UNDERSTANDING THE NATURE OF CYCLISTS' HEAD IMPACTS

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ABSTRACT

The aim of this research was to identify the head impact conditions of cyclists, as compared to pedestrians in impacts with vehicles. EEVC Working Groups 10 and 17 focussed on pedestrian safety with the assumption that cyclist safety would also be improved by their recommended test procedures, but that is not necessarily the case. Computer modelling was performed with four different vehicle shapes to calculate the trajectory path and impact conditions of a cyclist's head onto a vehicle. For all vehicles, apart from the Sports Utility Vehicle (SUV) case, the head impact location for cyclists was further rearward than the pedestrian, towards the windscreen and onto the roof. The cyclist's head also struck at a different angle, but at a velocity similar to a pedestrian's head.

KEYWORDS: Bicycles, Human Body, Kinematics, Finite Element Method, Head Injury

CYCLISTS AND PEDESTRIANS are known as vulnerable road users (VRUs), as they do not have a vehicle structure to protect them and associated safety features, such as airbags and seatbelts. Of the 37,000 people killed annually on European roads, 2000 of them are cyclists and 7000 are pedestrians, while in addition, several hundred thousands are injured, (European Commission, Directorate-General for Energy and Transport, 2008). Vehicle collisions with cyclists produce different injury results and kinematics for cyclists and vehicle occupants. In particular, the cyclists kinematics are of a different nature to vehicle occupants as they are not restrained within a vehicle and are likely to receive direct impact loads from a vehicle front structure. As there is limited scope to reduce cyclist injuries by changing the design of the bicycle, a more feasible approach is to investigate possible alterations to vehicles.

Attempts have been made to reduce the number of vulnerable road user accidents, by implementing improvements to driver behaviour, road layouts and vehicle designs. Legislation has also been introduced to prevent loss of life or serious injury by ensuring that vehicle manufacturers meet certain vehicle safety standards. This legislation has been introduced since 2005, but only for new type approvals and therefore, its effect on accident statistics is as yet unproven. However, it has raised the profile of vulnerable road users and focused manufacturers to consider the implications of producing vehicles that are not compatible with pedestrians or cyclists. In addition, the new EuroNCAP rating system will also promote VRU safety.

DIFFERENCES BETWEEN CYCLISTS AND PEDESTRIANS

One of the first attempts to reconstruct bicycle accidents using a mathematical technique was performed by Huijbers and Jansen (1988). They indentified that the vehicle shape had a considerable influence on the relative head impact velocity of the cyclist. Modelling techniques were used by Maki et al (2003) and Verschueren et al (2007), to investigate cyclist and pedestrian accidents, but only Maki reviewed accident statistics for both road user types and no modelling was performed for pedestrians.

There were fundamental differences between the two user groups in terms of their kinematics and injuries sustained as shown by Carter et al (2005), Janssen and Wismans (1985) and Otte (2004). Cyclists are struck by the vehicle in a different orientation and contact different parts of the vehicle, which have varying levels of stiffness. Research focussing on pedestrian safety over the last 30 years has provided a significant resource and background to the cyclist safety issue. Similarities do exist between the two road users, such as the exposure of limbs to direct contact with the vehicle and impact speeds are similar, but cyclists have a higher centre of gravity compared to pedestrians due to their positioning on the bicycle and their feet not being in contact with the ground on impact. A cyclist is likely to be travelling at a greater velocity compared to a pedestrian and this has consequences for their impact conditions with the vehicle.

It is an assumption that, the introduction of the current pedestrian legislation will also address cyclists, as they generally come into contact with the front of the vehicle. The cyclist has been conveniently labelled under the vulnerable road user category and legislation that has been targeted at protecting pedestrians, has also been labelled as contributing to protecting cyclists as well. The directive title refers to "pedestrians and other vulnerable road users before and in the event of a collision with a motor vehicle". The document mentions vulnerable road users, even though it concentrates on pedestrian protection only and no explicit reference is made to cyclists, (European Parliament and Council 2003). To understand if cyclists can be grouped with pedestrians in terms of the injury mechanism in vehicle collisions, further research work is needed to quantify their similarities and/or differences with pedestrians.

METHODOLOGY OF SIMULATIONS

Previous cyclist related activities, from the EC 6th Framework Integrated Project, APROSYS (Advanced Protection Systems) project have reported that there were insufficient bicyclist cases to examine the type, range or the severity of the injuries sustained by cyclists, (Hardy et al., 2007; Bovenkerk et al., 2008). Therefore, a programme of parametric studies using mathematical models was conducted, to examine vehicle to cyclist impacts from the point of the loadings to the head and to ascertain the likelihood and extent of injuries.

A total of 24 simulations were performed using the finite element software code, LS-DYNA, with a cyclist human model (Humanoid) to analyse cyclists' head trajectories, head impact speeds, impact location and impact angle. A further 22 simulations were conducted with a pedestrian human model (Humanoid), to compare between the two vulnerable user groups. All the simulations conducted are listed in the Appendix, Tables 1 and 2. Four different vehicle shapes were selected for use in the parametric study from the APROSYS project:

- Supermini (SM)
- Large Family Car (LFC)
- Multi-purpose vehicle (MPV)
- Sports utility vehicle (SUV)

A Humanoid model, developed by CIC from a previous project (Howard et al., 2000), was used to model a single size cyclist and pedestrian. The properties and dimensions represented an average 50th percentile human of 16 to 35 years of age. The Humanoid model was validated with a number of cadaver studies performed by (Ishikawa et al., 1994)). Three initial vehicle speeds were used, 5, 10 and 15m/s, which represented a broad range of impact scenarios within an urban environment.

CYCLIST AND PEDESTRIAN SIMULATION STANCES: For the four different vehicle shapes, two different cyclist 'stances' were used. The struck leg up (SLU) stance and the struck leg down (SLD) stance are shown in Figure 1 – both with the MPV shape. The pedestrian was positioned in two walking stances; D-stance with the struck leg forward and on the ground plane and the C-stance was the mirror image of the D-stance, with the struck leg back and off the ground plane, Figure 2.

The difference between the two cycling stances was the orientation of the lower limbs with respect to the vehicle. In the struck leg up scenario, the foot nearest the vehicle was in its highest possible position on the pedals of the bicycle. The struck leg down scenario was the opposite, with the foot nearest the vehicle being in the lowest possible position on the pedals of the bicycle. In the struck leg down scenario the vehicle struck the leg when it was almost straight and with minimal knee flexion or bend.

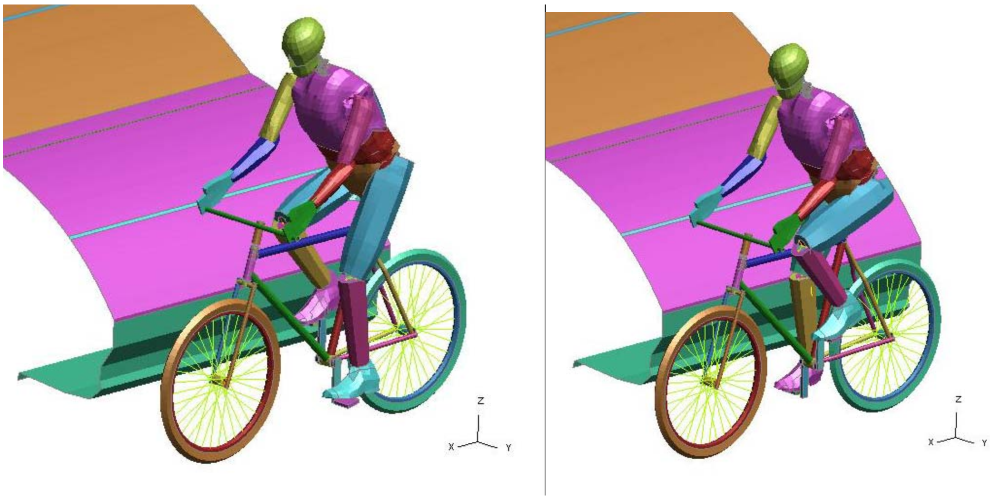

Figure 1: Struck Leg Up and Struck Leg Down Cycling Stances

PEDESTRIAN WRAP AROUND DISTANCES: In the current pedestrian legislative tests, the definition of the wrap around distance (WAD) of a pedestrian with a certain vehicle has been defined by Directive 2003/102/EC (European Parliament and Council 2003).The WAD of a pedestrian is used to determine the impact location for the impactors used in the impact tests. For the four vehicles used in this study, the WAD have been calculated and markers positioned on the vehicle shapes to indicate the ranges within which each impactor (lower leg form, upper leg form, child head or adult head) should be used. According to the legislation, the adult head impactor locations are between the 1500mm and the 2100mm lines and these distances are marked on the vehicle geometries by a line of single elements laterally across the vehicle, as illustrated in Figure 2 for the Supermini (SM) shape.

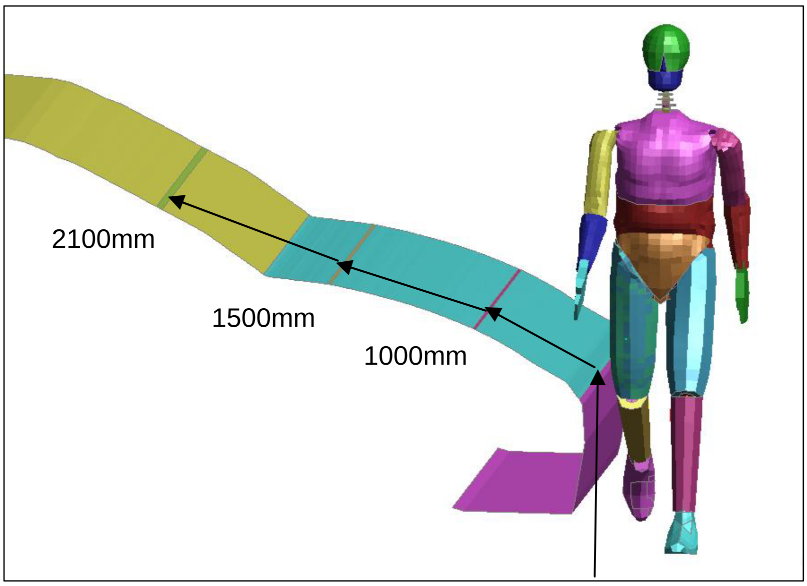

Figure 2: Wrap around distances for the Supermini

CALCULATION OF THE HEAD TRAJECTORY: The specific location of the head centre of gravity (cg) was identified and represented in the human model by a single reference point. The accelerations, velocities and displacements could be extracted for the cg and plotted against a time axis.

The trajectories for the cyclist and pedestrian cases were obtained by using the vertical and longitudinal displacements of the head during the simulations. Initially, the individual displacement components were plotted against time and then the longitudinal displacement of the vehicle was subtracted from the longitudinal displacement of the head, to determine the relative longitudinal head displacement. The vertical and relative longitudinal displacements were combined to produce a single trajectory plot for the head cg. The lateral displacement of the head across the vehicle body was negligible compared to the other values, and was not taken into consideration.

CALCULATION OF HEAD IMPACT ANGLE: To compare the impact angle of the head with the bonnet or windscreen, a reference point was recorded at first contact time between the head and vehicle. At this time, a graphical output of the head contact was plotted using the post-processor software. To aid the process, the head was plotted in a transparent mode in order to visualise the centre of the head. Two lines were then constructed to calculate the angle. The first one started at the head cg and extended along the longitudinal axis. The second was a tangent to the head cg trajectory curve, along the last few points of the path before vehicle contact. Finally, the angle between the two lines was determined. Figure 3, illustrates how the angle was calculated for an impact on the MPV shape, in the cyclist struck leg down simulation at 10m/s.

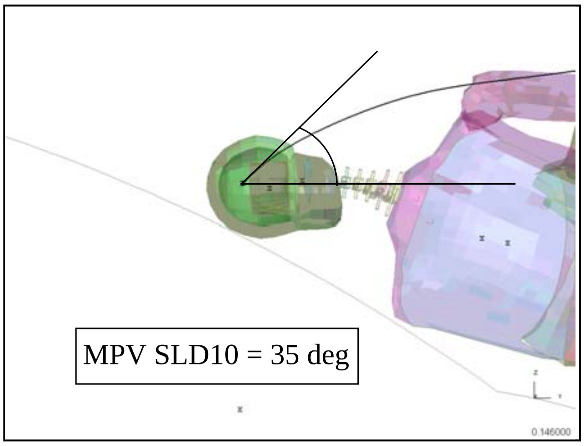

Figure 3: Calculation of head impact angle with vehicle contact

CALCULATION OF RELATIVE HEAD IMPACT VELOCITY: To calculate the velocity of the head prior to impact, the time value of head contact was used which had been calculated for the trajectory path results. At this time reference, the head cg velocity results were extracted for the three components and a resultant velocity was calculated by the following equation:

$$(V_{Resultant}Head)^2 = (V_xHead)^2 + (V_yVehicle - V_yHead)^2 + (V_zHead)^2$$

The vehicle velocity was in the y (longitudinal) direction and was subtracted from the y component of the head velocity, to calculate the head impact y velocity, relative to the vehicle velocity. The x-axis was in the lateral direction of the vehicle.

CYCLIST HEAD IMPACT RESULTS

All the head trajectory results and vehicle centreline side-on profiles are shown in Figure 4. The distinct grouping of the pedestrian and cyclist head trajectories can be seen. In general, the cyclist head impact trajectories (darker traces) extended further in the longitudinal direction towards the windscreen and are spaced out over a wider range. The pedestrian trajectories' (lighter traces) did not extend as far longitudinally and are grouped towards the rear end of the bonnet and with some striking the windscreen.

For all the pedestrian head trajectories the head struck the bonnet within the 1000mm to 2100mm WAD markers for their respective vehicles. This demonstrated that the pedestrian head impact points fell within the current legislative regions for pedestrian head impact testing. The change in vehicle velocity from 5m/s to 15m/s did not considerably change the impact position of the pedestrians' heads. The cyclist head impact locations were further up the bonnet and onto the windscreen.

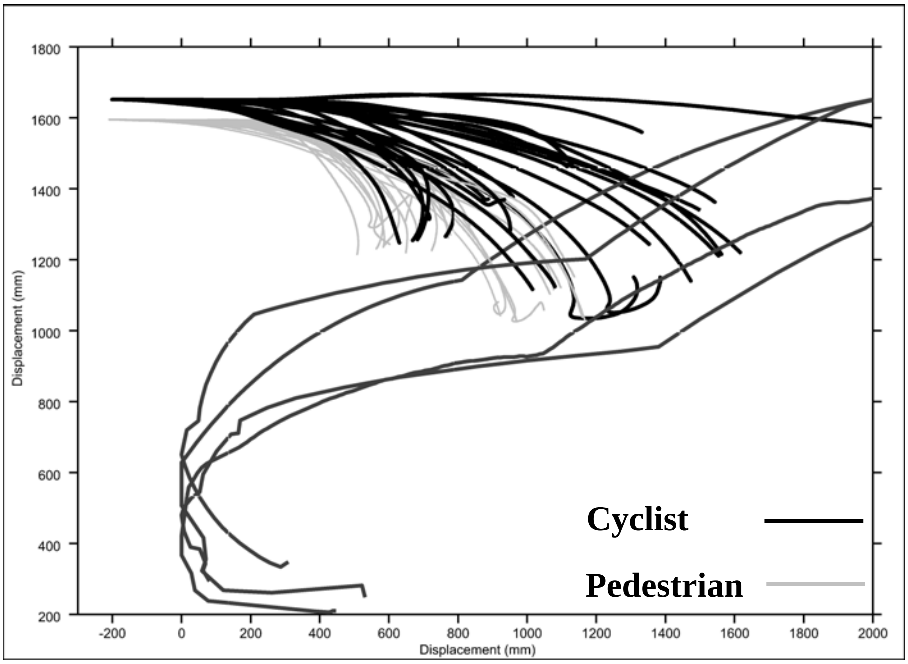

Figure 4: Pedestrian and cyclist head trajectories for all vehicles

COMPARISON OF HEAD TRAJECTORIES FOR THE DIFFERENT VEHICLES: The four different vehicle shapes had different effects on the cyclist and pedestrian kinematics. The trajectories for the SM, LFC, MPV and SUV vehicles and the range of impact locations are shown in Figure 5 and Figure 6.

To compare head impact location points the WADs of the individual vehicles were calculated. For the LFC and SUV, the 2100mm marker was just at the base of the windscreen, but for the SM and MPV the 2100mm marker was near the mid-position of the windscreen. The 2100mm marker is the highest position up the vehicle front that the head impactor can be used in the current pedestrian legislative test procedure and none of the pedestrian head impacts from the simulations landed above the marker. However, some of the cyclist head impacts for the SM, LFC and one for the MPV did land above the 2100mm marker. The cyclist simulations also had a wider spread of impact locations.

The SM and MPV vehicle shapes had shorter bonnet lengths, in comparison with the SUV and LFC, and resulted in the pedestrian head striking in the region at the rear of the bonnet and the base of the windscreen. For the SUV and LFC simulations, the pedestrian head predominately struck the bonnet region of the vehicle.

The SUV and MPV vehicles produced a range of pedestrian head impact results which straddled the 1500mm marker and landed on the bonnet of the vehicle. The LFC pedestrian results were grouped further up the bonnet towards the windscreen with the 5m/s and 10m/s head strikes for the two pedestrian stances being grouped together. For this vehicle, the difference in longitudinal displacement of the head for the 5 and 10m/s simulations was approximately 200mm.

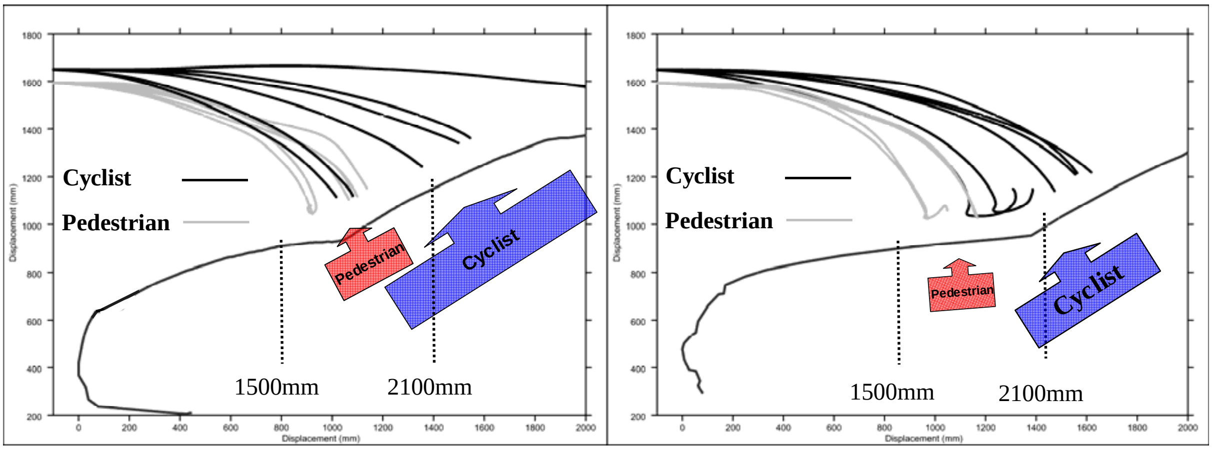

Figure 5: SM and LFC Head Trajectories

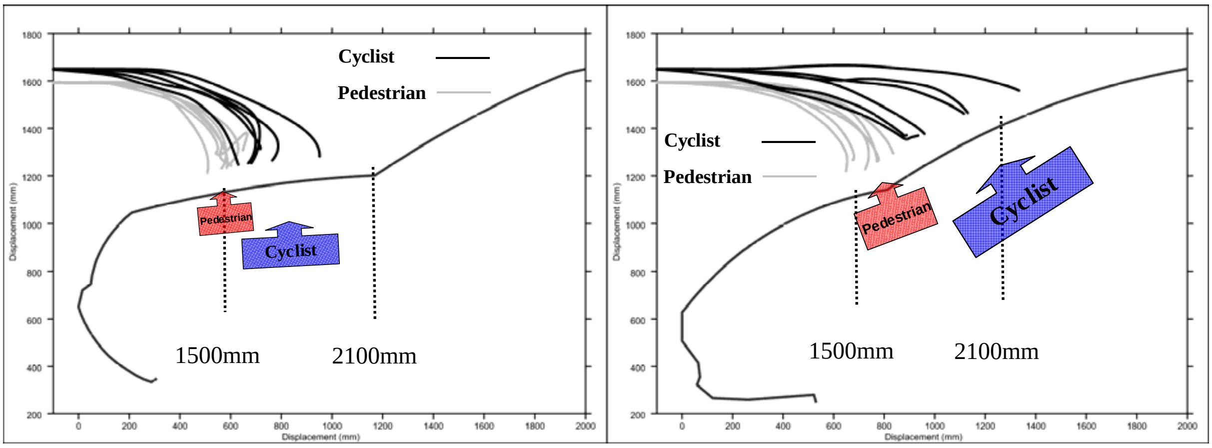

Figure 6: SUV and MPV Head Trajectories

The cyclist to vehicle head impact locations in general, were further up the bonnet, in comparison with the pedestrian, even with similar vehicle impact speeds for all vehicle types. For the SM and MPV, the cyclist head impacts were solely on the windscreen and for one simulation, (struck leg down at a vehicle speed of 15m/s), the head struck the roof of the vehicle. This was the only simulation across all vehicle types when this occurred. For the MPV, there was a distinct grouping of pedestrian head impacts in the region of the base of the windscreen (some locations on the bonnet and some on the windscreen), but cyclist impacts occurred solely on the windscreen.

In all vehicle types, the cyclist struck leg down scenario at 15m/s, produced the greatest longitudinal trajectory and the struck leg up scenario at 5m/s produced the shortest trajectory path. The amount of vertical head displacement was influenced by the vehicle shape and the length of the trajectory.

The spread over which the head impacted the vehicle for certain types of scenarios was calculated in the longitudinal direction only. The MPV head trajectories were grouped with less than 300mm spread, compared with the LFC head trajectories that were grouped with a spread of 600mm. This result indicated that the MPV vehicle produced a smaller range of scatter and the change in impact conditions did not influence the head impact location as much as the LFC.

HEAD IMPACT ANGLE AND RELATIVE VELOCITY RESULTS: The difference in vertical drop distance of the head, from initial position to vehicle impact, had a significant effect on the head impact angle. Although the vertical head drop heights were very similar for the MPV and SUV, the angle of head contact varied, with the SUV producing an impact angle greater than the other three vehicle types. The impacts occurred on the generally horizontal SUV bonnet, compared with the inclined angle of the windscreen. When the upper torso of the pedestrian or cyclist struck the rear of the bonnet for all simulations, there was no opportunity for the head to fully rotate and achieve a similar vertical displacement as the torso. In these cases, due to the vehicle geometry, the head struck the windscreen rather than the bonnet. For the SUV, the head contacts were all sufficiently towards the front of the bonnet, that the windscreen did not play a role in the head trajectory.

After initial contact between the vehicle and the Humanoid there was an increase in the relative head velocity for all simulations. The kinematics showed how, as the lower limbs and torso were struck, the head momentarily stayed in the same position. As the lower limbs and, subsequently, the lower torso, began to wrap around the front end of the vehicle, the head and neck began to translate and rotate. With the neck offering a degree of flexibility, the head was initially oriented away from the vehicle, but subsequently whipped back towards the vehicle front. It was during this state of the head being projected towards the vehicle, that the highest relative velocity of the head was recorded; see Figure 7 and Figure 8. As the head began to slow down, for most scenarios it dropped below the initial vehicle velocity by a considerable margin.

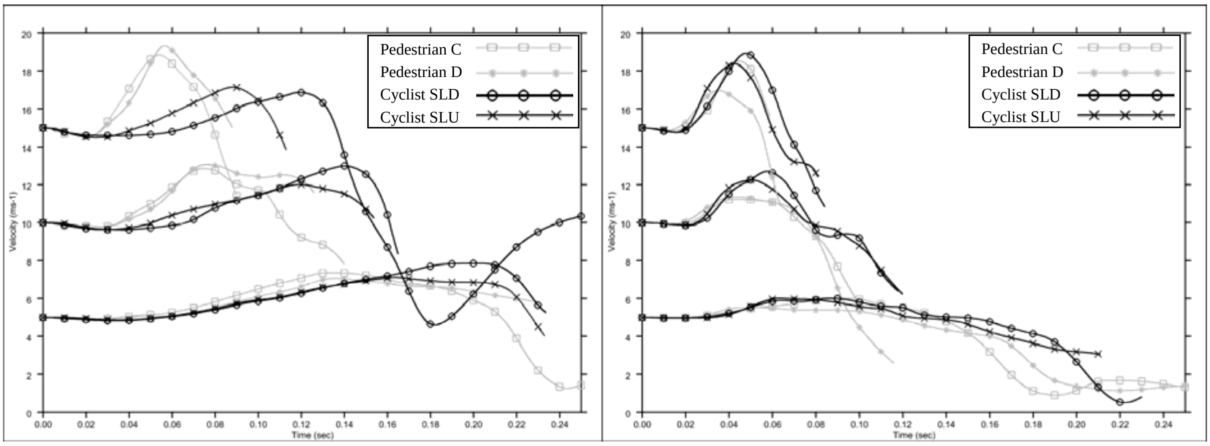

Figure 7: SM and SUV Head Velocities

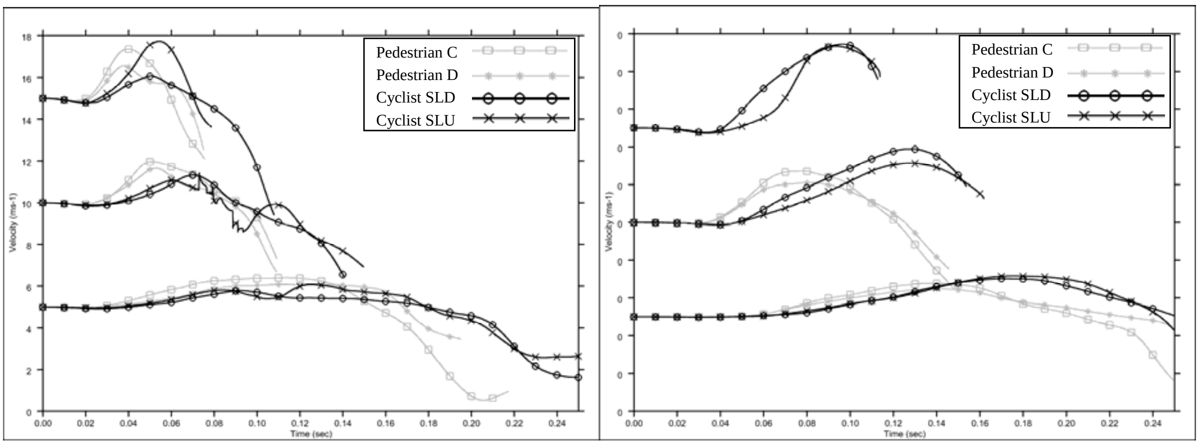

Figure 8: MPV and LFC Head Velocities

In addition, the highest relative velocities for the pedestrian cases occurred earlier than for the cyclist cases – at each vehicle speed. This was probably accounted for by the different kinematics in the pedestrian and cyclist simulations. As in the case of the SUV, in both cyclist SLU and SLD simulations at 10m/s, the head struck the vehicle at a velocity significantly lower than the initial vehicle velocity, in these cases below 7m/s and for the SM case much later than the pedestrian head impacts – a consequence of the longer trajectories and further rearward impact locations.

The head impact angles and head impact velocities for each cyclist and pedestrian stance, vehicle and vehicle velocity are given in the Appendix, Table 1and Table 2.

HEAD IMPACT DISCUSSION

For the graphs used in this discussion, the head impact angle or relative velocity were known as independent variables and were positioned on the y-axis. The categorical variables, such as vehicle type and user, were positioned on the x-axis and to investigate all the simulation results an ANOVA (analysis of variance) technique was used. If two vertical confidence bars did not overlap, they were concluded to have a significant statistical difference. For example, in Figure 9, the head impact angles for the SUV with cyclist simulations, was significantly higher than the other vehicle types. It can be concluded that there was no significant difference between the other three vehicle types, as their confidence bars were very similarly aligned.

The greater height of the cyclist's pelvis, compared to a pedestrian, had an important effect on the head impact position of the cyclist on the vehicle. When the cyclist's pelvis was higher than the bonnet edge the cyclist was more likely to wrap around the vehicle and then, in a secondary motion, slide up the bonnet. In the SUV case, the cyclist's pelvis was below the leading edge and subsequently the cyclist kinematics only showed the capability to rotate rather than slide.

HEAD IMPACT ANGLE: Some of the angles were unable to be calculated from the results due to the head not striking the vehicle and subsequently the impact velocity was not calculated. The ANOVA method was performed as it was able to accommodate for these absent results in the data set. For the lower vehicle speed, there was not always enough momentum of the cyclist or pedestrian to rotate to the extent that the head wrapped around and struck the vehicle. The lower legs and torso engaged with the vehicle and then the velocity of both entities reached an equal value and then subsequently started to move together before head impact.

In eight of the simulations, the head was very close (within 10-20mm) to impacting the vehicle but no head impact angle was recorded. The reason for no head strike in those cases was probably due to the lack of Humanoid momentum to fully wrap around the vehicle or the non biofidelic nature of the shoulder mechanism and the inability of the neck to flex sufficiently. The Humanoid shoulder model could be adapted in a further study, to represent a more biofidelic mechanism of the upper torso and offer the capability to analyse injuries to the shoulder.

The initial side ways alignment of the Humanoid with the vehicle also played a role in the subsequent head and shoulder interaction with the vehicle. If there had been an initial rotation in the stance of the Humanoid, the shoulder would not have necessarily come into contact before the head and hence played a less significant role. Nevertheless, the sideways alignment was dictated from preliminary cyclist simulations (not reported here) where the bicycle was rotated through 10 and 20 degrees (front wheel leading). In these configurations the first consequence of contact between vehicle and bicycle was to rotate the bicycle and cyclist to a near sideways alignment. To enable comparisons of the cyclist and pedestrian results the pedestrian alignment was necessarily set to be sideways.

Although the cyclists analysed in this study have been adults, there are a significant number of child cyclist casualties across European countries. The difference in initial head position for child cyclist and pedestrian stances is less than the differences shown for the adult cases. Therefore, head trajectories onto vehicles for child cyclists may show different trends to adult cyclists.

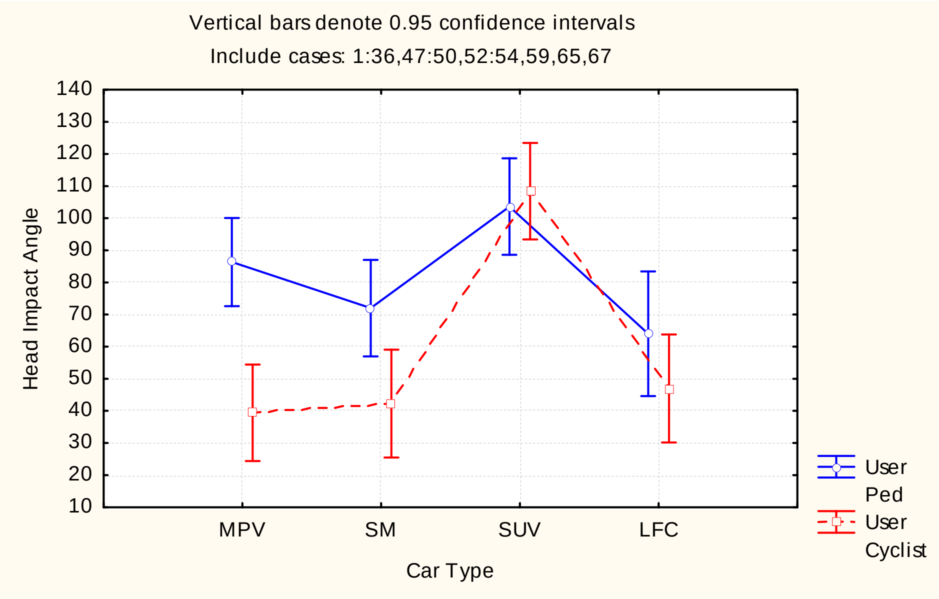

Figure 9: Head impact angle by car type per user

The SUV produced the highest impact angles for the pedestrian and cyclist, but in particular the cyclist head impact angles were significantly less than the pedestrian angles for the SM, MPV and LFC vehicles. The mean pedestrian head impact angles for the SM and MPV were above the values in current legislation. Except in the case of the SUV, all the cyclist head impact angles were below the current legislative values. However, the cyclist head impact angles for the SUV were far greater when compared with the other vehicle types, see Figure 9.

The angle of the adult head impactor, in the proposed GTR (Global Technical Regulation) pedestrian legislation, is set at 65 degrees, which falls approximately in between the cyclist and pedestrian head impact ranges. While the 65 degrees angle seemed to offer a good compromise between the two types of users, if a single pedestrian head impact angle was to be selected from this data, it would probably be closer to 90 degrees. It was difficult to choose a single cyclist head impact angle from this data, due to the large difference between the SM, LFC and MPV values (average ~43 degrees) and the SUV value (~109 degrees). It may also be worth considering a fuller range of angles for pedestrians and cyclists so that test values can be adjusted to be relevant for the particular vehicle geometry and to address the implications of their severity on consequent real world head injuries. For this to be realised, a different calculation method of WAD could also be considered to address the high bonnet leading edge of the SUV type.

HEAD RELATIVE VELOCITY RESULTS: The head velocities did not show any significant differences between the pedestrian and cyclist simulations for three of the vehicle types (SM, MPV and SUV), whereas the LFC showed a minor increase, as shown in
Figure 10.

When combining the different vehicle types, the higher vehicle speeds produced the greatest longitudinal head trajectory distances, some towards the top of the windscreen, across all vehicle types. Only the cyclist head impacts with the SUV were located solely on the bonnet.

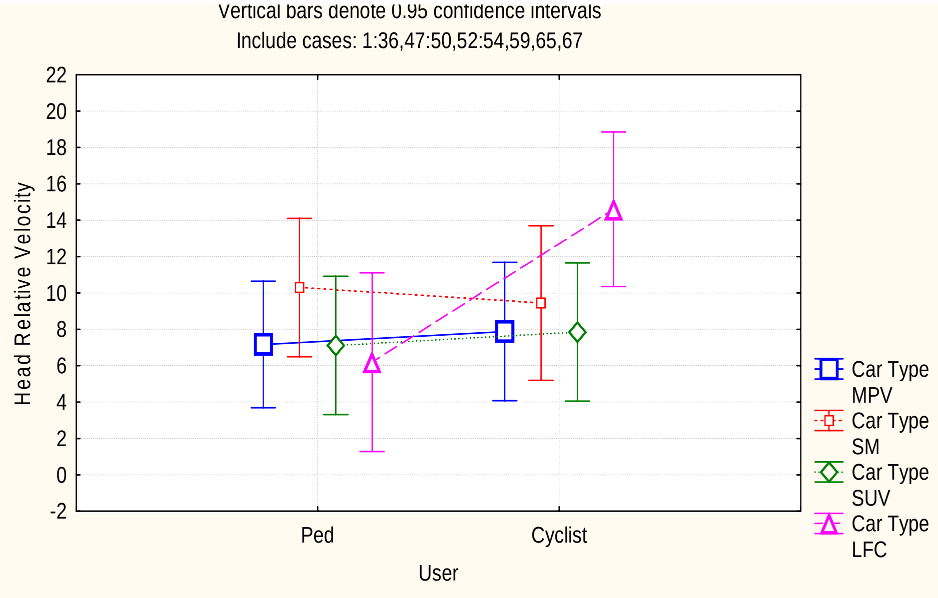

Figure 10: Head relative velocity by user per vehicle

In general, all the head relative velocities were below the impact speed of the vehicle with some exceptions. The dashed lines on Figure 11 at 5, 10 and 15 m/s represent the vehicle speeds used in the simulations and the long dashed line for 11.1 m/s or 40 km/h.

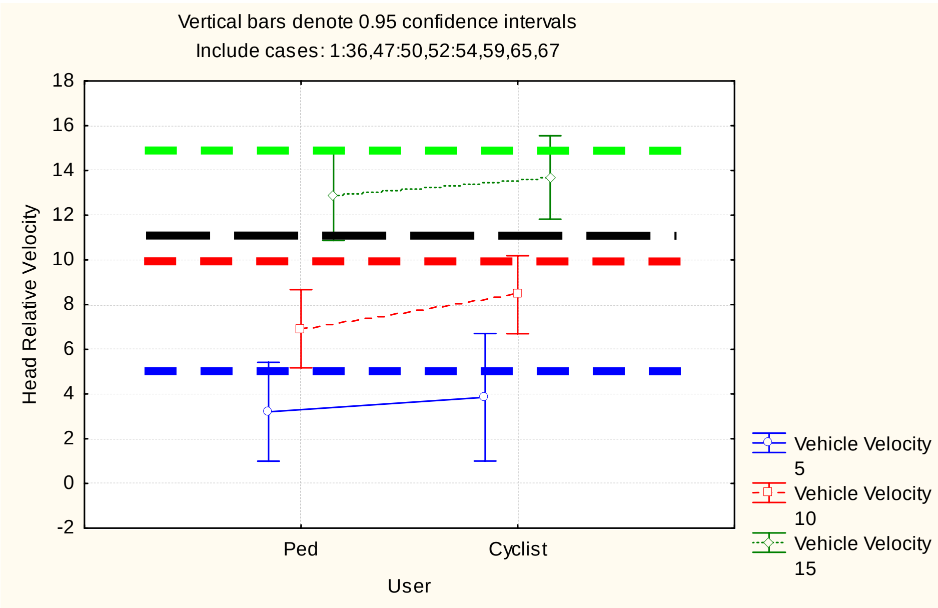

Figure 11: Head relative velocity by user per vehicle velocity

The pedestrian head results (velocities and impact angles) were generally grouped together more than the cyclists' results which showed more variability. An increase in vehicle speed was associated with a head impact location towards the windscreen or roof regions. With the pedestrian head impact locations being grouped together, this suggested that the current legislative test may be protecting pedestrians over a wider range of impact conditions than just those specified in the legislation. A proposal to adapt the current legislation to include cyclist, as well as pedestrian head impacts, may well need to cover a considerably greater area of the vehicle front. In addition, higher test speeds may be required for some vehicle geometries.

CONCLUSIONS

More detailed accident cases for cyclists need to be collected in order to better understand cyclist accidents and their consequences for injury causation. They can no longer be grouped with pedestrians as a vulnerable road user, but as a category on their own. The head impact conditions have been shown to be similar, in terms of impact speed for pedestrians and cyclists, but the impact location and angles were different. The SUV vehicle produced results that were significantly different than the other vehicle types, in terms of head impact angle and location. The impact locations for the pedestrian simulations showed that the current impact locations were valid.

Additional impact testing may be required to provide improved safety for cyclists by increasing the test locations or the number of tests performed with the current impactors.

ACKOWLEDGEMENT

This research was funded by the 6th Framework project APROSYS (Advanced PROtective SYStems) with support from the European Commission, under the title of Sub-Project 3 Pedestrian and Pedal Cyclist Safety.

APPENDIX

Table 1: Cyclist head impact angle and relative velocity results

Model description	Vehicle type	Vehicle velocity (m/s)	Head impact angle (deg)	Head impact velocity (m/s)
Struck leg up	SM	5	++	++
		10	41	10.2
		15	33	14.1
Struck leg down	SM	5	50	5.2
		10	45	8.3
		15	#	#
Struck leg up	LFC	5	++	++
		10	43	11.2
		15	45	17.7
Struck leg down	LFC	5	++	++
		10	58	11.9
		15	42	17.6
Struck leg up	MPV	5	33	3.1
		10	55	6.9
		15	44	13.6
Struck leg down	MPV	5	++	++
		10	35	6.4
		15	30	9.4
Struck leg up	SUV	5	71	3.1
		10	129	6.2
		15	125	12.6
Struck leg down	SUV	5	++	++
		10	123	6.4
		15	94	10.8

++ Head did not strike the vehicle

Head struck the roof

Table 2: Pedestrian impact angle and relative velocity results

Model description	Vehicle type	Vehicle velocity (m/s)	Head impact angle (deg)	Head impact velocity (m/s)
C-Stance	SM	5	++	++
		10	63	7.8
		15	89	11.4
D-Stance	SM	5	75	5.8
		10	66	11.6
		15	67	14.9
C-Stance	LFC	5	++	++
		10	64	6.5
D-Stance	LFC	5	67	4.5
		10	61	7.6
C-Stance	MPV	5	71	0.9
		10	85	7.3
		15	114	12.1
D-Stance	MPV	5	100	3.5
		10	77	6.7
		15	71	12.5
C-Stance	SUV	5	++	++
		10	124	5.3
		15	99	15.6
D-Stance	SUV	5	64	1.3
		10	128	2.6
		15	103	10.8

++ Head did not strike the vehicle

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