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TNO report

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Bicyclist safety in bicycle to car accidents: an inventory study

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Summary

In Europe pedestrian safety is a significant issue and has been researched in working groups and research projects. Among others this has resulted in European legislation related to pedestrian protection provided by passenger cars fronts. However, in the Netherlands more bicyclists than pedestrians get killed in road traffic, which is a main concern of the Fietsersbond. Although it is currently investigated in APROSYS Sub Project 3 if pedestrians and cyclists have to be seen as separate groups of vulnerable road users, it is unknown if pedestrian protection legislation also has a significant benefit for cyclists. Hence, the Fietsersbond has requested TNO to perform an inventory study with the aim to:

- make an investigation in pedal cyclist to car accidents using simple vehicle, bicycle and cyclist models, and
- indicate possible measures to vehicles for improved bicyclist safety.

The study has been performed using numerical simulations in the MADYMO simulation software. First multibody models were developed of passenger cars (small family, mid-sized family and SUV) and a bicycle. The models were used together with a released average male human model (as cyclist) in a baseline simulation representing a typical cyclist-vehicle impact where the cyclist is laterally impacted by a mid-sized passenger car with an initial velocity of 50 km/h. In addition a simulation study was performed varying both impact conditions and vehicle parameters.

The analysis of the vehicle-bicycle impact event was done using the global cyclist kinematics and impact velocities for the relevant body parts. In addition, the head, chest, pelvis and lower leg accelerations and the HIC value were used as indication of the injury. Due to the conceptual nature and the limited level of validation of the models, the results were used to study global trends, instead of absolute, precise values.

In the baseline simulation the most severe loading was found to be on the lower leg and the head, which is in line with the findings from an earlier study that the head and the legs are the most frequently injured body regions for cyclist and pedestrians. In the variation study it was found that:

- a reduction in the impact velocity reduced the injury levels estimated by the models. A reduction in impact velocity could for instance be obtained by infrastructural measures.
- the shape had a large influence on the kinematics of the cyclist. The small vehicle model with a shorter and steeper bonnet resulted in a better load distribution over the body and reduced head loading. The SUV model, with its high bonnet leading edge, caused a direct load on the pelvis and upper legs, which could result in severe injuries in the pelvic region.
- a reduced stiffness of the rigid parts in the windscreen area resulted in a significant reduction of head injuries estimated by the models.
- the velocity and the impact position influenced the possibility of having a ‘second impact’ with the ground and its severity. This impact is not taken into account in this study.

As the current study was an inventory study, it is recommended for future research to:

- validate the models more specific for cyclist-vehicle impact loading which will lead to an improved predictive capability. Furthermore, although it is realized

that only limited data might be available, accident data could be analyzed to derive the relevant parameters and ranges in bicycle to car accidents.

- study the front-end and bonnet stiffness in more detail. In the current study these components were found to have only a limited influence, which is partly because only the (initial) deformation force level was varied and not the stiffness and position of underlying rigid components. Further research could indicate the effects of e.g. varying the available deformation space and could lead to an optimized design towards injury minimization.
- investigate the difference between pedestrian-vehicle and bicyclist-vehicle impacts as this could indicate if the measures for pedestrians could also have a significant benefit for cyclists or if additional measures are needed.

Contents

1 Introduction

A lot of attention is being paid to pedestrian safety by for instance international working groups as EEVC WG17 and in research projects as APROSYS [1]. In addition legal requirements are in place, like the EU directive 2003/102/EC. However, it can be seen from the BRON (Bestand geRegistreerde Ongevallen Nederland) accident database that in the Netherlands more people get killed or injured while riding a bicycle than as a pedestrian [2]. This is a main concern of the Fietsersbond, the Dutch Cyclists' Union that campaigns for better cycling conditions in the Netherlands.

Although it is currently investigated in APROSYS Sub Project 3 if pedestrians and cyclists have to be seen as separate groups of vulnerable road users, it is unknown whether the improvements in pedestrian safety, enforced by legislation, are also beneficial for cyclists. Hence, the Fietsersbond has requested TNO to perform an inventory study with the aim to:

- make an investigation in pedal cyclist to passenger car accidents using simple vehicle, bicycle and cyclist models, and
- indicate possible measures to vehicles for improved cyclist safety.

The study has been performed using numerical simulations in MADYMO, which is a simulation software that is widely used in the automotive safety field. As a first step generic multibody models were developed of different sized passenger cars (a small family car, a mid-sized family car and a Sports Utility vehicle (SUV)). In addition a generic bicycle model was developed of a typical men’s cycle. Next a baseline simulation was developed using the mid-sized family car model and the cycle model together with a released average male human model as cyclist. This simulation represented a typical cyclist-vehicle impact where the cyclist is laterally impacted by a mid-sized passenger car with an initial velocity of 50 km/h. Finally a simulation study was performed using the baseline simulation as a basis, varying both impact conditions and vehicle parameters to study the influence (in terms of trends) on the cyclist kinematics and loads.

The developed multibody models and the model assembly are described in chapter 2. Chapter 3 and 4 describe the results of the baseline and the variation simulations respectively. In chapter 5 the results are discussed and chapter 6 lists the conclusions and recommendations.

2 Model setup

For this study a MADYMO multibody model has been developed consisting of a vehicle, a bicycle and a cyclist. In the next sections these components and the model assembly are described.

2.1 Vehicle models

Since in this study different vehicle shapes have been studied, three different vehicle models were created, as shown in Figure 2: small family car / mini-Multi Purpose Vehicle (MPV; 1000 kg), mid-sized family car (1250 kg) and SUV (1600 kg). The geometry of these models has been based on generic vehicle geometry data for different vehicle classes [3]. Except for the geometry and mass, all the models have a similar set-up and do contain the same parts. The vehicle front-end consists of four ellipsoids above each other: spoiler, bumper, headlights/grille and bonnet leading edge. The ellipsoids are rigidly connected to the vehicle. The deformation characteristics of the parts, including bottoming out against the underlying stiff structures, are modelled in the contact characteristics (force-penetration and damping) of the ellipsoids. In this way a local deformation has been modelled, with the deformation resulting from an impact taking place mainly in the impacted area itself. The bonnet and windscreen are represented by one ellipsoid each, connected to the vehicle with a translational joint in which the deformation characteristics are included. With this modelling technique a more global deformation can be simulated, with the deformation resulting from an impact being spread over a larger area. Under the bonnet the main rigid and structural parts are included: engine, bonnet side wings and lower windscreen cross member, with a stiff contact characteristic. Furthermore, an ellipsoid has been included for the roof. The deformation characteristics of the different parts of the vehicle have been derived from an earlier vehicle modelling study [4]. For the usage in this study the characteristics are generalised.

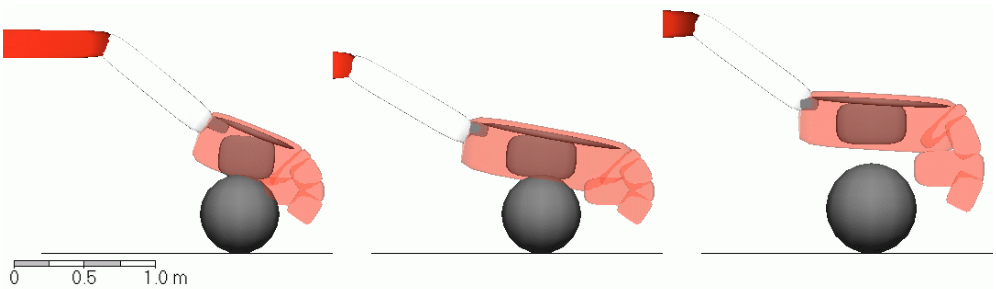

Figure 2 Vehicle models (left: small family car, middle: mid-sized family car, right: SUV)

2.2 Bicycle model

The bicycle model shown in Figure 3 has been based on global measurements done on a popular men's bicycle. The height of the saddle and steer are 100 cm and 106 cm, respectively. The bicycle has a total mass of 20 kg. All main degrees of freedom are included in the model, like rotation of the wheels, crank, pedals and steering. Deformation of the front fork (bending) has been included, which is mainly important for frontal impact. Contact characteristics of the wheels and the steel parts and the front fork deformation characteristic have been derived from experimental tests published by Maki [5]. The contact characteristics are implemented as force-penetration characteristics. The deformation characteristics for the bending of the front fork are implemented as torque versus angular displacement.

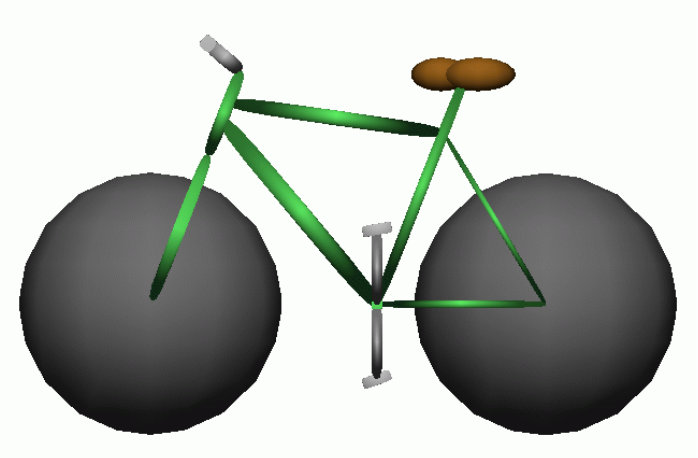

Figure 3 Bicycle model

2.3 Cyclist model

As cyclist model, the MADYMO average male human pedestrian model has been used. The model has been created using multibody techniques. The outer surface of the model is represented by 64 ellipsoids and is based on the anthropometry data of an average Western European male obtained from the RAMSIS software. Biomechanical data for the joints and segment parts were implemented from a variety of publications, together with detailed validation for the whole body as well as components. The majority of this data is concerned with the average male model.

The contact characteristics for the various body regions were based on data found in literature and optimized in simulations of a large range of PMHS impactor tests on various body parts. The validation results obtained with the pedestrian model are published by van Hoof *et al.* [6]. In general, the model approximates the measured PMHS response well, especially when the large range in test conditions and impacted body parts is considered.

The average male model has a weight of 75.6 kg and a standing height of 1.74 m. With a limited CPU usage this model is able to predict realistic body kinematics, accelerations and global injury parameters. Furthermore the possibility of leg fracture is included in this model. Besides the average male model used in this study, also other body sizes are available, including 3 and 6 year old children, a small female and a large adult male. The average male cyclist model has been positioned on the bicycle, as shown in Figure 4.

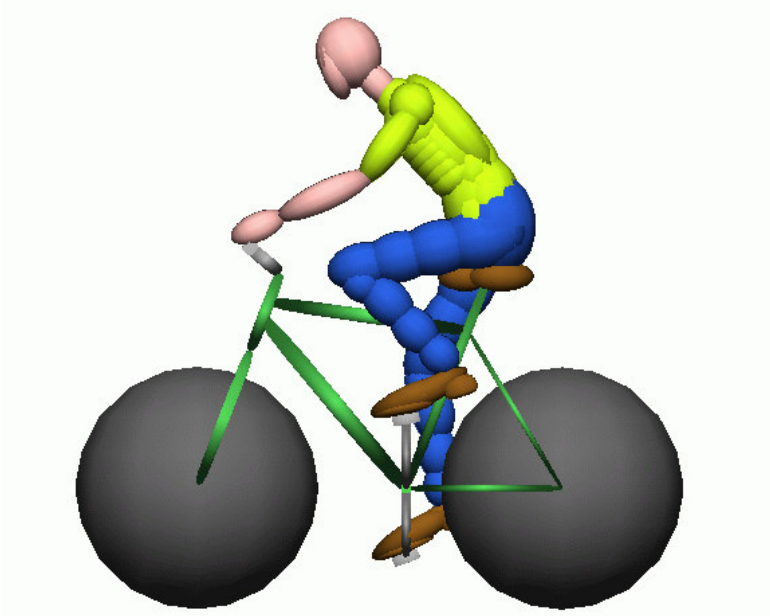

Figure 4 The average male model on bycicle

2.4 Model assembly

Using the mid-sized family car, bicycle and cyclist models described before, a complete bicycle impact model has been created, as shown in Figure 5. In this model the cyclist is laterally impacted by the mid-sized family car, while middle in front of the vehicle. As can be seen in Figure 5, the cyclist's leg which is directly impacted by the vehicle is down. The initial velocity of the bicycle is 15 km/h, while the vehicle has an initial velocity of 50 km/h and brakes with 5 m/s^2. The simulations have been performed until all major contacts of the cyclist with the vehicle have taken place, and the maximum loading of the body by the vehicle is completed (primary impact). A secondary impact with the ground, which might occur if the cyclist flies over or slides off the vehicle, has not been included in the simulations. Although the secondary impact is thought to be relevant, Otte [7] indicates that in general the injuries due to the secondary impact are not so frequent and do not have such a high severity as the injuries resulting from the primary impact.

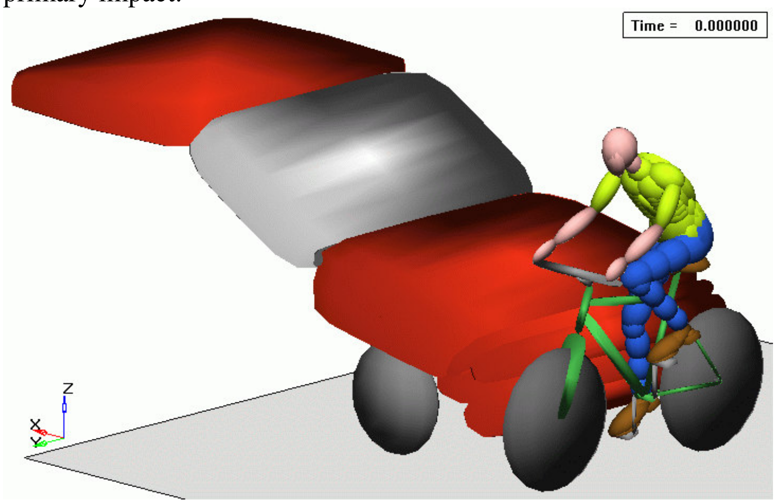

Figure 5 Bicycle impact model setup

Contacts between the vehicle, the cyclist and the bicycle have been defined using combined characteristics to taken into account the compliance of the vehicle, the cyclist and the bicycle models. The friction coefficient between the cyclist and the vehicle has been set to 0.3. In the contact between the bicycle and the vehicle, a friction coefficient of 0.8 has been defined.

Two Kelvin restraints (springs) are used to keep the hands fixed at the steer initially. If the force level exceeds 500 N, the spring stiffness is reduced to zero and the hands are released from the steer.

All simulations are performed in MADYMO v6.3. The EULER integration method was used with an integration time step of 10 microseconds. A typical runtime of the simulation on a regular PC is about 2 minutes.

2.5 Output

It should be noted that due to the conceptual nature of the models and the level of validation of the complete simulation model, the results obtained should not be interpreted as accurate predictions, but only as an estimation of the phenomena occurring. Therefore, in this study the focus is on determining global trends (whether things get better of worse), instead of the absolute, precise values.

The analysis of the vehicle-bicycle impact event was done using the following output:

- global cyclist kinematics: The kinematics were analysed to determine at which locations the cyclist impacts the vehicle
- contact velocities: For the relevant body parts the impact velocity of the first occurring contact of that body part with the vehicle have been calculated based on the penetration velocity. Body parts investigated are head, (impacted) shoulder, (impacted) upper arm, torso, pelvis, (impacted) upper leg and (impacted) lower leg. Contact velocities of the non-impacted limbs are not analysed, since the loads are expected to be lower than on the impacted limbs. Also the lower arm contact velocity is not analysed, since this contact is not expected to cause significant loading on the body.
- injury parameters (Figure 6): The loading on the cyclist body is determined by means of the accelerations of head, chest, pelvis (hip) and tibia (lower leg). From these accelerations the 3ms peak value is extracted, which is the maximum level that the acceleration exceeds for a continuous period of 3 ms. For the head also the HIC value is calculated, which is a commonly used injury parameter based on the head acceleration. For easier comparison of the different injury parameters, the actual values obtained have been normalised using commonly accepted injury criteria indicating a significant risk on severe injury. Hence it could be said that, to prevent serious injuries, the normalised injury values should be below 1. The injury criteria used for normalisation are:
  - HIC 1000
  - head 3ms peak acceleration 80 g
  - chest 3ms peak acceleration 60 g
  - pelvis 3ms peak acceleration 60 g
  - tibia 3ms peak acceleration 150 g

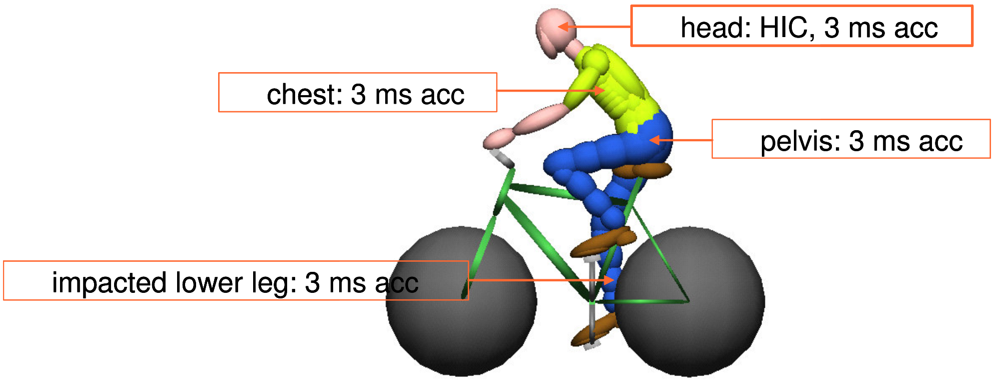

Figure 6 Cyclist injury parameters

Filtering of the output signals is done in accordance to SAE J211 [8].

3 Baseline simulation results

A side view of the vehicle-bicycle impact simulation kinematics is shown in Figure 7. The contact velocities and resulting normalised injury parameters are shown in Figure 8.

In Figure 7 it can be seen that the cyclist model rotates around its vertical axis with its back to the vehicle. This is caused by the fact that the impacted lower leg is in front of the pelvis. The first contact between the vehicle and the cyclist is at 2 ms between the bumper and the lower leg, with a velocity equal to the initial vehicle velocity (14 m/s). Due to this direct impact a relatively high tibia 3ms peak acceleration is found. The following contacts with upper leg (knee) and pelvis take place with a lower velocity, since the cyclist body is already accelerated by the vehicle due to the earlier contacts: the knee contact with the bonnet leading edge is at 8 ms with 8 m/s, and the pelvis contact with the bonnet is at 60 ms with 3 m/s. Due to the limited contact velocities the pelvis 3ms peak acceleration is relatively low. After this, the contact velocities start to increase again for the upper body. This increase is caused by the rotation of the upper body of the cyclist due to the impact below the body centre of gravity (against the legs). Due to this rotation the upper body gets a velocity towards the vehicle, which is higher further away from the centre of gravity. For the arm, shoulder and chest this effect is still limited, resulting in upper arm contact at 100 ms with 7 m/s, shoulder contact at 116 ms with 6 m/s and torso (chest) contact at 126 ms with 5 m/s, all with the (lower) windscreen. Due to the limited contact velocities the chest 3ms peak acceleration is relatively low. For the head, which is the furthest away from the centre of gravity, the effect of the rotation is much larger. At 130 ms the head contacts the windscreen with a velocity of 13 m/s, close to the initial vehicle velocity, causing a relatively high head 3ms peak acceleration and HIC value.

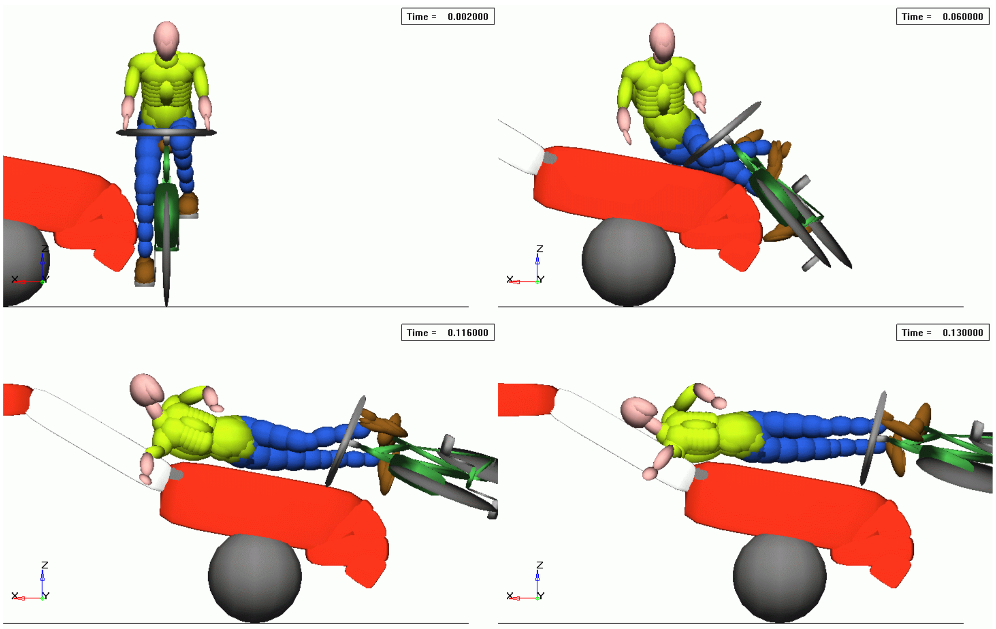

Figure 7 Cyclist kinematics in baseline simulation (at 2, 60, 116 and 130 ms)

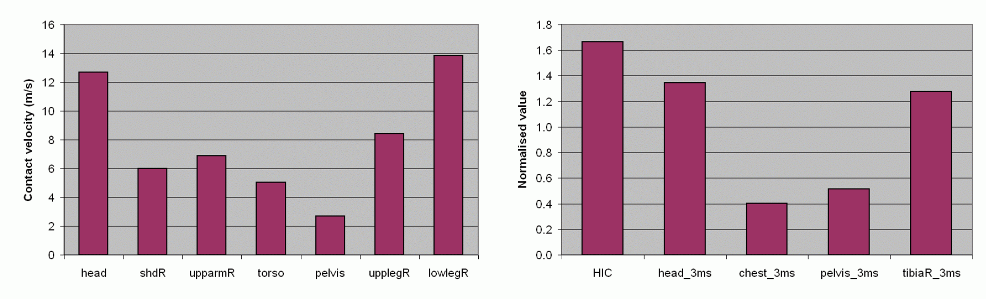

Figure 8 Contact velocities and injury parameters in baseline simulation

4 Variation study

4.1 Setup

Starting from the baseline simulation, several parameters have been varied to study their influence on the cyclist kinematics, contact velocities and cyclist injury parameters. The parameters that were investigated are:

- Impact angle: 80, 90 (baseline) and 100 degrees from frontal, see Figure 9;
- Impact position: left (-40 cm), mid (baseline) and right (+40 cm), see Figure 10;
- Initial vehicle velocity: 30, 40, 50 (baseline), 60, 70 and 80 km/h;
- Vehicle shape: small family car, mid-sized family car (baseline) and SUV, see Figure 2;
- Vehicle stiffness: Force scaling factor 0.5, 1.0 (baseline), 1.5 and 2.0;
- Windscreen stiffness: Force scaling factor 0.5, 1.0 (baseline).

For the variation of the vehicle stiffness only the characteristics of the bonnet and vehicle front-end have been used. The stiffness and position of the stiff parts under the bonnet has not been varied. For the variation of the windscreen stiffness it should be noted that although changing the actual stiffness of the windscreen might not be feasible, the effective stiffness could also be reduced by other measures like e.g. and airbag inflated on top of the windscreen.

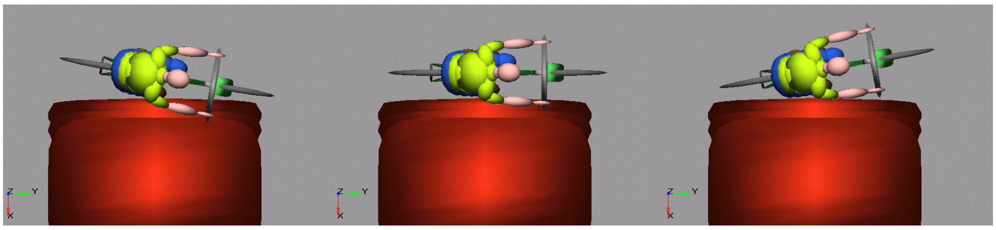

Figure 9 Angle variations (80, 90 and 100 degrees)

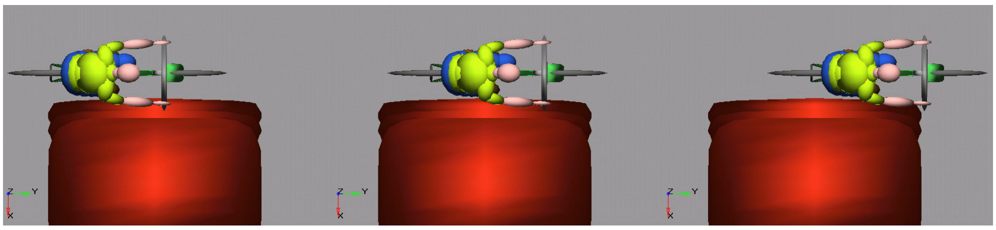

Figure 10 Position variations (left, mid and front)

4.2 Results

4.2.1 Impact angle

The difference in kinematics caused by the variation of the impact angle is shown in Figure 11 and the resulting contact velocities and injury parameters are shown in Figure 12.

For a smaller impact angle, it can be seen that the cyclist contacts the vehicle further towards the windscreen, and with a higher velocity compared to a higher impact angle. This is caused by the velocity component of the bicycle towards the vehicle. With a 90 degree impact, the bicycle velocity is perpendicular to the vehicle velocity. With an 80 degree impact however, the bicycle moves a little bit towards the vehicle, resulting in an increased effective impact velocity. With a 100 degree angle the bicycle moves a little bit away from the vehicle, resulting in a reduced effective impact velocity. Besides this influence on the effective impact velocity, no clear trend could be observed. The variations in contact velocity are too small to have a clear effect on the injury parameters.

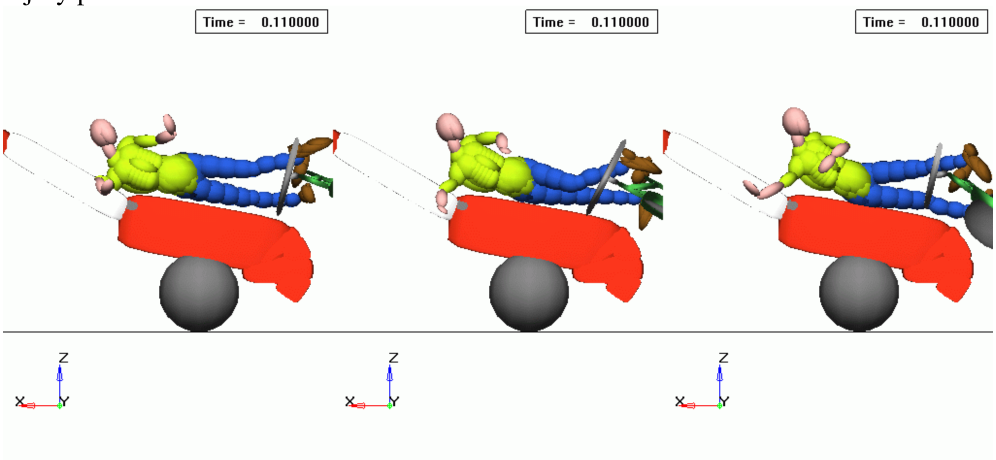

Figure 11 Influence of impact angle on kinematics (80, 90 and 100 degrees)

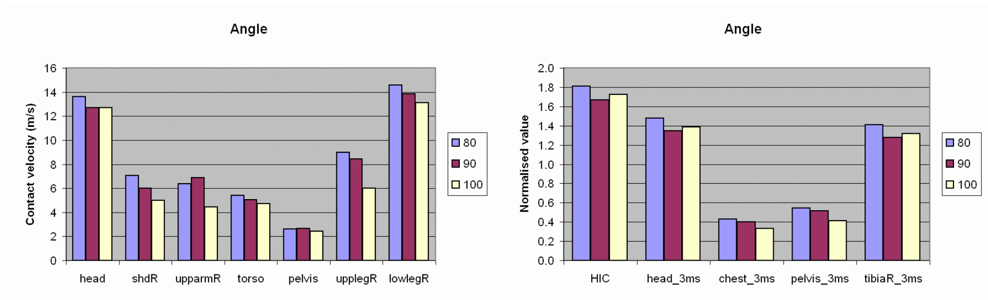

Figure 12 Influence of impact angle on contact velocities and injury parameters

4.2.2 *Impact position*

The difference in kinematics caused by the variation of the impact position is shown in Figure 13. The resulting contact velocities and injury parameters are shown in Figure 14.

The only significant effect of the impact position on the kinematics observed is a corresponding difference in the lateral impact location of the cyclist on the bonnet and windscreen. However, as a result of this, the upper body of the cyclist does not contact the vehicle at all for the impact in the rightmost position. Therefore, the differences between the left and mid position are only small, but for the rightmost position the injury parameters of the upper body show a large reduction. It should however be noted that this is only valid for the direct contact between the vehicle and the cyclist. In the rightmost position the cyclist flies over the vehicle and falls to the ground head-first and the second impact with the ground might cause head injuries. Finally, in a position between mid and right, the head directly impacts the A-pillar, which in most current vehicle designs is much stiffer than the windscreen and might cause increased head injuries.

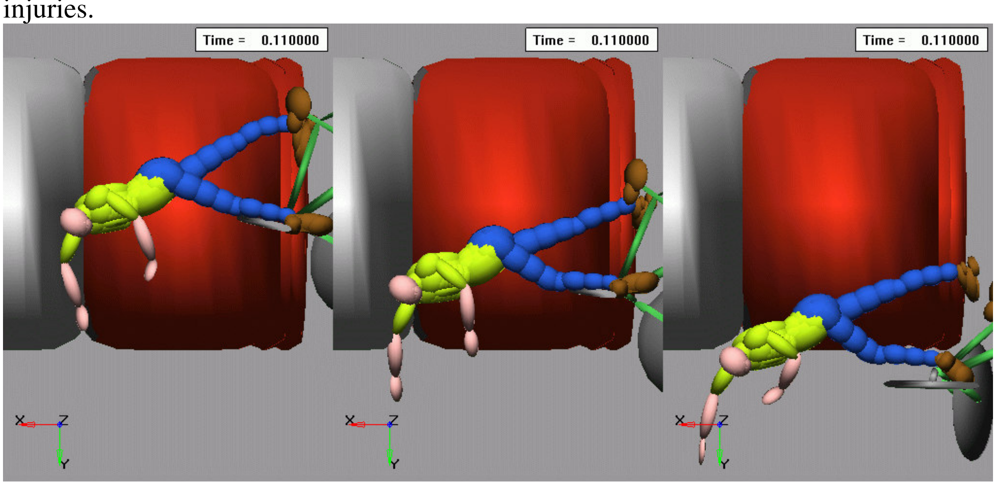

Figure 13 Influence of impact position on kinematics (left mid and right)

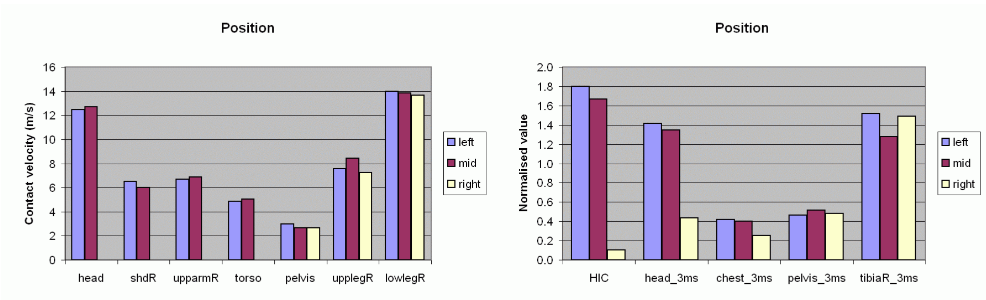

Figure 14 Influence of impact position on contact velocities and injury parameters

4.2.3 *Initial vehicle velocity*

The difference in kinematics caused by the variation of the vehicle velocity is shown in Figure 15. The resulting contact velocities and injury parameters are shown in Figure 16.

An increased initial vehicle velocity causes the contact between the cyclist and the vehicle to be earlier, located further on the vehicle and with an increased velocity. The increased contact velocity results in an increase of the injury parameters.

Besides the difference in impact direction, also the lateral impact location of the cyclist (upper) body is influenced by the vehicle velocity. This difference is caused by a changing ratio between the vehicle and bicycle velocity. With a high vehicle velocity the relative bicycle velocity is only small, causing the cyclist to impact the centre of the vehicle. With a low vehicle velocity the bicycle velocity has more effect, causing the cyclist upper body to impact the vehicle more to the right side. For vehicle velocities of 50 km/h and higher, the head contact is with the windscreen, but for vehicle velocities around 40 km/h the head impacts the A-pillar, with the possibility of increased head injuries. For 30 km/h, the head slightly contacts the A-pillar, but mainly flies over the vehicle to fall off head-first at the right side, in which case the second impact with the ground might cause head injuries. Since the second impact has not been evaluated in this study, the 30 km/h simulation shows only very low head loading.

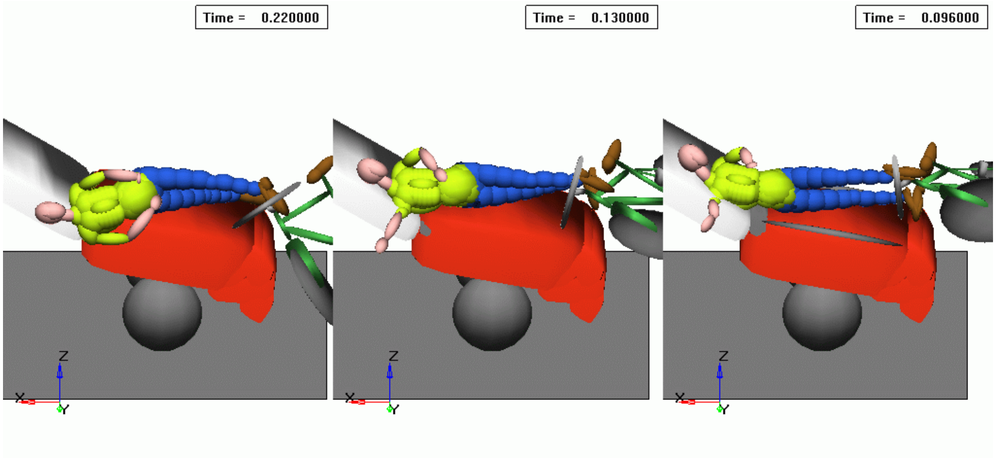

Figure 15 Influence of vehicle velocity on kinematics (30, 50 and 70 km/h, at different times)

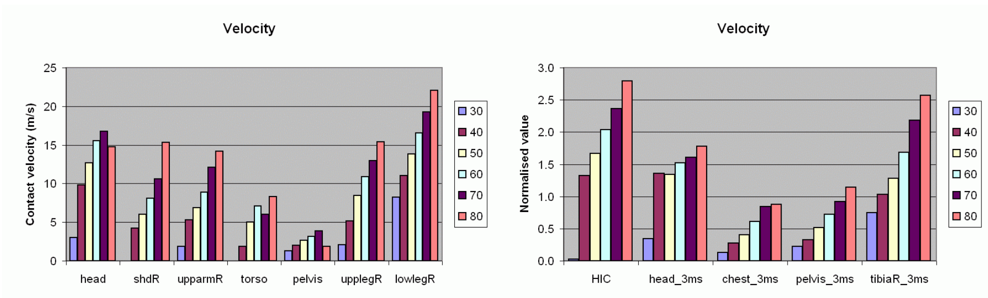

Figure 16 Influence of vehicle velocity on contact velocities and injury parameters

4.2.4 *Vehicle shape*

The difference in kinematics caused by the variation of the vehicle shape is shown in Figure 17. The resulting contact velocities and injury parameters are shown in Figure 18.

The small family car has a shorter and steeper bonnet. Due to this the contact velocity of the pelvis and chest increases, which also results in an increased chest acceleration. Due to the more continuous loading and the shorter bonnet the effect of the upper body rotation towards the windscreen (section 3) is reduced, resulting in reduced head contact velocity and injury parameters. So the more continuous front shape of the car results in a more evenly distributed load with a reduction for the most critical parameters. The shorter bonnet also results in the shoulder and head contacts to be further on the windscreen.

The SUV has a higher front, with the bonnet leading edge close to the pelvis, while it is close to the knee for the mid-sized family car. This high front causes a direct impact of the vehicle on the upper leg and pelvis of the cyclist, resulting in a high pelvis 3ms peak acceleration. Also the chest acceleration increases. Due to the increased loading on the lower body, the contact velocities of the arm, shoulder and head are reduced. Also the resulting HIC value is reduced. The head and shoulder do not contact the windscreen as for the mid-sized family car, but hit the bonnet of the SUV.

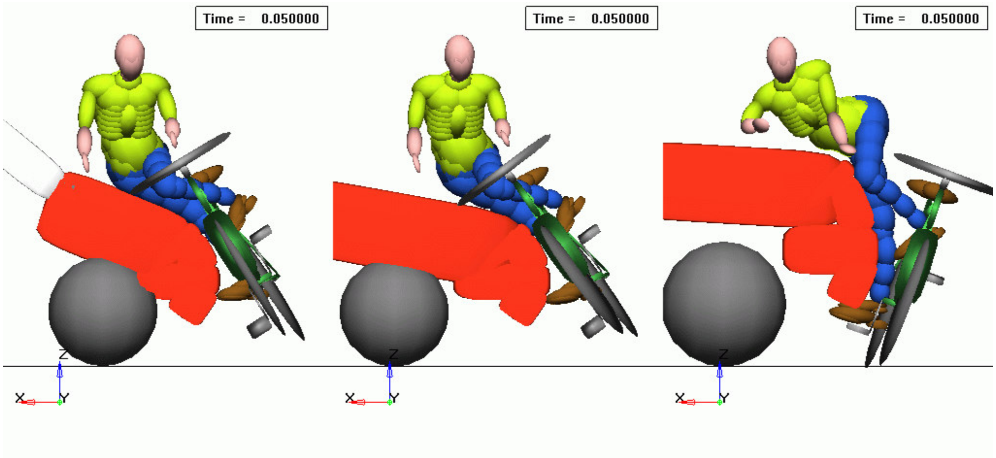

Figure 17 Influence of vehicle shape on kinematics (small, mid-sized and SUV)

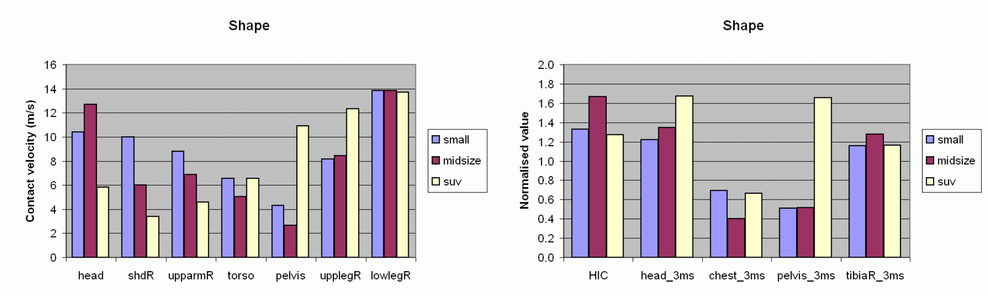

Figure 18 Influence of vehicle shape on contact velocities and injury parameters

4.2.5 *Vehicle stiffness*

The difference in kinematics caused by the variation of the vehicle stiffness is shown in Figure 19. The resulting contact velocities and injury parameters are shown in Figure 20.

The variations in stiffness have only limited influence on the results. The main effect observed in the kinematics is that with a lower stiffness the cyclist rolls or slides over the vehicle, while with a higher stiffness the cyclist ‘flies’ over the bonnet, due to the more stiff impact with the vehicle front. This effect can also be seen in the torso contact velocity, which reduces for increasing vehicle stiffness. With the torso ‘flying’ over the bonnet, the body is slightly less loaded before head impact, which causes a small increase in HIC value. Furthermore for the lower leg 3ms value a slightly decreasing trend can be observed with increasing vehicle stiffness. This is caused by the increased bumper stiffness reducing the contact with the rigid bumper beam behind.

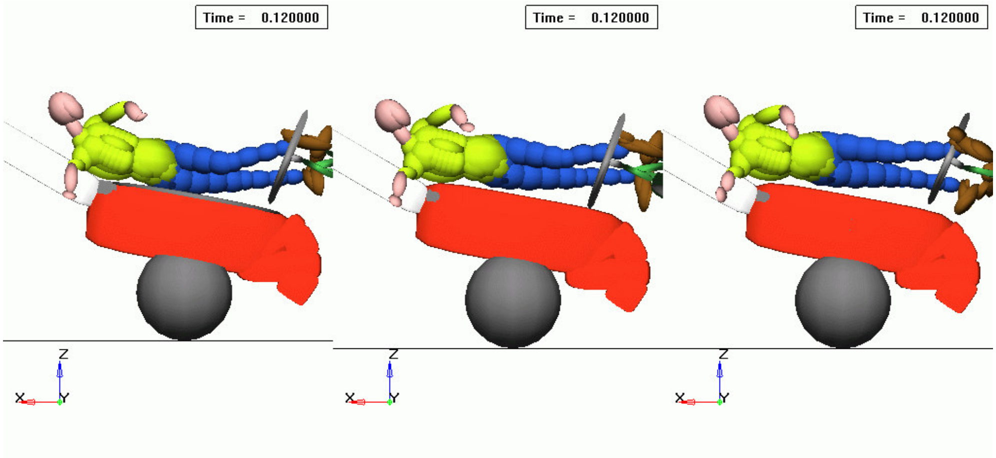

Figure 19 Influence of vehicle stiffness on kinematics (from left to right: stiffness scale factor 0.5, 1, 2)

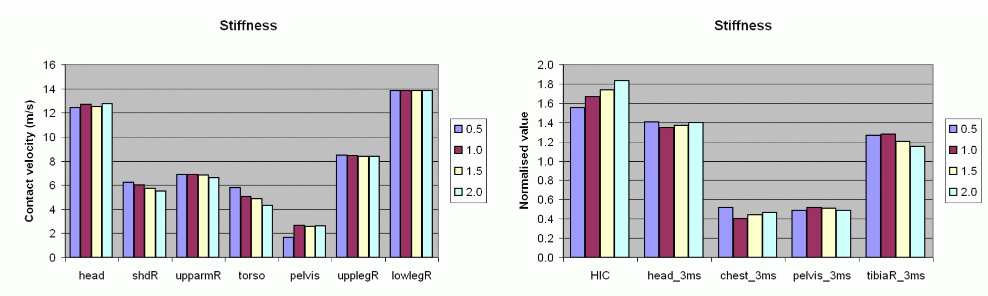

Figure 20 Influence of vehicle stiffness on contact velocities and injury parameters

4.2.6 *Windscreen stiffness*

The difference in kinematics caused by the variation of the windscreen stiffness is shown in Figure 21. The resulting contact velocities and injury parameters are shown in Figure 22.

The windscreen stiffness does not have any significant effect on the body kinematics and contact velocities. Hence, also the injury parameters for body parts not loaded directly by the windscreen do not show much difference. For the head however a clear influence can be observed. A reduction of the windscreen stiffness with a factor 2 results in a reduction of the HIC value with more than 50%, indicating a large potential reduction in the risk on severe head injury.

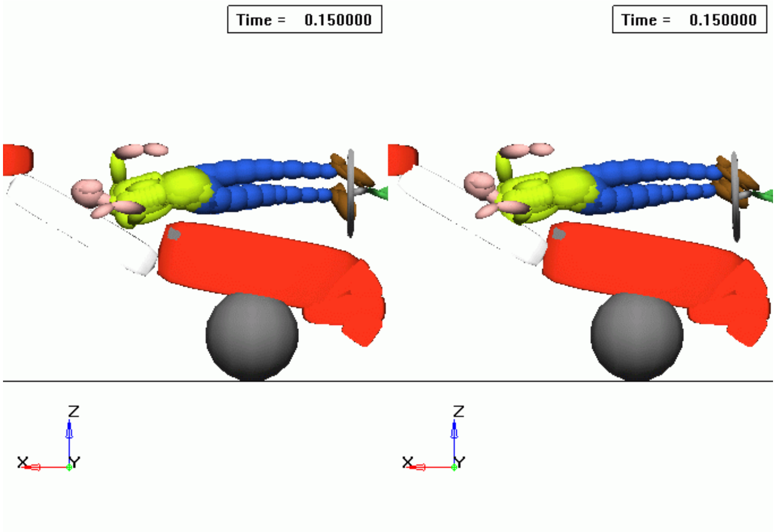

Figure 21 Influence of windscreen stiffness on kinematics (from left to right: stiffness scale factor 0.5 and 1)

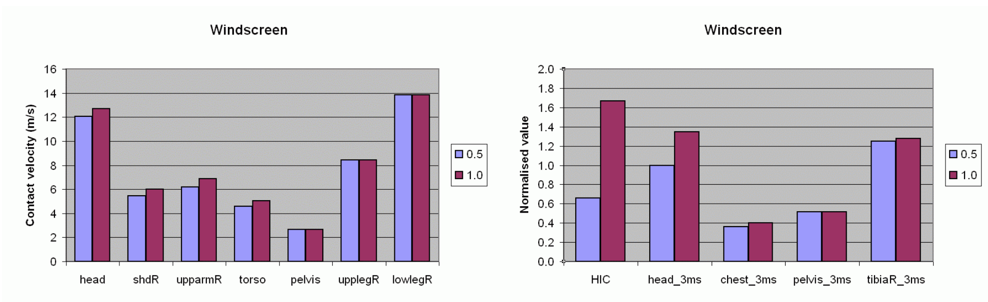

Figure 22 Influence of windscreen stiffness on contact velocities and injury parameters

5 Discussion

In the baseline simulation, in which a mid-sized family car impacts a cyclist laterally with 50 km/h, the most severe loading was found to be on the lower leg and the head. The pelvis and chest loads in this study are in general less severe and are considered not to be most critical. This is in line with a study from Janssen and Wismans [9] who conducted a study in which pedestrian-vehicle impacts and cyclist-vehicle impacts were compared using both experiments and simulations. They concluded that the head and the legs are the most frequently injured body regions for both cyclist and pedestrians. Head injuries are often more serious and life threatening at short term; leg injuries can also lead to serious injuries such as disability at long term.

In the variation study, the influence of two different types of parameters has been investigated: parameters related to the impact conditions and vehicle related parameters. The initial impact conditions include impact angle, position and velocity, while the vehicle characteristics include vehicle shape, front-end and bonnet stiffness and windscreen stiffness.

From the impact conditions the velocity has the most influence on the injury parameters. Although the exact relation between the velocity and the injury risk is subject for further study, it can be seen that an increasing velocity increases injury parameters and thus the chance of injuries and fatalities. A reduction of the impact velocity, by means of e.g. infrastructural measures, thus could contribute to improved cyclist safety. The velocity as well as the impact position have an effect on the contact locations in lateral direction and thus on the possibility and severity of having a second impact with the ground. In this study this secondary impact has not been investigated, but since in several cases the cyclist was found to fall down to the ground head-first, severe head loading might be possible. However, it should be noted that in real world also the cyclist's reaction could influence the severity of a secondary impact, especially with lower vehicle impact velocity. The impact angle has only minor influence within the range studied. For larger impact angles, like a straight frontal impact (zero degrees), the kinematics and resulting injury parameters could be completely different.

From the vehicle characteristics the shape has a large influence on the body kinematics. The more continuous front surface of the small vehicle model with a shorter and steeper bonnet (and a higher roof leading edge) results in a better distribution of the load over the cyclist model. Also a reduced head loading was found due to a reduced head impact velocity. The SUV has a high bonnet leading edge which causes a direct load on the pelvis and upper legs. This could result in severe injuries in the pelvic region. A reduction of the windscreen stiffness was found to have a large effect on the head injuries. If the stiffness of the rigid areas of the windscreen (as for instance the A-pillars) could be reduced, this could result in a significant reduction of head injuries. This could for instance be done by inflating an airbag preventing hard contact between the head of the cyclist and the rigid car structures in the windscreen area as shown in Figure 23.

Figure 23. Example of an airbag used to prevent hard contact between the head and the A-pillar (Source: www. Autoliv.com)

The front-end and bonnet stiffness was found to have only limited influence on the cyclist kinematics and loading. This is however partly caused by the fact that in this study only the (initial) deformation force level was varied and not the stiffness and position of underlying rigid components like the engine or structural parts. Further research should indicate what the effect of e.g. varying the available deformation space is on the cyclist kinematics and injuries. This could then lead to an optimization of the available space towards injury minimization.

In the study mentioned earlier, Janssen and Wismans [9] reported that the results of the comparison between the pedestrian-vehicle impacts and cyclist-vehicle impacts indicated important similarities between pedestrian- and cyclist-vehicle impacts. The bumper loads and head impact velocities were similar. However, a major difference was found in the head impact locations and as a consequence, the impact of the cyclist's head with the windshield or even with the roof is more likely than for a pedestrian. Furthermore, the initial velocity of the bicycle can have a significant influence on the contact locations or can even cause the cyclist to fly over the bonnet and impact the ground, while a pedestrian will only have a limited initial velocity. Further research is required to determine to what extend the current pedestrian safety regulations will improve cyclist safety and whether separate requirements will be needed to obtain a significant reduction of cyclist injuries and fatalities.

As mentioned before, in this study conceptual models have been used. Therefore the current simulations only provide a rough estimation of the global kinematics and resulting parameters and can indicate global trends in results depending on parameter variations. The precise values obtained in this study should not be interpreted as accurate predictions.

The model of the cyclist has been validated for lateral pedestrian impacts up to 40 km/h, while the vehicle and bicycle model were not validated. Although the model set-up and characteristics were chosen realistic, the component models and the full model should be validated more specifically for this load case to improve the predictive capabilities of the simulation model. This could be combined with an increased complexity of the model to get more detailed results. Furthermore, the results of the simulations could be compared to accident statistics e.g. to validate the trends estimated by the models, although it is realized that only limited data might be available. In addition accident studies could be used also to investigate the relevant parameters and ranges as input for an extended simulation study.

6 Conclusions

6.1 Conclusions

The study has been performed using numerical simulations in MADYMO. First models were developed and a baseline simulation was performed. Using the baseline simulation as a reference, impact conditions and vehicle parameters were varied and the influence on the cyclist model kinematics, contact velocities between cyclist and vehicle (indicating the contact severity) and injury parameters was studied. In the study, conceptual models have been used. Therefore the current simulations indicate global trends in results depending on parameter variations. The absolute, precise values obtained in this study should not be interpreted as accurate predictions.

In the baseline simulation, in which a mid-sized family car impacts a cyclist laterally with 50 km/h, the most severe loading was found to be on the lower leg and the head. The pelvis and chest loads in this study are in general less severe and are considered not to be most critical. This is in line with the findings of Janssen and Wismans [9] who found that the head and the legs are the most frequently injured body regions for both cyclist and pedestrians.

In the variation study, both parameters related to the impact conditions (impact angle and position of the cyclist and velocity of the vehicle) and vehicle related parameters (vehicle shape, front-end stiffness, bonnet stiffness and windscreen stiffness) have been varied. From the variations in the impact conditions it was found that:

- the velocity had the most influence on the injury parameters estimated by the models. An increased velocity increased injury parameters and thus the chance of injuries and fatalities. A reduction of the impact velocity, by means of e.g. infrastructural measures, thus could contribute to improved cyclist safety.
- the velocity as well as the impact position had an effect on the contact locations in lateral direction and thus on the possibility and severity of having a second impact with the ground. This is not taken into account in this study.
- the impact angle had only a minor influence within the relatively small range studied.

From the variations in the vehicle characteristics it was concluded that:

- the shape had a large influence on the body kinematics. The more continuous front surface of the small vehicle model with a shorter and steeper bonnet, resulted in a better distribution of the load over the cyclist model and reduced head loading due to the reduced head impact velocity. The SUV model has a high bonnet leading edge which caused a direct load on the pelvis and upper legs. This could result in severe injuries in the pelvic region.
- a reduction of the windscreen stiffness had a large effect on the head injuries estimated by the model. A reduced windscreen stiffness could result in a significant reduction of head injuries estimated by the models.
- the front-end and bonnet stiffness were found to have only limited influence on the cyclist kinematics and loading estimated by the models. This is however partly caused by the fact that in this study only the (initial) deformation force level was varied and not the stiffness and position of underlying rigid components like the engine or structural parts.

6.2 Recommendations

The model of the cyclist has been validated for lateral pedestrian impacts up to 40 km/h, while the vehicle and bicycle model were not validated. Although the model set-up and characteristics were chosen realistic, the component models and the full model should be validated more specifically for this load case to improve the predictive capabilities of the simulation model. This could be combined with an increased complexity of the model to get more detailed results. Furthermore, although it is realized that only limited data might be available, the results of the simulations could be compared to accident statistics e.g. to validate the trends estimated by the models. Accident studies could be used also to investigate the relevant parameters and ranges as input for an extended simulation study.

In the current study, the front-end and bonnet stiffness were found to have only a limited influence on the cyclist kinematics and loading. This is however partly caused by the fact that in this study only the (initial) deformation force level was varied and not the stiffness and position of underlying rigid components like the engine or structural parts. Therefore further research should indicate what the effect of e.g. varying the available deformation space is on the cyclist kinematics and injuries. This could then lead to an optimization of the available space towards injury minimization.

In the current study the difference between pedestrian-vehicle and bicyclist-vehicle impacts was not studied. However, such a study could provide more insight in the effectiveness of measures taken to protect pedestrians for bicyclists. Here it should be noted that Janssen and Wismans [9] compared pedestrian-vehicle and cyclist-vehicle impacts using both experiments and simulations. They reported that the results indicated important similarities between pedestrian- and cyclist-vehicle impacts. The bumper loads and head impact velocities were similar. However, a major difference was found in the head impact locations and as a consequence, the impact of the cyclist’s head with the windshield or even with the roof is more likely than for a pedestrian. Furthermore, the initial velocity of the bicycle can have a significant influence on the contact locations or can even cause the cyclist to fly over the bonnet and impact the ground, while a pedestrian will only have a limited initial velocity. Further research is required to determine to what extend the current pedestrian safety regulations will improve cyclist safety and whether separate requirements will be needed to obtain a significant reduction of cyclist injuries and fatalities.

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