatal injuries in car-to-pedestrian or bicyclist accidents [1]. In order to minimize the risk of pedestrian head injuries in accidents, subsystem test procedures with headform impactors were proposed by EEVC/WG10 and WG17 to assess the passenger car front performance for pedestrian protection. However, these sub-system tests cannot evaluate the integrated safety performance of a vehicle design in terms of the overall responses of pedestrians. In addition, the pedestrian protection testing protocols did not take into account the influence of different vehicle-front geometries as well as pedestrian or bicyclist gaits and positions on passive safety. Liu *et al.* in 2002 [2] studied the influence of vehicle speed and front structure geometry on pedestrian impact responses. The authors aimed to predict injury risk of a pedestrian against four shapes of vehicles: large and compact cars, minivans and light trucks. They finally proposed a speed limit per vehicle. More recently in 2012, Peng *et al.* [3] investigated the effect of pedestrian gait, vehicle-front geometry and impact velocity on the head impact speed and velocity. The authors used two pedestrian multi-body models (adult and child). In addition five vehicle models were selected to consider different vehicle shapes and sizes: Super Mini Car (SMC), Small Family Car (SFC), Large Family Car (LFC), Multi Purposes Vehicle (MPV) and Sport Utility Vehicle (SUV). The results highlighted the influence of the front geometry especially for children. Other authors, such as Yang and Untaroiu, have focused on the effect of different vehicle fronts and impact speed on the dynamic responses of pedestrians [4-6]. In these studies, standard geometries were used and no results were derived for small cars and future designs.

Maki *et al*. [7] analyzed pedestrian and bicycle accidents from Japan regarding the head impact locations and came to the conclusion that the locations next to the A-pillar and near windscreen edges are more severe because of the stiffer vehicle parts. In Japan the first nearside half seems to be the most frequent impact area. Another study from Sturgess *et al.* [8] showed a similar trend. The analyzed pedestrian accidents showed an accumulation of head impact points close to the A-pillar at the nearside.

In a recent study, Bourdet *et al.* 2012 [9] reconstructed a total of 24 bicyclists' accident cases with head injuries. For each accident case, body kinematics has been simulated using Madymo. The results show that the head is impacted more often on the top parietal zone, and the mean impact velocity is 7 m/s with 5.5 m/s and 3.4 m/s for normal and tangential components, respectively. All reconstructed head impacts gave results in

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accordance with the damage actually incurred by the victims.

The present study is a part of the SafeEV European project focusing on the development of a seamless tool chain for virtual certification of Small Electric Vehicles (SEV), especially in urban areas. In this work, the influence of front-end geometry of SEVs on pedestrian and bicyclist accidents is studied. Indeed, the use of SEVs will increase significantly in urban areas over the next twenty years [1]. The shape and mass of these SEVs show distinctive differences compared to the traditional car, especially concerning the front-end design and the wheels' positions. Thus the consequences of impacts of SEVs with vulnerable road users (VRU) and other vehicles will be different from traditional collisions. These fundamental changes are not adequately addressed by current vehicle safety evaluation methods and regulations.

II. METHODS

The objective of this work is to analyze the pedestrian and bicyclist kinematics and head impact conditions during an accident against a SEV. The method is to simulate a large number (a total of 11 904) of accidents using multi-body systems considering four SEV geometries, a number of pedestrian sizes and positions, and different car impact velocities. The main outputs are the head impact conditions expressed in terms of head impact location, head velocity vector, impact location on head, secondary impact characteristics and throw distance. Several specific softwares for vehicle kinematic reconstruction exist that are state of art, but the computation of the human body kinematics is very poor. In order to evaluate accurately the initial head velocity and position just before impact, there is a need to simulate the human body behavior properly. Madymo® is a software from TNO Automotive using multi-body computation dedicated to victim kinematic analysis. The principle of solving multi-body system is to define a set of rigid bodies represented by ellipsoids and connected by joints. Unlike finite elements methods, contact between two bodies is not a deformable surface but a penetration force defined by a function. The computational time for this multi-body approach is significantly reduced in comparison with FE simulation. For the present study, the vehicle models are developed using ellipsoids in such a way that the geometry is respected, as depicted in figure 1. The contact force functions used on each part of the car are extracted from Martinez *et al.* 2007 [10] as illustrated in figure 2.

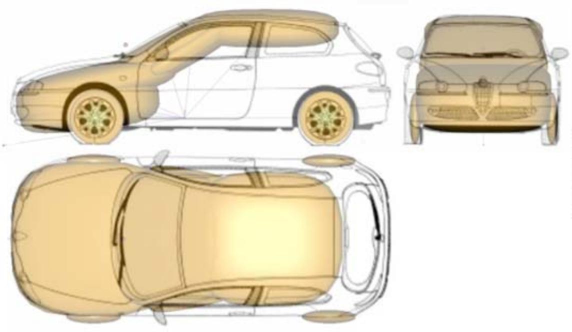


Figure 1 Superimposition of ellipsoid modelling with vehicle outline.

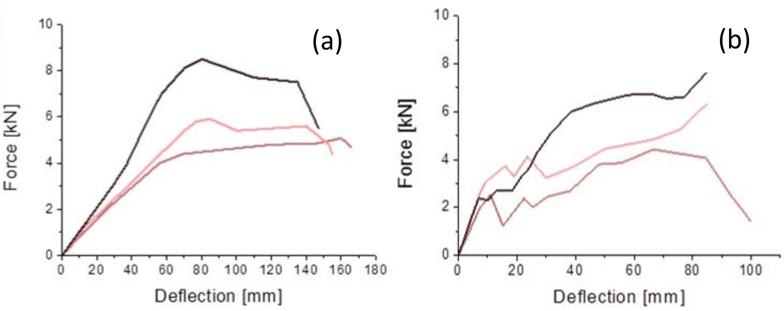


Figure 2 Example of simplified average force deflection curves (a) bonnet and (b) windscreen. The colors represent EuroNCAP rating data, (Martinez *et al.* 2007 [10]).

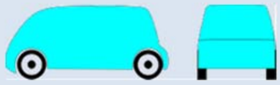
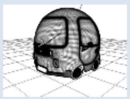
The pedestrians and cyclists are modelled in accordance with geometry, mass and inertia. The human model is a scalable multi-body model named TNO human model (TNO, 2001). This human model is described in Hoof *et al.* 2003 [11] and De Lange *et al.* 2005 [12].

In the literature a number of car geometries are available. As described in Lesemann *et al.* [13] some of the vehicle shapes were designed within the ELVA Project, a research project funded by the European Commission. In this project a special feature was a design contest in which free-lance designers and design studios as well as students and other interested parties were able to take part. Several geometries and designs have been proposed and added to other existing ones. Four categories can be proposed as reported in table 1:

- Bonnet shape represents a car including a small bonnet, with an angle between the windscreen and bonnet smaller than 135 deg.
- Inclined shape represents a category of car in which the bonnet and windscreen have the same inclination of less than 45 deg against the horizontal.
- Flat shape represents a category of car in which the bonnet and windscreen have the same inclination of more than 45 deg against the horizontal.

- Out-wheels shape represents a car with outstanding wheels.

Table 1. Car shape categories

Bonnet		Inclined		Flat		Outwheels	
							
Bugaboo		worm-e		BMW Isetta		Honda 3R-C	
Firefly		MOD3		Cherry Car		Aptera 2e	
Elva		FUN_car		Bajaj Rickshaw			
Fiat 600 toon		Venture one		Yamaha Grizzly			
Peugeot Concept		Avenger		GM Segway PUMA			
Triac		Clever		Fiat MIO			
Hyrban		VW Nils					

The procedure implemented into the parametric study is represented in figure 3 for the pedestrian and bicyclist virtual accident against a SEV. A total of 6,720 accident scenarios were simulated for the pedestrian and 5,184 for the bicyclist. For all simulations, the car kinematics is considered with braking just after body contact. The braking distance is calculated from equation 1 for each car velocity with a friction coefficient of 0.7. The braking distance ranged from 0.53 m to 20 m for car velocity of 2.7 m/s to 16.6 m/s respectively.

$$D_f = \frac{V_{car}^2}{2gf} \qquad (1)$$

with : V_{car} : car velocity, g : gravity 9.81 m/s², f : friction coefficient

A pre-processing program developed under Python language [14] is used in order to compute all the simulations. It consists of selecting the parameters according to the design of the experiment, which is based on a full factorial table. After setting the human body initial conditions and the vehicle initial velocity, the simulations are run automatically. Similar to pre-processing, an automatic methodology is also used to extract the data from the simulations via a post-processing program. This program is able to express the influence of the different parameters on the pedestrian head impact conditions.

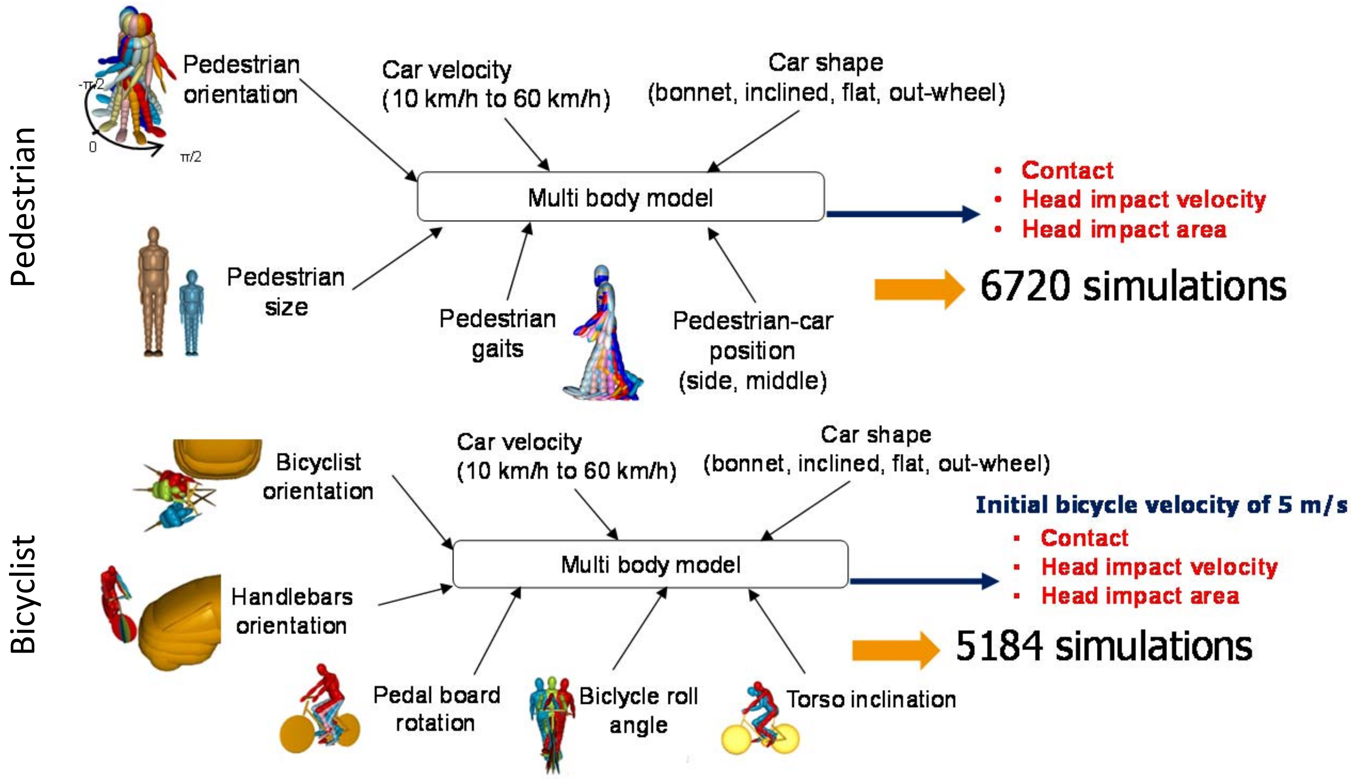
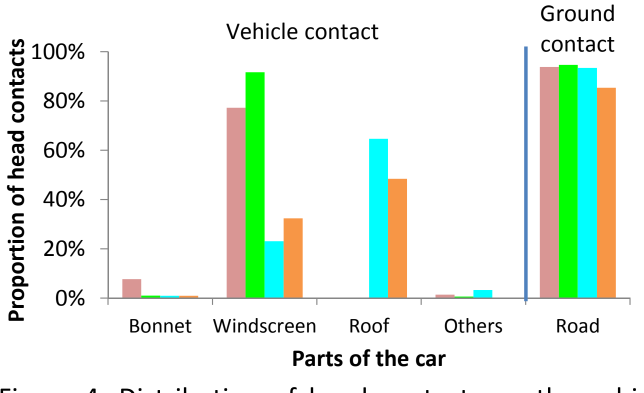


Figure 3. Design of the simulation plan for pedestrian and bicyclist virtual accident simulations.

III. RESULTS

All 11 904 simulations have been carried out and analyzed according to the car geometries, i.e. bonnet, inclined, flat and out-wheels shapes. Each simulation can be divided into two phases: the first considers the first impact of the head against the vehicle when it occurred; the second looks at the head impact on the ground after the body impacted the car (with or without head contact). For each car geometry, the head-vehicle and the head-road relative velocity are studied separately for the two human sizes, i.e. for the adult and the child in the case of a pedestrian accident and for the adult in the case of a bicyclist accident. Figure 4 and figure 5 show the distribution of the head contact against car parts. It can be observed that for adults the parts often impacted are the windscreen and roof, while children mainly impact the windscreen. Considering the secondary head contact on the ground, a clear influence of car geometry cannot be observed. In about 90% of virtual accidents the head impacts the ground for both adult and child. The same results can be observed for the bicyclist virtual accidents. Most of the head impacts are located on the windscreen for the bonnet, inclined and flat shapes, as illustrated in figure 6. For the out-wheels geometry, the head impacted the car in less than 33% of the cases. Considering the head contact on the ground, except for the bonnet shape, the proportion of head impacts is about 90% as it is for the pedestrian.



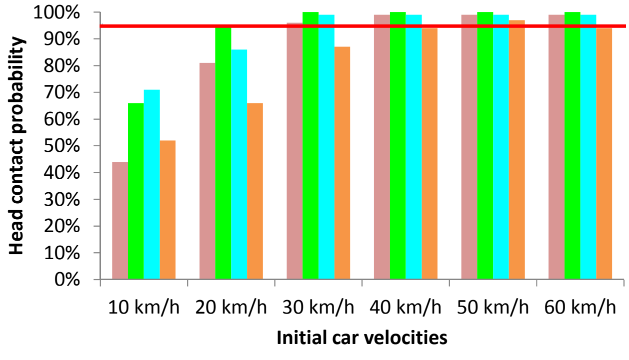


Figure 4. Distribution of head contacts on the vehicle parts and ground in case of adult pedestrian virtual accident (left) and probability of head contact on the vehicle according to car velocities (right) (bonnet shape, .inclined shape, flat shape and out-wheels shape).

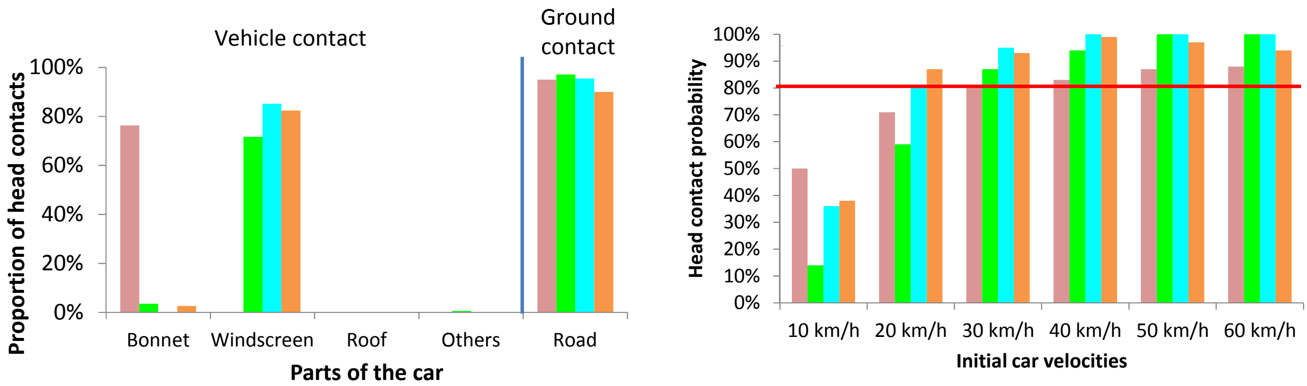


Figure 5. Distribution of head contacts on the vehicle parts and ground in case of child pedestrian virtual accident (left) and probability of head contact on the vehicle according to car velocities (right) (bonnet shape, .inclined shape, flat shape and out-wheels shape).

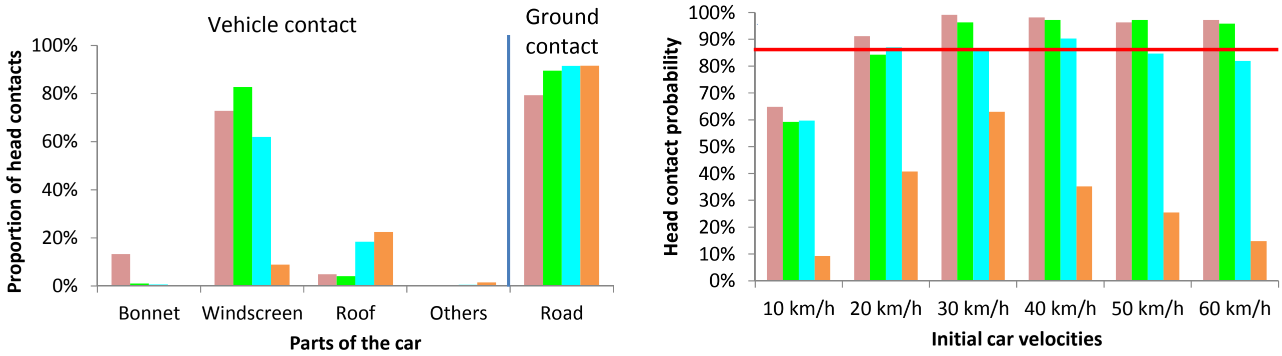


Figure 6. Distribution of head contacts on the vehicle and ground parts in case of adult bicyclist virtual accident (left) and probability of head contact on the vehicle according to car velocities (right) (bonnet shape, .inclined shape, flat shape and out-wheels shape).

Regarding the probability of head contact, 30 km/h can be considered as the threshold above which the probability is higher than 98%, 87% and 85% for the adult and child pedestrian and bicyclist respectively, values corresponding to the mean of probability between the four shapes at the initial velocity of 30 km/h.

A. Pedestrian virtual accidents

Considering the pedestrian virtual accidents only, figure 7 and figure 8 represent the resultant of head impact velocities against vehicles according to the initial car velocities as well as the angle of velocity vector (angle with normal of the contact surface) for both adult and child. In the case of the adult, the head impact velocity increases with the initial car velocity from about 3 m/s to 18 m/s. Moreover, the angle gets more tangential at high velocities except for the bonnet shape with an impact velocity angle about 20 deg.

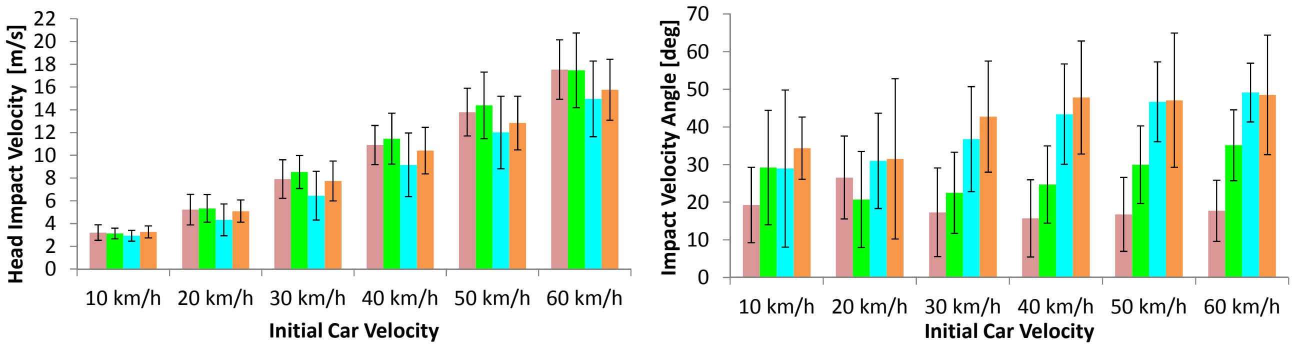


Figure 7. Head-car velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface (right), for adult (bonnet shape, .inclined shape, flat shape and out-wheels shape).

Considering child accidents, the head impact velocities are lower than for the adult but more tangential at the initial car velocities varying from 20 to 60 km/h, especially for the bonnet shape where the velocity angle reaches 60 deg versus normal.

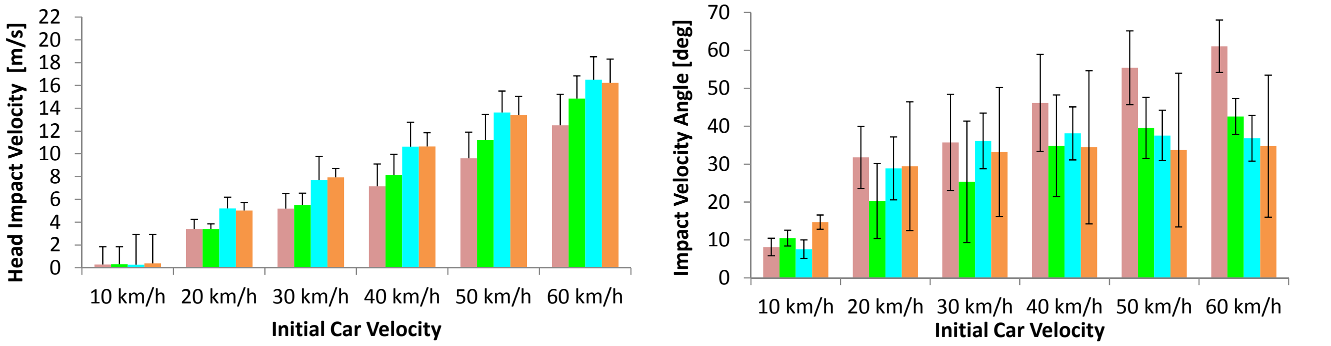


Figure 8. Head-car velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface (right), for child (bonnet shape, .inclined shape, flat shape and out-wheels shape).

From all the pedestrian accident simulations, the head impact points have been computed. Figure 9 illustrates the distribution of the head impact points for both adult and child. On the head, the focus is on three areas: facial-frontal, lateral and occipital. For each area a mean velocity can be calculated, as illustrated in figure 10. Thus, for the adult, the occipital head impact velocity is about 10 m/s for all front end shapes whereas for children the head impact velocity at occipital varies from 6.5 m/s to 11.5 m/s.

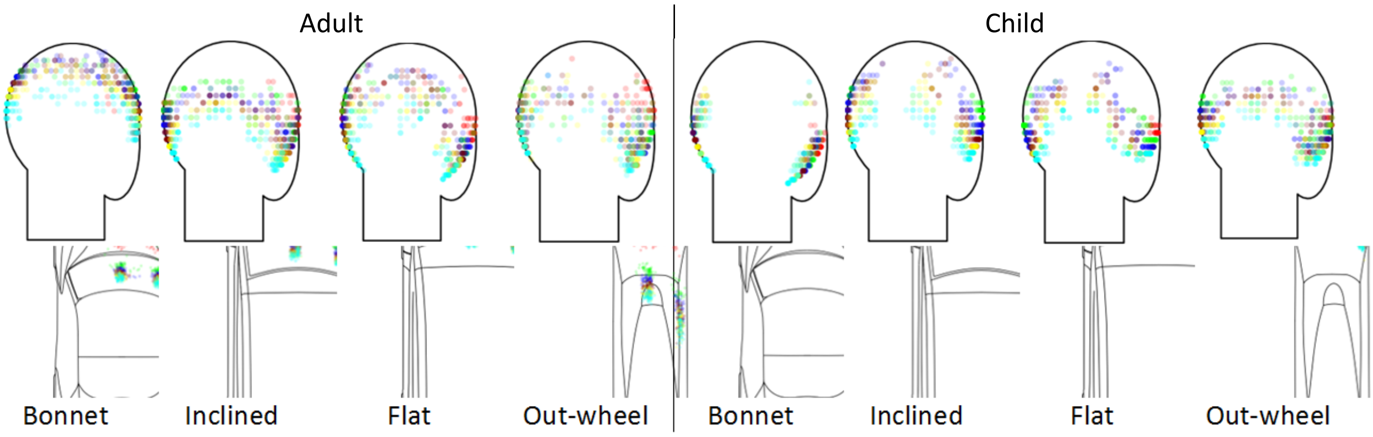


Figure 9. Representation of head impact points extracted from all the pedestrian virtual accidents on head and vehicle for both adult and child (• 10km/h, • 20km/h, • 30km/h, • 40km/h, • 50km/h, • 60km/h).

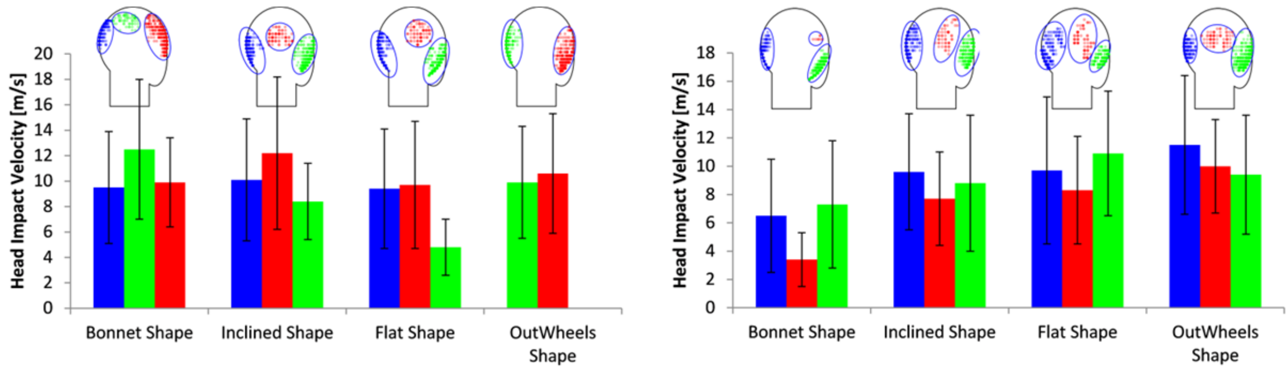


Figure 10. Head impact points and velocity according to the vehicle shape for adult (left) and child (right).

In contrast to the contact on the car (figure 11), the resultant of the head impact velocity on the ground is higher for the child than for the adult (figure 12). However, the normal components are similar at low velocities but are higher for the adult at high velocities. Except for the initial car velocity of 10 km/h, the impact of the head is more tangential with an angle versus normal ground of 60 deg for the adult and 70 deg for the child considering the secondary impact on the ground. Figure 13 represents the impact points of the body on the ground, corresponding to the throw distance, as a function of initial car velocity and for the four front end shapes. It can be observed that the flat shape gave a maximum throw distance for the adult of 26.5 ± 3.2 m while for the child it is the inclined shape with 27.8 ± 2.6 m. But in general, except for the out-wheels shape, the throw distances are similar for all considered shapes and ages.

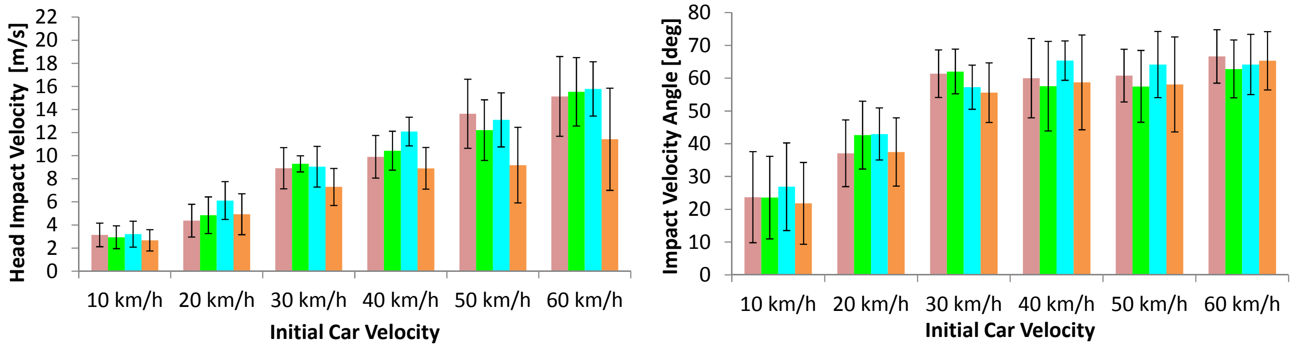


Figure 11. Head-road velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface on the ground (right), for adult (bonnet shape, .inclined shape, flat shape and out-wheels shape).

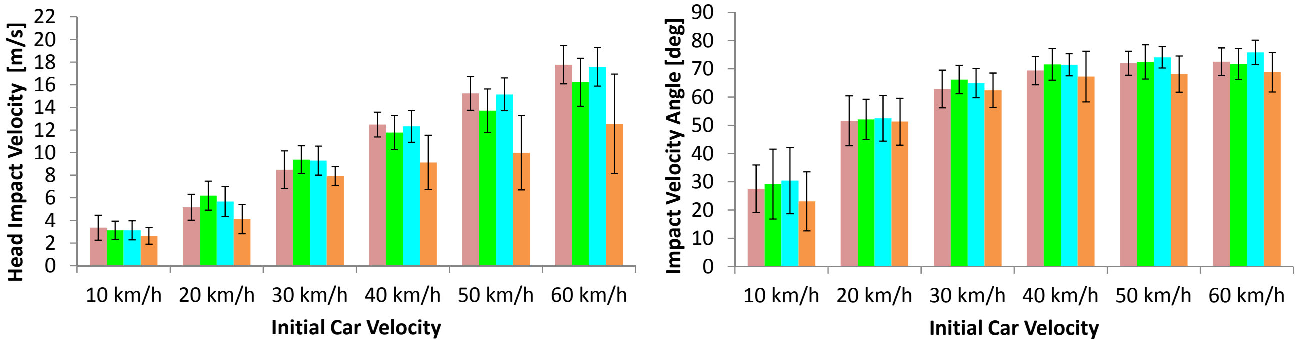


Figure 12. Head-road velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface on the ground (right), for child (bonnet shape, .inclined shape, flat shape and out-wheels shape).

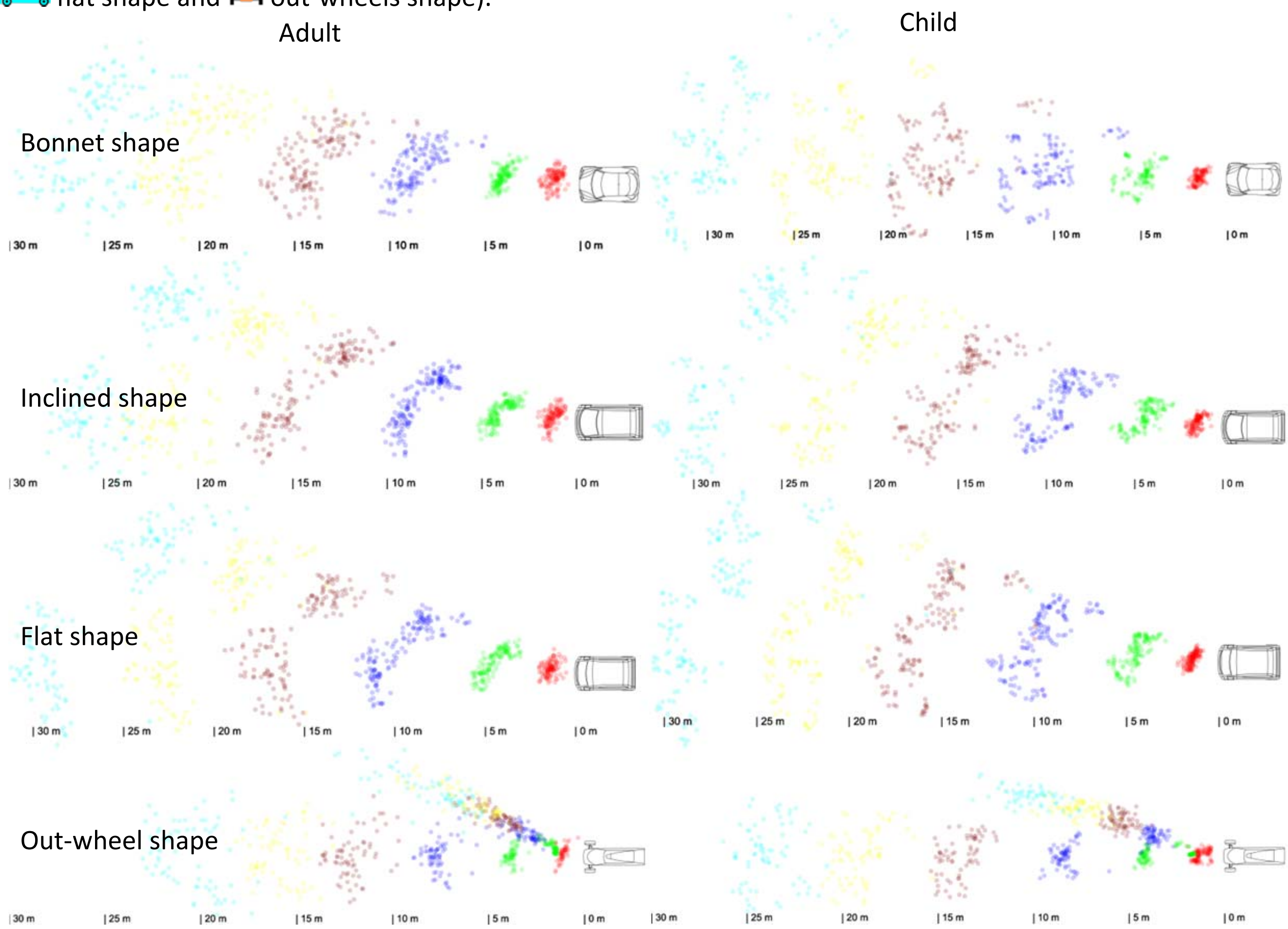


Figure 13. Throw body distance in function of initial car velocity for both adult and child and for the four front end shapes (• 10km/h, • 20km/h, • 30km/h, • 40km/h, • 50km/h, • 60km/h)

B. Bicyclist virtual accidents

Figure 14 shows the head impact velocities against the vehicle as well as the vector angle versus normal. The components of the velocities are similar as the angle ranged between 35 deg and 55 deg. Until 40 km/h, the front-end shape of the car has no real influence. The location of the impact points on the head and on the car are illustrated in figure 15. For the first three front-end shapes, the impact points are located in the fronto-lateral zone of the head. For the out-wheels shape, the occipital area is impacted as well.

On the vehicles, the impact areas are clearly spread as a function of the initial car velocities. On the bonnet shape, the head impacts the bonnet for a car velocity of 10 km/h and reaches the roof at 60km/h. Concerning the inclined and flat front ends, the head impacts the windscreen from the bottom to the top as the car velocity increases.

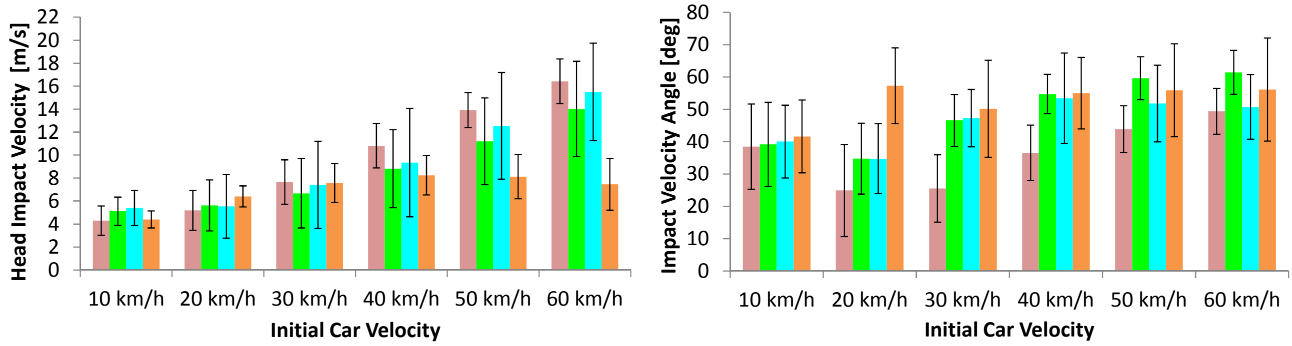


Figure 14. Head-vehicle velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface (right), for bicyclist adult (bonnet shape, .inclined shape, flat shape and out-wheels shape).

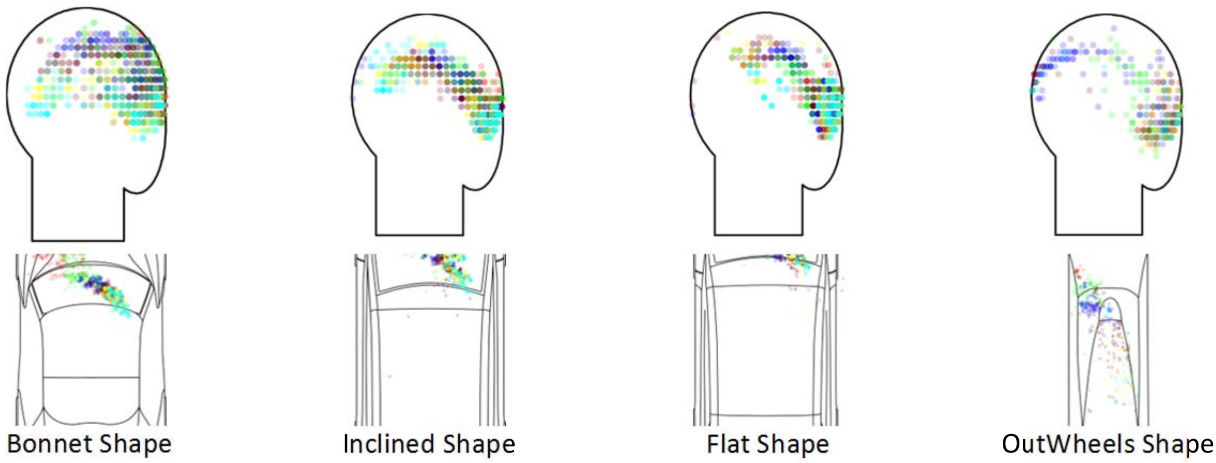


Figure 15. Distribution of head impact points on the head and the car according to the initial car velocity (• 10km/h, • 20km/h, • 30km/h, • 40km/h, • 50km/h, • 60km/h).

Concerning the secondary impact on the ground, the head impact velocity is more tangential than previously, particularly for the flat shape with an angle versus normal of about 60 to 70 deg°, as illustrated in figure 16. Contrary to the pedestrian accident, the throw distances are smaller. Figure 17 shows the distribution of the body impact points according to the car velocities. The maximum throw distance does not exceed 30 m. In the range of 20 to 50 km/h, the groups of body points according to the car velocities overlap, particularly in case of an accident with the out-wheels front end.

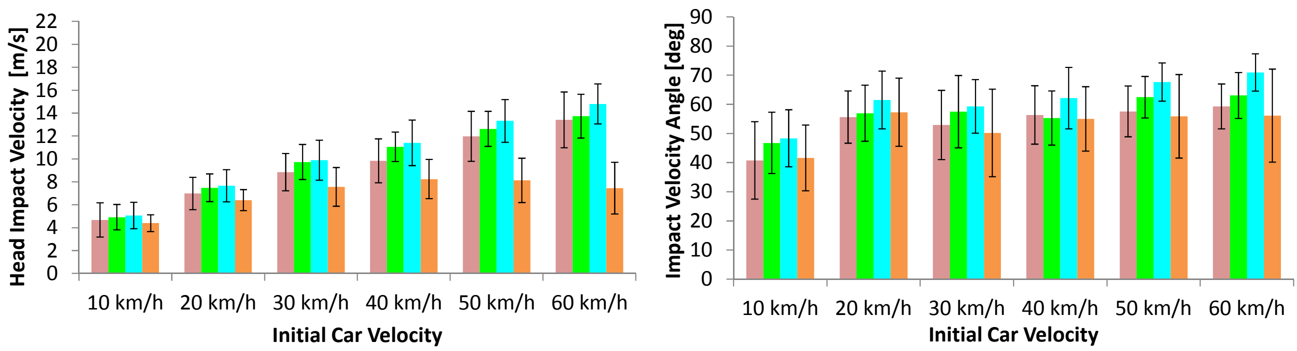
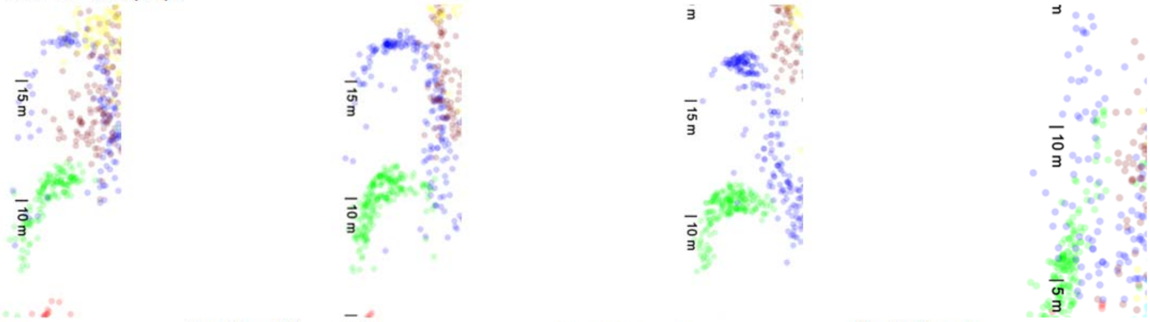


Figure 16. Head-road velocities according to the vehicle shape and the initial car velocities (left) and velocity angles versus normal contact surface (right), for bicyclist adult (bonnet shape, .inclined shape, flat shape and out-wheels shape).



Bonnet Shape Inclined Shape Flat Shape OutWheels Shape

Figure 17. Distribution of head impact points on the head and the car according to the initial car velocity (• 10km/h, • 20km/h, • 30km/h, • 40km/h, • 50km/h, • 60km/h).

IV. DISCUSSION

In the next 20 years the number of small and light-weight full EVs will substantially increase especially in urban areas, as mentioned in the Roland Berger study [1]. These SEVs show distinctive design differences compared to the traditional car (e.g. no bonnets, vertical windscreens, outstanding wheels). Thus the consequences of impacts of SEVs with vulnerable road users (VRU) and other (heavier) vehicles will be different from traditional collisions. These fundamental changes are not adequately addressed by current vehicle safety evaluation methods and regulations. VRU protection, compatibility with heavier opponents and the introduction of active safety systems have to be appropriately taken into account in order to avoid any SEV over-engineering (e.g. heavy or complex vehicle body) by applying current regulations and substantially impairing the SEVs' (environmental) efficiency.

For protection of vulnerable road users and occupants a revision of the test configurations is essential to address the needs of the above-mentioned SEV designs. To successfully develop and validate such new and more appropriate test configurations, 11 904 simulations using multi-body models have been carried out to enable a comprehensive analysis of the pedestrian and bicyclist safety needs for SEVs in a cost-efficient manner. The results can also address the issues of active safety which can be taken into account in SEVs, because these systems are entering the market and vehicle fleet and consequently will have a significant influence in future crash scenarios.

The main limitation of this work is the reduction to four front-end geometries as SEVs tend to have an original shape. However, this simplification allows evaluating the method on main geometries. The four chosen shapes have been selected from a range of geometries. This study constitutes a first step and can be continued. Otherwise, in the global SafeEV project, in which the present study is a part, several survey and other accident scenario analysis like stochastic accident simulation or Delphi study [17] concluded that possible future accident scenarios have to be defined [18-20] which can be correlated with other projects as AsPeCSS or working groups as vFSS. From these conclusions, the main interest will be in selection of three vehicle front-end shapes (bonnet, inclined, flat). This proposal comes from the fact that the survey conducted in the Delphi study led to the three selected designs that would probably be seen in the future. Another limitation concerning the bicyclist virtual accident is its orientation which only takes into account frontal and side impact. For cyclist accidents, Maki *et al.* [7] found that 90% of all accidents happened with a cyclist speed below 10 km/h and a higher injury risk (>50 %) occurred when the cyclist was struck on the side. The location of the cyclist in case of impact against a motorized vehicle with a head impact on the front was found to be with a saddle position between the first two thirds of travelling direction on the vehicle front end and with a cyclist speed below 10km/h. Boufous *et al.* [15] did a database analysis for cyclist accidents in Victoria (Australia) and showed that 94.6% are urban accidents where one of the most frequent and more severe accidents was an adjacent type at intersections. 82.6% of all accidents occurred at a maximum vehicle speed limit of 60 km/h. Schijndel *et al.* [16] found that the average car velocity in an impact was 35 km/h and most frequently occurred in crossroads (Dutch cases). Therefore the lower speed range should be in focus for the proposal. However, pedestrians should be tested with a higher speed range anyway, which means there will be a certain protection for cyclists, too. A third limitation is that the paper only focused on the head impact conditions and not on the body kinematics.

The head impact conditions can be compared to the standard front-end geometry using the study of Peng et al. [3]. The authors simulated a numbers of virtual accidents against SMC, SFC, LFC, MPV and SUV car geometries at four velocities (30km/h, 40km/h, 50km/h and 60km/h) at different gaits and for both adult and child pedestrians. The results showed that for the adult, the head often impacted the bottom of the windscreen and sometimes the top of the bonnet while against SEVs the middle top of the windscreen is most often impacted by the head. However, the impact velocities are similar. Concerning the child, Peng's results show that the head often impacted the bonnet and fender, while the virtual accidents against inclined and flat front-end geometries show the head impacts at the windscreen bottom. Moreover, a selection of two vehicle initial speeds (30 km/h and 50 km/h) for both pedestrian sizes (adult and child) can be proposed to extract the head impact velocities. The velocity proposal can be explained by the fact that 30 km/h initial car velocity can be considered as a threshold since the probability of the head to impact the car is above 95% and 80% for the adult and child respectively, and 50 km/h as the majority of urban speed limits in Europe is 50 km/h. In addition, low speed (between 10km/h to 30km/h) may occur in areas of dense pedestrian population or due to the fact that nearly all vehicles will be equipped with driver assistance systems but for an initial car speed of 20 km/h, the probability of head impact decreases by 10 %. A second higher velocity was proposed which permits to not exclude higher speed (between 30 km/h to 50 km/h).

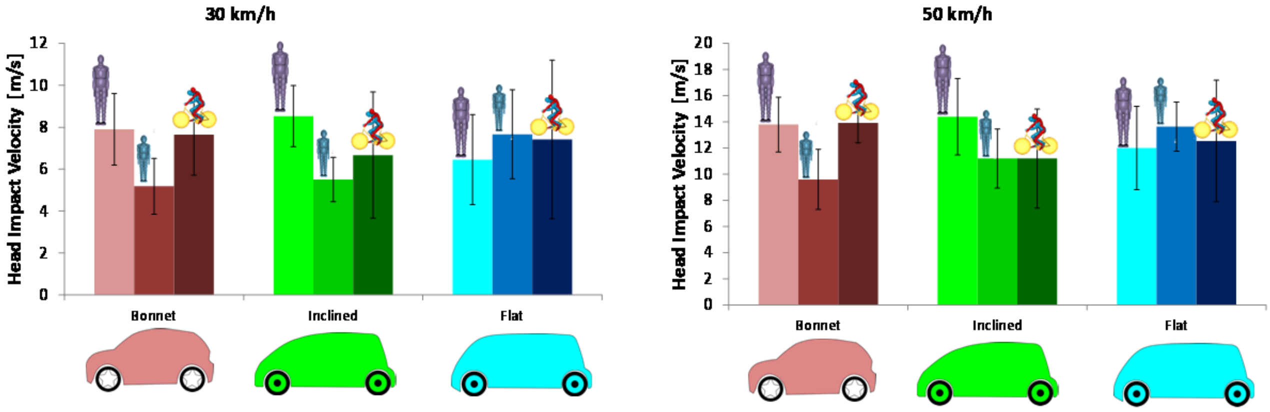


Figure 18. Head vs car impact velocity for adult and child pedestrian as well as bicyclist for a car initial speed of 30 (left) and 50km/h (right).

Considering these two initial car velocities and the three front-end geometries, the head impact velocities from the 11 904 simulations are summarized in figure 18 and table 2. Considering the car velocity of 30 km/h, the head impact velocity is ranged from 23 to 28 km/h for the adult pedestrian and from 19 to 28 km/h for the child pedestrian according to the car shape geometry. Thus, these results should be considered in new test protocol when it comes to the definition of head impact conditions, e.g. a head impact velocity against the windscreen of 27 km/h and 22 km/h for the adult and child, respectively.

Table 2: Mean head impact velocity (km/h) in case of adult and child pedestrian and adult bicyclist impact at 30km/h and 50 km/h for bonnet, inclined and flat vehicle front end.

Accident		Bonnet	Inclined	Flat
Adult Pedestrian	30 km/h	28 ± 6 km/h	30 ± 5 km/h	23 ± 8 km/h
	50 km/h	50 ± 8 km/h	52 ± 10 km/h	43 ± 12 km/h
Child Pedestrian	30 km/h	19 ± 5 km/h	20 ± 4 km/h	28 ± 8 km/h
	50 km/h	35 ± 8 km/h	40 ± 8 km/h	49 ± 7 km/h
Adult Bicyclist	30 km/h	27 ± 7 km/h	24 ± 11 km/h	27 ± 14 km/h
	50 km/h	50 ± 5 km/h	40 ± 14 km/h	45 ± 17 km/h

V. CONCLUSIONS

The present work is part of the SafeEV European project and considers the kinematics of adult and child pedestrians as well as the adult bicyclist when impacted by a car via multi-body simulation for a set of four vehicle front-end geometries and a large range of impact speeds and human positions. No less than 6720 accident configurations for pedestrians and 5184 for bicyclists were simulated. The automation of the simulations and their analysis enable detailed investigations by covering an extensive set of pedestrian and cyclist head impacts.

The results give an overview of the head impact conditions against SEV vehicles for the first contact as well as against the ground for the second impact. Some differences appear between front-end shapes especially for the out-wheels geometry. The head impacts on the vehicle are often located on the windscreen while for standard front-end geometries the impacts are often on the bonnet.

Moreover, from the results of the global work on the analysis of accident scenarios of the SafeEV project, gathering survey studies considering only three vehicle front-end shapes (bonnet, inclined, flat) for future car and accident reconstructions, two car velocities (30 km/h and 50 km/h) have been proposed. The 30 km/h initial car velocity can be considered as a threshold since the probability of the head to impact the car is above 95% and 80% for the adult and child, respectively. According to the proposed scenarios, a new standard could consider a head impact velocity of 27 km/h and 22 km/h for the adult and child, respectively, in case of an initial car velocity of 30 km/h with impacts the vehicle at middle top windscreen level for the adult and windscreen bottom as well as the bonnet for children with an impact velocity angle versus normal of about 30 deg. The 30 km/h initial car velocity can be considered as a threshold since the probability of the head to impact the car is above 95% and 80% for adult and child, respectively. In case of an initial car speed of 50 km/h, the head impact velocities reach 48 km/h, 41 km/h and 45 km/h for the adult and child pedestrian and bicyclist, respectively. The surface impacted at this speed is often the windscreen but the impact velocity angle versus normal is 20 deg to 60 deg depending on front-end geometry. These results should be considered in future standard test procedures when it comes to the definition of head impact conditions.

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VII. References

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