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Bicycle safety in bicycle to car accidents

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1 Introduction

Much attention is being paid to pedestrian safety by international working groups such as EEVC WG17, in research projects such as APROSYS (www.aprosys.com) and consumer organisations like Euro NCAP (www.euroncap.com). 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. This is a main concern of the Fietsersbond, the Dutch Cyclists' Union that campaigns for better cycling conditions in the Netherlands.

From a preliminary study performed by TNO for the Fietsersbond it was found, that parameters like impact speed and angle as well as car geometry are likely to have significant influence on obtainable injuries. The main objective of the current study was to investigate these issues more in detail. This study is build up in four steps:

1. Literature study and an analysis of actual accidents to investigate most common injuries and impact scenarios in bicycle to car accidents (Chapter 2) and related questions on bicycle to car accidents.
2. Extensive numerical parameter study to indicate the most important parameters influencing injuries (Chapter 3) as well as injury severity, impact speeds and main impact locations.
3. Development of an assessment methodology proposal based on the results of step 1 and 2 to be used in current or future regulations and testing protocols (Chapter 4)
4. Indication of possible safety measures on vehicles for improved cyclist safety. (Chapter 5).

The parameter study has been performed using numerical simulations in MADYMO (MAthematical DYynamic MOdel), a simulation software program that is widely used in the automotive safety field. For the simulation set up an easily scalable car built up trough 8 planes representing the most important surfaces of a vehicle was used. In order to be able to draw conclusions on different seating positions and smaller cyclists, the study was carried out with two cyclists (Dutch 50th percentile male and standard 5th percentile female) both on a hybrid and on a granny bicycle.

In Chapter 6 conclusions and recommendations are provided.

2 Literature Study

2.1 Objective

The main aims of this literature review were:

Review of bicyclists accidents:
The aim was to find the most important factors related to bicycle accidents to set-up the simulation study and to analyze the results. The literature review focused on the following aspects:

- Accident configuration and vehicle specification (car type, impact location, impact velocity).
- Bicyclist specification (age, gender, anthropometry, posture, reaction).
- Importance of a secondary impact (the ground impact).
- Differences and similarities between \pedestrian and cyclist accidents in terms of injury severity and body region, impact location etc.
- Injury criteria related to bicyclist accidents taking into account the age of victims.

Remarks
The various international accident databases use different ways of registration. Therefore the comparison between the information of these databases especially for minor injuries, MAIS 1, is less relevant. Therefore study is limited for MAIS2+ injuries only and focussed on severe injuries MAIS3+ or higher.

The reviewed sources included Dutch and international statistical studies and computational simulations.

Revision of advanced protection systems of vulnerable road users focusing on cyclists' protection:
The aim was to review and evaluate current advanced systems in terms of bicyclist's safety and if possible suggest improvements that would increase it.

Revision of current pedestrian or vulnerable road users testing protocols and its relevance towards bicyclist's safety.

2.2 Results

2.2.1 *Accident configuration and vehicle specification*

Collision partner
A vehicle (car, bus, truck, motor cycle, tram, agricultural vehicle, moped) is the most common collision partner for a bicycle and consists of ~60% of all bicycle accidents (Otte 1989, AP-SP31-005R, SWOV 2007) in UK, NL, Germany, Spain . In second place is a pedestrian ~5-6%, while about 12-16% accidents happened without partners. The most common vehicle involved in collision with a bicycle is a passenger car. This is valid for the Netherlands as well as for other European countries. For the Netherlands a passenger car was involved in of 78-80% of all accidents (SWOV, 2003). Looking at

injury severity a passenger car was involved in 47% of fatalities and in 59% of severely injured (Zeegers, 2007). The second most common collision partner for a bicycle in NL was a truck – 22% of fatal injuries and 3% severely injured. In Germany a passenger car was involved in 60-70%%, in UK in 85% and in Sweden in 89 % of all cyclists accidents (AP-SP31-005R).

Bicycle type

SVOV (2003) reported that the most common bicycle involved in an accident was an average city bicycle (83%), followed by an ATB/mountain bike (5%), a children's bicycle (3%), a race bicycle (1%) and unknown in 8% of cases.

Vehicle and bicycle speed

According to EU (AP-SP31-005R) data the most common location for a car-bicycle accident was an urban area (60-80%); in NL it was 79%. In NL most of accidents happened on roads with a speed limit around 50 km/h (42%) while for zones with speed limit 30 km/h it was 5%. However, the actual vehicle speed at time of impact might be higher. On one hand it was shown that on roads with speed limit of 30 km/h the actual speed was about 40-45km/h. On the other hand roads with 50 or 60km/h are more often jammed and an actual speed might be below the speed limit. In other countries (UK, Sweden) ~85% of bicyclist accidents happened on roads with speed limit 50 km/h. Otte (1989), based on accident reconstruction showed that 75.6% of bicyclist accidents happed with collision velocity up to 50km/h, with an average velocity of 35 km/h. Recent German data (1999-2004) showed that in most cases the collision speed was 20-30 km/h and in half of all car-cyclist accident there was no braking from driver and in about 30% of all cases a driver broke with 7 m/s^2. The bicycle speed was estimated in a Japanese study (Maki, 2002) and for 60% of all cases it was 18 km/h or less and for 90% it was 36 km/h or less.

Accident scenarios

On possibility to classify injuries is the so called "Abbreviated Injury Scale" (AIS). It is the most widely used and accepted system, classifying injury by body part and severity on a 6-point ordinal scale where severity is looked at in terms of the threat to life of a single injury without respect to combined effect of multiple injuries on one person. According to SWOV data (2007) most of AIS2+ accidents (meaning accidents with at least moderate injuries) in NL happened:

- On crossroad when both partners were crossing straight-on (40 %)
- When one partner turned left while the second went straight-on (12 %)
- When one partner crossed the road laterally while the other went straight-on (12 %)
- When one partner turned left while the other was going straight-on from the opposite direction (8 %).

In UK most of accidents happened on or near some kind of junctions and the majority of cyclists were travelling straight ahead at the time of the accident (75%) and a small proportion turning right (8%). The vehicle in 43.5% of all cases was moving straight ahead and in 30% it was turning. Comparing vehicle and bicycle relative heading direction grouped accidents:

- Vehicle moving straight ahead and cyclist is crossing lateral to vehicle heading direction - 22.8%
- Vehicle moving straight ahead and cyclist is moving in same or opposite direction - 20%
- Vehicle not moved ahead and cyclist all manoeuvres - 37%.

In Sweden the most common accidents scenarios were when the bicycle was going straight ahead or turning left and was hit by vehicle which was going straight ahead or turning right. In Germany 60% of accidents happened when a vehicle was going straight ahead and cyclist was crossing lateral to vehicle heading direction which is close to one of the Dutch accident configurations (AP-SP31-005R).

Contact locations

Vehicle
SWOV data (considering serious injuries : MAIS2+) showed that in 75% of accidents, the contact impact point was located on the frontal part of vehicle, 20% on the side of the car (left or right) and only 5% or less on the rear of the car. Similar data were presented by Otte (1989) who stated bicyclist in collision with cars are hit by the vehicle front and only 13.6% of the total collisions are located on the side of a car.

Bicycle
SWOV (2007) data showed also that in almost 60% of bicycle accidents the contact point was located on the bicycle's side (left or right), in 30% of cases it was located on the bicycle front and in 4% it was the bicycle rear part.

Impact mode (side, frontal, rear)
Considering combination of a vehicle-bicycle impact location, data from SWOV (2007) showed that most common accident mode (for MAIS2+) was a side impact (80%). The side impact is followed by a frontal impact (7 %) and a head tail impact (5 %). Considering MAIS2+ cases it was shown that cyclists collided with a vehicle front on their: side (50%), front (15%) and rear (5%) while side of bike-side of car combination was valid for 15% of all cases. Similar results were reported by Otte (1989): 73% of cyclist collided with a car front, where most common combination was a front of a car - side of a bike collision.

2.2.2 *Bicyclist specification*

Age
The level of exposure varies significantly with age and sex. Most groups with higher number of casualties have higher exposure rate at well, however, this is not true for age 65 +, see Dutch data (SWOV 2003, Maring and Schagen,1990) which showed the most frequent injured bicyclist (all injuries, front of car - side of bicycle impact scenario) were in age group 0-14 (20%) year and second peak was observed for age group 65 year and older (19%). Data from different European countries (AP-SP31-005R) showed a similar high number of children casualties:

- UK (2005): 20% age group (11-15)
- Sweden (2005) – 13% age group (11-15)
- Germany (2005) - 14% age group (10-15)
- Spain (2005)- 30% age group (15-24).

The severity of injury was age dependent and was further discussed in chapter 2.2.3.

Sex
The female-male casualty's ratio for Sweden and NL was 50:50, for Germany it was 38.5:61 while for UK it was 20:80.

Behaviour and posture
Little is known about the posture and bicyclist reaction before and during the collision and its influence on the injury outcome. Rasanen (1998) reported that in 37% of collisions, neither a driver nor a cyclist realized the danger or had time to yield. In the remaining collisions, drivers (27%), cyclists (24%) or both (12%) did something to avert the accident. The most frequent accident type among collisions between bicyclists

and cars at bicycle crossings was a driver turning right and a bicycle coming from the driver's right along a cycle track. Based on recorded videos, it was concluded that drivers turning right hit cyclists because they looked left for cars during the critical phase. Only 11% of drivers noticed the cyclist before impact. On the other hand 68% of bicyclists noticed the driver before the accident, and 92% of those who noticed believed the driver would give way as required by law.

2.2.3 Injury – severity and injured body region

The injury severity depends on many factors like the vehicle type, the bicyclist age, the impact speed, the body region, the impact configuration, the contact point and their combinations. In this study the focus was on passenger cars as these vehicles are the most frequent collision partner for the bicycle.
Overall, the most frequent injured body part according to SWOV (2003) was: the head 22%, combination including a head 15%, the leg 13%, unknown 24% and 5% of all reported hospital cases were fatal. The most frequent injuries were slight injuries (UK 74%, Germany 78%) followed by serious injuries (UK17%, Germany 22%) and fatal injuries (UK 1.4%, 0.9%), (AP-SP31-005R). Similar trend was observed in the Netherlands. According to SWOV data (SWOV 2007) slight and moderate injuries were the most frequent (65%), followed by serious (30%) and fatal injuries (1-5%).

The head injuries are the most frequent cause of serious injuries and death (McCarthy 2005, Wood and Milne, 1988). Zenter (1996) showed that 33% of admitted bicycle victims sustained severe head injuries and neurosurgical operations were performed in 49% of the patients. A 3% of those of injured bicyclists were severely disabled and 16% had died at follow-up. From SWOV (2007), it follows that in the Netherlands in case of bicycle-car accidents, life-threatening injuries (MAIS 5+) are head-injuries in 85 % of the cases. In nearly all of these cases, no other life-threatening injury is present. For MAIS 4, the percentage of head injuries is still 68 %.

McCarthy (1996) reported that while injuries to the head were the common reported direct cause of death, Inner London deaths were frequently due to multiple injuries.

Injury and age
Several sources showed that bicyclist and pedestrian injury is sensitive to age. The injuries to older cyclists appear to be more severe than injuries to younger cyclists. A Dutch study demonstrated that hospital admissions as a result of cycling crashes increased with age, from 25% for 50 to 54 year olds to 45% for cyclists aged 75 years or over (Kingma, 1997). Danish data also confirms the overrepresentation of serious injuries among older cyclists compared to younger cyclists. In this country, 19% of cyclists aged 65 years or older were seriously injured in cycling crashes between 1980 and 1992, compared with only 2 percent of those aged 65 years and younger (Larsen et al. 1995). Olkkonen et al. (1993) reported permanent disability in 11% of children, in 47% of adults and in 67% of elderly adults admitted to Finnish hospitals due to the bicycle injury. Klop and Khattak (1999) further noted that, while children were over-represented in all bicycle crashes in the USA, those 44 years and over were over-represented in intersection crashes resulting in a fatality, providing additional evidence that negotiating intersections may be more difficult for older cyclists. Blankendaal and Den Hartog (1998) investigated 7219 cyclist collisions resulting in hospital admission (excluding fatal crashes). The most frequent primary injury for all ages was fractures (58%), followed by intra-cranial injury (25%). There were marked changes in injury patterns over age. Fractures accounted for 41% of the admissions in 0-14 year olds and

this gradually increased to 74% in hospitalized persons over 75 years of age. The reverse pattern was seen for intra-cranial injury, which gradually decreased from 38% for 0-14 year olds to 13% for persons over 75 years of age. The type of fracture was also different. Lower extremity injury was dominant amongst older people (51%), compared with only 15% of younger people suffering lower extremity injury (this group suffered more upper extremity injuries). These differences cannot be attributed to differences in body height, as the same differences – albeit less extreme – were also found between young adults (25-39 year olds) and older people. The injuries sustained by older cyclists were also much more severe than those suffered by younger adult cyclists. The median number of days hospitalised increased from 3 days for 0-14 year olds and 4 days for 25-39 year olds to 8-14 days for people aged 55 years and older. The percentage of cyclists hospitalised longer than 28 days remained stable at 3-4% until the age of 55 years and then increased to 15% for cyclists over 75 years of age. Otte (1989) showed that fatal injuries were more frequent for adults (11.6%) comparing to children (6.7%). The slight injuries are more frequent for children and young people (age 5-30 year). The proportion of serious and fatal injuries increases with age starting from age 50-60 year. SWOV data (2007) showed that proportion of injuries MAIS4+ was almost doubled for age group 56+ year comparing to age 0-14 year.

The reason for higher proportion of serious or fatal injuries in elderly group is the lower tolerance limits.

It is well established that the human injury tolerance decreases as the age increases however in the development of the human injury tolerance criteria for automotive crashes, only a few researchers have paid attention to age effects (AP-SP51-0038B, Kleerekoper et al. (1986). Willinger (2008) has developed age dependent head injury criteria based on computation simulation of different type of head impacts (pedestrian, football players, motorcyclist etc). HIC versus injury probability were adjusted for elderly and its thresholds were also dependent on injury type (skull fracture or neurological injuries or brain vascular injuries with bleeding). For computational simulations, where more detailed data could be derived, other injury predictors were scaled. Similar approaches have been tried for other body parts like thorax and lower limbs. An aging person becomes increasingly susceptible to sustain thoracic injuries, primarily rib fractures due to age-related degeneration of human bones and soft tissues which modified significantly their mechanical properties (Kent et al. 2003). The author suggested reduction of the injury tolerance from the young adult age group to the elderly group for serious thoracic injury in terms of the normalized belt force by over 80%. The above examples have showed that in automotive safety the age influence on the injury thresholds and injury criteria is being taken into account, however still much research must be done till the age related criteria are acknowledged and commonly used.

Otte (1989) checked the injured body part and noticed that adult cyclist had more frequently neck injuries (4.8%) and thorax injuries (33.43%) comparing to children (2.9% and 21.2% respectively). Children had slightly more frequent injuries in abdomen and pelvis part, this increase is seen particularly for the impact scenario with the cyclist side impacted by the front of the car.

Injury and impact speed

The collision speed influences the injury severity such that with increasing collision speed the frequency of slight and minor injuries decreases while increase of serious injuries is observed (AP-SP31-005R.). For instance for impact speed 50-70km/h 67.4% of involved cyclist sustained MAIS1/2 injury and 7.4% sustained MAIS 5/6. With speed impact above 70km/h only 10% of cyclist sustained minor injuries and 50% sustained MAIS 5/6 injuries. With higher impact speed an increase in the frequency of head injury, both soft and bone part was observed. For instance for adult cyclist for 30km/h impact the brain injury is 17% while for impact speed above 51km/h the frequency of brain injuries increased to 66% . (Otte, 1989,1994).

Injury and collision mode

Based on the literature, the worst case impact scenario is when the rear of a bike is impact by front of a car. This impact scenario has the highest number of serious injures as well as the highest degree of fatality (15% fatality for adults, 12.4 for children) (Huijbers, 1984, Otte 1989). For adults, in this impact scenario cervical spine injury is more frequent. The most dangerous impact scenario for child bicyclists is when the side of bicycle is impact by front of the vehicle. The high fatality rate is associated with serious thorax injuries.

Injury and injury causing part

Otte (1989, 1994) looked into the injury causing parts. Apart from road surface, injuries were caused mainly by front parts of a vehicle and less frequently by more distant part (vehicle rear). The part which caused injury depends on speed and up to 30km/h about 50% of injuries were caused by the vehicle front. The other parts were responsible for 20% for adults and 10% of injuries for children. Increase in the speed increases probability of injuries caused by the windscreen to about 30% in speed 50-60 km/h compare to 10% in speed limit up to 30-40 km/h.

When analysing only head injuries, the windscreen was the most frequent cause of injury and was responsible for 30% of injuries for children and 26% of injuries for adults. Moreover, the proportion of head injuries MAIS 3/6 was highest (5-7%) for the windscreen comparing with other injuring parts (for instance front of the hood caused only 1.9% of all injuries. Analysing only the windscreen and its frame, an impact of the windscreen in the region of the frame had most serious consequences and resulted in the highest proportion of AIS3+ head injuries (10-12% vs. 22.8%) (Otte, 1989). Maki (2002) analysed the reconstructed bicycle accidents and concluded that serious head injuries (AIS3+) were caused by vehicle parts that lied above the hood like windshield, windshield frame and roof.

Secondary impact

Road surface is a common secondary collision partner. Cross and Fisher (1977) found that 60.4% of the injuries were the result of the bicyclist's impact with the roadway and 24.1% of the injuries resulted from impact with the motor vehicle. Otte (1980) analyzed bicycle and motorcycle accidents and stated that secondary injuries caused by the impact on the road-surface had nearly the same (30%) frequency for all types of two-wheel vehicle. The degree of injury caused by the impact upon the road-surface was low, on average it was AIS 1. Based on a pedestrian accident data Ashton (1983) reported that the aggressively of the road surface was less than that of car body for speed range over 20 km/h and moreover the injury level rarely reached moderate level even for impact speed 70 km/h. Otte (1989) reported that adult and child cyclist suffered injuries by the road to approximately 65%, however AIS3-6 injury were caused by road only in 2.4% of adults and of 3.8% children victims. Considering only the head injury, the road surface was responsible for about 30% of injuries and its proportion was decreasing with the impact speed. The major head injuries (AIS3-6) were caused by the road surface only up to 3%. Maki (2002) reported that 26% of bicyclist' head injuries of severity AIS3+ were caused by the road-surface. In cases of head injury level less than AIS2 the proportion of injuries caused by the road surface was higher (44%). Overall, the injuries inflicted by the road surface impact although are counted for up to 65% they cause only slight injury.

2.2.4 *Differences and similarities between pedestrian and cyclists*

Analysing pedestrian and cyclist accidentology there are a lot of similarities. In both cases victims are struck mostly by a passenger car and mostly by the front of the vehicle. Most of pedestrians and cyclists are struck side-on. In both groups the risk of fatality and serious injury increases with age. Most frequently injured age group are children. The most frequently injured body region is the head followed by the lower limbs. The frequency of serious head and serious lower limb injuries per 1000 accidents is smaller for bicyclists than pedestrians (Maki, 2002).

The proportion of fatalities differed for each country, but with exception of NL, the pedestrian had always a higher rate of fatalities than cyclists. In NL, 2006, the pedestrian fatalities were 9% of all fatal accidents while cyclist was 27%,the averages figures for the period 2004 -2006 were 9% pedestrian and 23% cyclists. For comparison on average in Europe it was 6% of cyclist against 15%of pedestrian. Maki (2002) reviewed Japanese accident data and showed that fatality rate (calculated as the ratio of fatalities to total number of injuries) was higher for pedestrian (3.11%) than for cyclists (0.75%) regardless of the type of vehicle involved in a collision. He also concluded that for each age group bicyclists were more prone to sustain slight injuries while pedestrians were more likely to be killed or seriously injured. For both groups, the main cause of death was head injuries while most of serious injuries were sustained for lower limbs and thorax. Also for both groups the head fatal injuries were mostly inflicted in collisions with minivans, followed by SUV and mini car. Serious leg injuries for pedestrians were mainly caused by bonnet type vehicle while for cyclists it did not differ by car type. The highest proportion of serious thorax injuries was caused by mini car for cyclists while for pedestrian by cab-over chassis type. Typical leg injury for pedestrian was damage of knee ligament. For cyclist more frequent were femur fracture and tibia fracture.

Collision speed

For pedestrian and for cyclists majority of accidents happened in area with speed limit 50 km/h. Typical collision speed for cyclists was 0-30 km/h and for pedestrian 15-30 km/h (AP-SP31-005R, Otte 1980). Maki (20002) showed that number of serious and fatal injuries increases with collision speed (perceived by driver) for pedestrians and for cyclists. There were however some differences: in low and medium range of collision speed (60 km/h and less) a higher proportion of cyclists was seriously injured compared to pedestrians. On the other hand for collision speeds more than 40 km/h higher proportion of fatal injuries was observed for pedestrian than for cyclists.

Contact locations

Janssen and Wismans (1987) performed experimental tests and computational simulations and compared pedestrian and bicyclist head trajectories. They concluded that bicyclist head impact position is significantly shifted towards the windshield compare to the pedestrian. Similar conclusions were drawn by Maki (2002) based on accident reconstruction. He analysed distribution of head impact location and showed that bicyclists' head in most of cases did not contact the bonnet but rather the upper part of windscreen and the front portion of the roof. In case of pedestrians it was observed that heads made contact with lower parts of the windscreen and the rear part of the bonnet. Relatively, the so-called Wrap Around Distance (WAD = distance from the ground to the impact point of the head on the car along the vehicle front structure) was 15% larger for cyclists than for pedestrians. Considering lower limbs, the main source of tibia fractures for pedestrians was the bumper. In case of bicyclist this injury was more often caused by the bonnet leading edge than the bumper. Moreover, it was bonnet leading edge which caused also femur fracture – the most frequent lower limb injury in cyclists.

Summary

For pedestrians and cyclists the body parts which should be protected are head and lower limbs as they are the most frequent injured body parts and also the cause of death and serious injuries. The most frequent collision speed is similar in both cases. However due to different kinematics there are different contact locations:

- For head in case of pedestrians it was mainly bonnet and lower windshield.
- For head in case of cyclist it is mainly bonnet/windshield, windshield and A-pillars and even roof.
- For limb injuries in case of pedestrians the most frequent contact location was bumper and bonnet leading edge.
- For limb injuries in case of cyclists the most frequent contact location area was bonnet leading edge.

2.3 Injury criteria and its limits

Following the preliminary study on cyclist injuries (Hassel (2006)) the following injury criteria were used:

- Head- HIC, acceleration 3ms,
- Chest – 3 ms acceleration
- Pelvis – 3ms acceleration
- Lower limb (tibia) – 3ms acceleration.

Head injury criteria (HIC)

The most popular head injury criterion is HIC. HIC was introduced in its present form in crash testing by the National Highway Traffic Society Administration (NHTSA, 1972) and has been used for many years in crash injury research and prevention as a measure of the likelihood of serious brain injury. HIC only treats the resultant translational acceleration and the duration of the impulse and no consideration is given to the direction of the impulse or rotational acceleration components. Because of those issues, the validity of HIC is intensively debated and there is reason to believe that the safety development could be made more efficient by taking into account the effect of rotational kinematics into current safety procedures.

The HIC value is the standardized maximum integral value of the head acceleration. The length of the corresponding time interval is: unlimited (HIC), maximum of 36ms (HIC36) or maximum of 15ms (HIC15). For pedestrian and cyclist impact the HIC15 was chosen based on EEVC WG 17 recommendation with its threshold below 1000. HIC is calculated as

$$HIC = \max_{t_1,t_2}\left(\left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \right) \qquad (1)$$

where a is the resultant head acceleration expressed as a multiple of the gravitational acceleration g, and t1 and t2 are any two points in time during the impact which are separated by 15 ms or less giving the maximum HIC. The unit of HIC is seconds but it mostly presented without unit. HIC has no specific meaning in terms of injury mechanism; it is a pass/fail baseline measure. Despite this, some researchers tried to correlate its value to injury severity. Tyrell studied the train impacts (1995) and proposed loss of consciousness in relation to HIC levels (Table 1). This table could only be use as a general indication on of injury severity for the cyclist impact.

Table 1 - Levels Of Consciousness In Relation To Head Injury Criteria (Tyrell, 1995)

Head Injury Criteria	**AIS Code**	**Level Of Brain Concussion And Head Injury**
135 – 519	1	Headache or dizziness
520 – 899	2	Unconscious less than 1 hour – linear fracture
900 – 1254	3	Unconscious 1 – 6 hours – depressed fracture
1255 – 1574	4	Unconscious 6 – 24 hours – open fracture
1575 – 1859	5	Unconscious greater than 25 hours – large haematoma
> 1860	6	Non survivable

Table 2 - Proposed HIC Tolerance Levels Correlated To Brain Injury.

Injury Level	**Proposed Tolerance Level**	**Equivalent Acc g**	**Equivalent AIS**	**Equivalent Legislation**	**Equivalent Euro NCAP**
	HIC (15 ms)	**(For 3ms)**		**HIC**	**HIC**
0 (No concussion)	< 150	<55	0	-	<650 Green
1 (No concussion)	< 150	<55	1	-	<650 Green
2 (Mild concussion <1hr)	150 – 500	55-90	2	BCT609 / ECE80 500	<650 Green
3 (Severe Concussion 1 – 24hr)	500 – 1800	90-150	3 / 4	FMVSS 208 1000 EC/79/96 1000	<650 Green 650 – 767 Yellow 767 – 883 Orange 883 – 1000 Brown >1000 Red
4 (Life threatening coma >24hr)	>1800	>150	5	-	-

Table 3 - Proposed HIC Tolerance Levels Correlated To Skull Fracture

Injury Level	Proposed Tolerance Level	Equivalent Acc	Equivalent AIS	Equivalent Legislation	Equivalent Euro NCAP
	HIC **(15 msec)**	**g**		**HIC**	**HIC**
0 (No Fracture)	<500	< 90	-	-	<650 Green
1 (No fracture)	<500	< 90	-	-	<650 Green
2 (Minor fracture)	500 – 900	90 – 115	2	BCT609 / ECE66 500	<650 Green 650 – 767 Yellow
3 (Major fracture)	900 - 1800	115 - 150	3	FMVSS 208 1000	767 – 883 Orange 883 – 1000 Brown
4 (Severe life endangering fracture))	>1800	>150	4/5	-	>1000 Red

Head injury criteria –acceleration 3ms
The acceleration is calculated as maximum level that the acceleration exceeds for continuous period of 3 ms. The peak resultant acceleration injury criteria threshold is set at 80 g for the midsize adult male; a commonly accepted injury criteria indicating a significant risk on severe injury.

Chest injury criteria
The chosen injury criteria for this computational study is 3ms acceleration. It is the highest acceleration level with a duration of at least 3ms which corresponds to AIS ≥ 4 injury level. Mertz and Gadd (1972) recommended that the peak chest acceleration measured at the mass centre of the chest does not exceed the value of 60 g longer then 3 ms for acceleration pulses of 100 ms and shorter, in order to avoid severe thorax injuries.

Pelvis injury criteria
One of injury criteria for pelvis region is 3ms acceleration: maximum linear acceleration sustained for 3ms or longer. The injury threshold was set at 60 g., a commonly accepted injury criteria indicating a significant risk on severe injury.

Lower leg injury criteria
The loading of lower leg is determined by the linear acceleration of tibia. The acceleration is calculated as maximum level that the acceleration exceeds for continuous period of 3ms. Zeidler (1984) suggested the conservative limit of 150 g for foot acceleration based on tests with volunteers and dummies. This level of acceleration is associated with jumps from a height beyond which injury was feared.

3 Parameter study

3.1 Simulation set – up

3.1.1 Objective

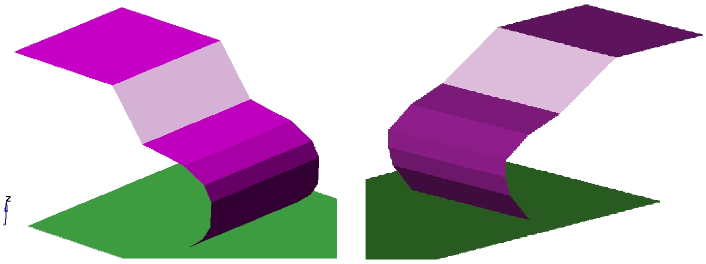
As the literature review showed that the lateral impact between a passenger vehicle and a bicyclist is the most frequent accident for bicyclists, a numerical parameter study has been carried out to investigate this type of accidents in detail.
The main goal of the parameter study was to derive indicative relations between the input parameters as bicyclist size, seating position, bicycle orientation, vehicle geometry and impact speed and the requested outputs such as the cyclist's kinematics and injuries.

- Cyclist kinematics are defined as:
  - Contact locations (cyclist – vehicle) of the head, the thorax and the pelvis
  - Contact velocities of the head, the impacted shoulder, the thorax, the pelvis, the impacted upper leg and the impacted lower leg.
- Cyclist injuries are defined as:
  - HIC value (15 ms).
  - 3 ms head CG acceleration.
  - 3 ms chest acceleration.
  - 3 ms pelvis acceleration.
  - 3 ms impacted lower leg acceleration.
- Vehicle parameters are defined as the vehicle front-end geometry, especially bonnet length and the angle between bonnet and windscreen.
- Accident parameters are defined as the vehicle and bicycle speed and the angle between bicyclist and vehicle at the moment of impacts.

3.1.2 Models

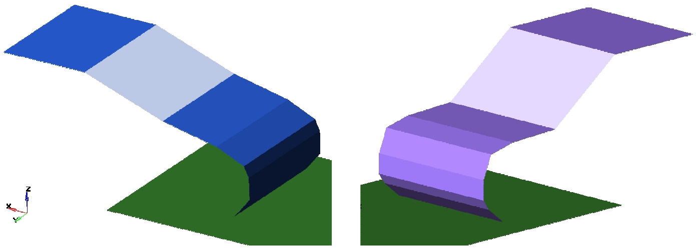
Vehicle models:
The study is set-up using four different multi -bode (MB) vehicle models modelled in MADYMO. The vehicle models represent:

- Model A: a vehicle with a small bonnet and a large windscreen angle (Figure 1a)
- Model B: a vehicle with a large bonnet and a small windscreen angle (Figure 2a)
- Model C: a vehicle with a small bonnet and a small windscreen angle (Figure 1b)
- Model D: a vehicle with a large bonnet and a large windscreen angle (Figure 2b)



(a) Model A (SB – LA) (b) Model C (SB – SA)

Figure 1 - Vehicle models: Short bonnet



(a) Model B (LB – SA) (b) Model D (LB – LA)

Figure 2 - Vehicle models: Long bonnet

The vehicle geometry is set-up by defining nine significant points on the car as shown in Figure 3. This modelling technique allows an easy parameterization and variation of the geometry.

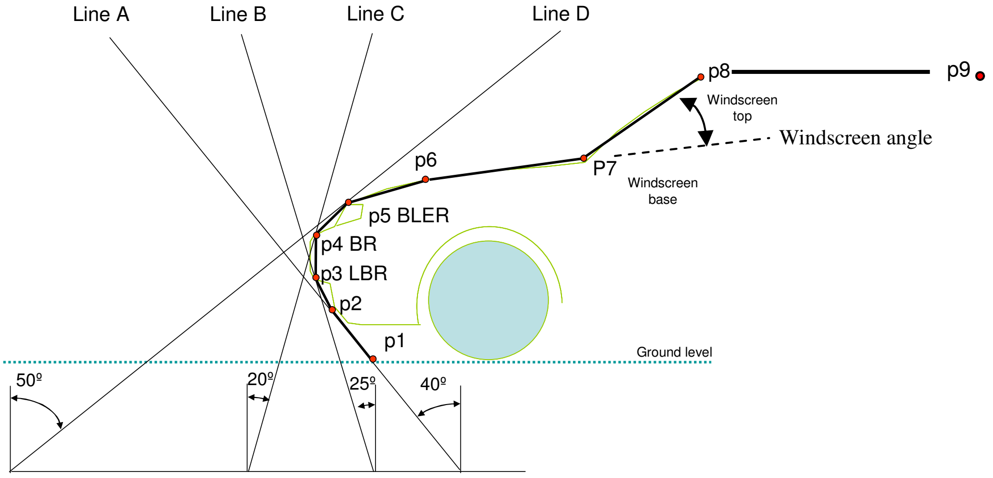


Figure 3 – Vehicle model geometry

The stiffness of the vehicle front and bonnet has been based on the average force - deflection profiles as developed within the APROSYS project (Martinez (2005)). The windscreen stiffness has been estimated based on windscreen impact tests performed at TNO.

The mass of all vehicle models was set to 1300 kg. A preliminary simulation study has shown a negligible influence of the variation of vehicle mass (between 1100 kg and 1600 kg) on the cyclist kinematics and the cyclist injuries estimated in the simulations.

Bicycle models:
Two significantly different bicycle models have been developed (see Figure 4 and Figure 5):

- a granny bicycle with a upright seating position
- a hybrid bicycle with a sportive seating position

The bicycle models have been modelled using the Multibody modelling technique (simulation of gross motion of systems of bodies connected by kinematical joints) in MADYMO. The frame is taken rigid; however stiffness is added to the wheels and the front fork. The mass of the granny bicycle is 19.7 kg, the mass of the hybrid bicycle is 16.3 kg, based on the information of various bicycle manufacturers.

The saddle and steer height are adapted according to the cyclist anthropometry. For the granny bicycle an upright seating position is maintained whereas for the hybrid bicycle a sportive seating position is maintained. Table 4 shows the saddle and steer height for the different cyclist models.

Parameter	Granny bicycle small female	Granny bicycle average male	Hybrid bicycle small female	Hybrid bicycle average male
Saddle height	0.87 m	0.98 m	0.89 m	1.05 m
Steer height	1.12 m	1.17 m	0.93 m	1.05 m

Table 4 - Saddle and steer heights for the different bicycle-cyclist combinations

Cyclist models:

Two MADYMO cyclist models have been used, representing:

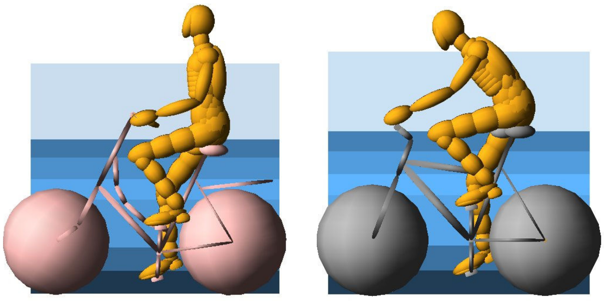
- An average Dutch male. The main anthropometry (standing height, seating height and weight) has been based on the so-called Dined 2004 anthropometric database (http://dined.io.tudelft.nl/nl,dined2004,304).
- A small female model representing both a small female and a child with an age around 12 years. The anthropometry has been based on UMTRI.

The main anthropometry of both cyclist models used can be found in Table 5.

Parameter	Female	Male
Standing height [m]	1.53	1.82
Sitting height [m]	0.81	0.95
Body mass [kg]	50.2	83.7

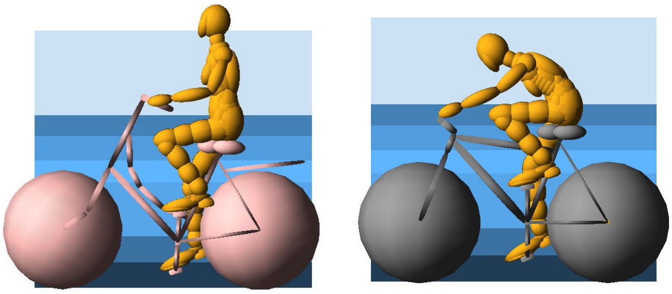
Table 5 – Main anthropometry of the cyclist models

The models have been developed as pedestrian models and are validated for lateral pedestrian impact. The average Dutch male has been scaled from a standard 50th percentile male towards the requested anthropometry and the small female model is a model that is released with the MADYMO software. More information on the development and validation of these models can be found in Hoof (2003). The different cyclist-bicycle configurations are provided in Figure 4 and Figure 5.



(a) (b)

Figure 4 - Average Dutch male riding the granny bicycle (a) and the hybrid bicycle (b)



(a) (b)

Figure 5 - Small female riding the granny bicycle (a) and the hybrid bicycle (b)

3.1.3 Parameter settings and variations

An overview of the parameter settings as used in the simulation study can be seen in Table 6. The influence of the car braking was not included for the main simulation study, but investigated separately in a small set up beforehand (see Appendix A).

Parameter	Unit	Type	Min.value	Max.value	Stepsize	Remarks
Accident parameters						
Vehicle impact velocity	[km/h]	Variable	30	80	10	
Vehicle braking	[m/s^2]	Fixed	0	-	-	No braking
Cyclist impact velocity	[km/h]	Fixed	18	-	-	
Impact angle	[º]	Variable	- 45	45	15	Figure 6
Impact location	[-]	Fixed	Mid vehicle			
Vehicle parameters						
See Table 7 and Figure 7						
Cycle parameters						
Cycle type	[-]	Variable	Granny bicycle	Hybrid bicycle	1	Figure 4 Figure 5
Cyclist parameters						
Anthropometry	[-]	Variable	female	male	1	Table 5

Table 6 – Parameter settings for the simulation study

Note that the bonnet leading edge height, the bonnet length and the windscreen angle are varied per vehicle model. The variations per vehicle model can be found in Table 7.

Vehicle model	BLE height [mm] *)		Bonnet length [mm]		Windscreen angle [º] **)	
	min	max	min	max	min	max
A	500	850	500	900	20	50
B	500	850	900	1300	0	20
C	500	1000	500	900	0	20
D	500	850	900	1300	20	50

Table 7 - Parameter variations for the different vehicle models

*) BLE = bonnet leading edge

**) Windscreen angle is defined as the angle between the bonnet and the windscreen as shown in Figure 3

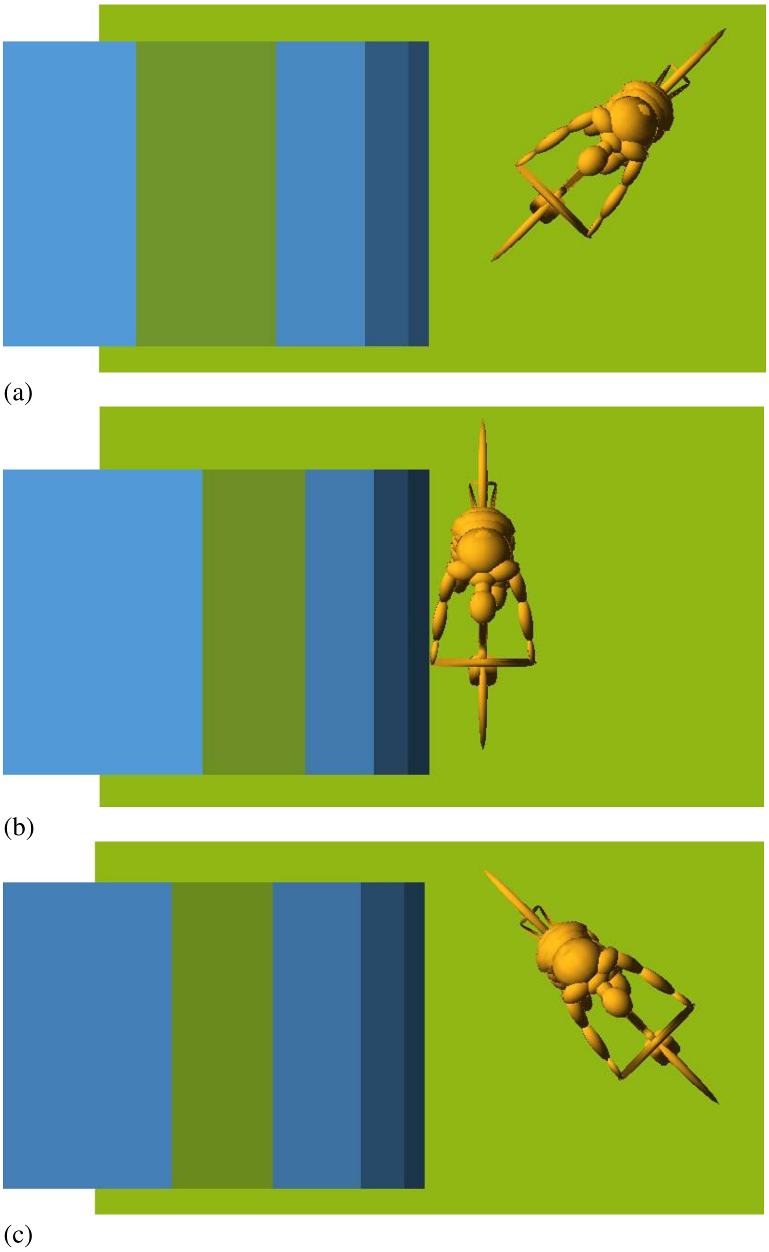
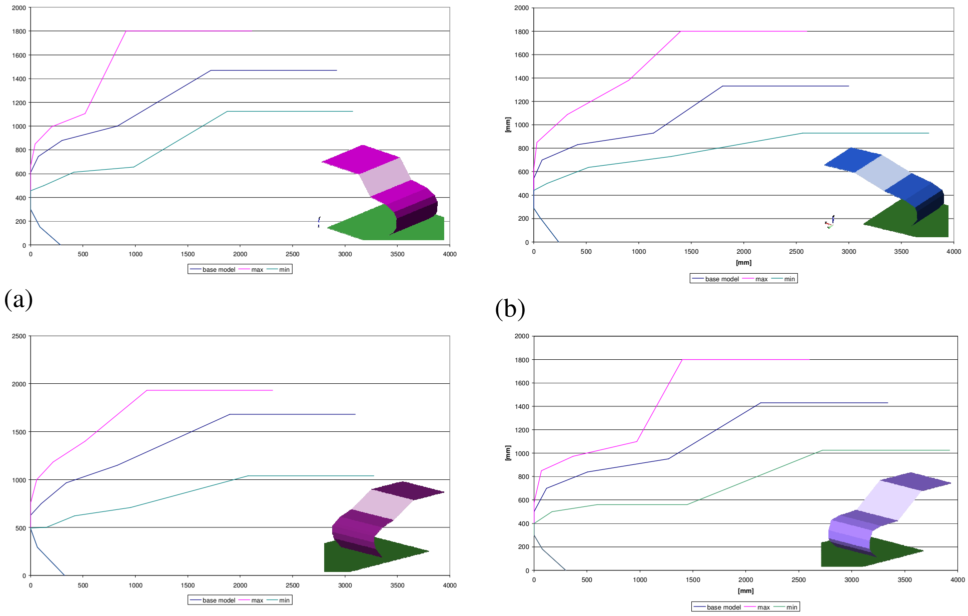


Figure 6 - Bicycle orientation of -45 deg (a), 0 deg (b) and +45 deg (c)

The reference vehicle contour (blue) and the maximum allowed variations per vehicle model as provided in Table 7 are visualized in Figure 7. The chosen bandwidth of car geometries per car model does not only cover the current car fleet, but also possible future car shapes. Like this, advises for future car designs could be made that would possibly result in lower cyclist injuries during a car to bicycle accident in case such geometries could be identified during the study.



(a)

(b)

(c)

(d)

Figure 7 - The vehicle contours for the 4 different vehicle models with the reference model contour (blue) and the two most extreme variations (pink and green); (a) is model A, (b) is model B, (c) is model C and (d) is model D.

The more input variables are present in a sensitivity study, the more simulations are needed to be able to draw proper conclusions from the obtained results. In order to reduce the number of runs as much as possible, the following assumptions have been made:

- The locations p1, p2, p3 and p4x, see Figure 3, were fixed within one car model resulting in a fixed lower part of the bumper
- Location p6 was chosen relative to p5 and p7, resulting in a fixed shape of the bumper with respect to BLER and windscreen base
- Location p9 was chosen relative to p8 resulting in a fixed shape of the roof
- A full factorial analysis of about 3000 simulations was performed per model taking into account a reduced number of car speeds (30 km/h, 50 km/h and 70 km/h) and bicycle orientations (-30 deg, 0 deg and + 30 deg). Unfeasible designs with respect to the chosen constraints (BLER height, bonnet length, bonnet windscreen angle and car height) were neglected and not simulated.
- In order to cover the whole spectrum of defined variables, another 2000 simulations were run per model using the Monte Carlo and Latin Hypercube sampling method.

This means, that in total for each model a simulation study of approximately 5000 simulations have been performed. Such a big number of simulations was considered necessary due to the high number of input variables.

3.1.4 Analysis

First, the simulations had to be checked for feasibility as unfeasible designs would possibly falsify the study results. Designs are considered unfeasible if they aborted or showed unrealistic model behaviour for examples due to contact problems. It should be noted, that the chosen car model is fairly simple as it had to be easy to adapt towards a broad bandwidth of car geometries. Therefore, feasibility of the model cannot be guaranteed for all possible car geometries and impact scenarios.

Within each of the four car models it could be found, that a certain number of simulations resulted in a HIC value greater than 3000. As these values cannot be considered realistic any more and HIC is in general the most acknowledged injury parameter, only simulations resulting in HIC $\leq$ 3000 are considered for further analysis. Please note, that HIC is highly influenced by the peak value of the head acceleration. If therefore a high peak is found in the head acceleration for example due to mathematical instabilities of the simulation software, HIC will automatically rise significantly.

In total, approximately 16.000 simulations were found feasible. 12.600 of these simulations were considered for further analysis, as for those simulations HIC was found below 3000. The results of simulations resulting in HIC > 3000 were also checked briefly and it was found, that they both showed similar trends as simulations with HIC < 3000 and that neglecting them did not result in deletion of certain scenarios.

The analysis itself was performed similar to the previous study. This means that the injury values were made relative to the selected injury thresholds which were defined as follows:

HIC:	1000
Head 3ms peak acceleration:	80g
Chest 3ms peak acceleration:	60g
Pelvis 3ms peak acceleration:	60g
Tibia 3ms peak acceleration:	150g

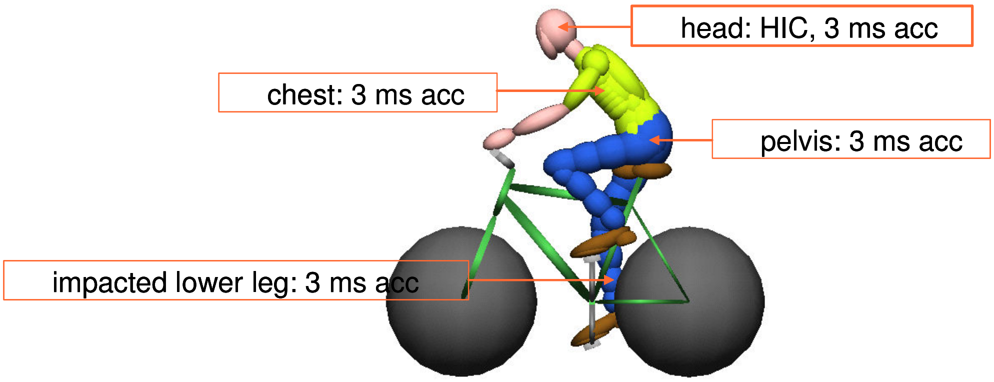


Figure 8 - Cyclist injury parameters

Additionally to those thresholds, for elderly people a HIC threshold of 600 was defined based on the literature study of paragraph 2.3. Please note, that this value is only a proposal and not as well accomplished as the threshold of HIC 1000 for middle aged adults.

Filtering of signals is done in accordance to SAE J211. For more information on the requested output please refer to the TNO Report of the inventory study (TNO Report, Hassel (2006)) as well as chapter 2.

3.2 Study Results

3.2.1 Charts provided separately with this study

In order to be able to draw proper conclusions from all obtained simulation data, a huge set of scatter charts and other data output plots have been created. As many of these charts do provide similar information only the most important charts are provided within the main report. All other graphs are provided on a separate CD delivered with this report. In this section a short summary is given on the data provided on the CD.

Scatter Plots:
A scatter plot is a 2-dimensional chart, which reveals relationships between two variables. It shows immediately if two variables are related and allows easy detection of outliers or anomalies in the database.

Files:

- Influence of car velocity_scatter_all data.pdf
- Influence of bicycle orientation_scatter_alldata.pdf
- Influence of bicycle cyclist combination_scatter_alldata.pdf

Contents:
Global scatter plots of the normalized injury criteria as well as the impact velocities of different body parts over car velocity, bicycle orientation as well as bicycle – cyclist combination are provided separate for each of the four Models. In these plots, all feasible simulations with HIC ≤ 3000 are included.

Files:

- Influence of bicycle orientation_scatter_40kmh.pdf
- Influence of bicycle orientation_scatter_70kmh.pdf
- Influence of bicycle cyclist combination_scatter_40kmh.pdf
- Influence of bicycle cyclist combination_scatter_70kmh.pdf

Contents:
Detailed scatter plots of the normalized injury criteria as well as the impact velocities of different body parts over bicycle orientation as well as bicycle – cyclist combination including output from simulation with car velocities of 40 km/h and 70 km/h only, respectively.

Files:

- Influence of BLER height_40kmh.pdf
- Influence of BLER height_50kmh.pdf
- Influence of Bonnet_Length_40kmh.pdf
- Influence of Bonnet_Length_50kmh.pdf
- Influence of Bonnet_Windscreen_Angle_40kmh.pdf
- Influence of Bonnet_Windscreen_Angle_50kmh.pdf
- Influence of car height_40kmh.pdf
- Influence of car height_50kmh.pdf

Contents:
In depth scatter plots including only simulations which fulfil the following criteria:

- Car velocity: 40 km/h and 50 km/h
- Bicycle orientation: 0 deg and -30 deg
- Bicycle – Cyclist combination: 5th female on hybrid bicycle and 50th male on granny bicycle

Going from the global scatter plots towards the in-depth scatter plots more and more information is filtered out from one set of charts to the next, going from a general overview on the study results towards a more in-depth view on selected parameters.

3.2.2 *Obtained injuries*

In Appendix C the mean as well as median values of the injury parameters over car velocity as well as bicycle orientation are provided for all four models. Additionally, for all four models charts are provided stating the chance of obtaining injuries above the thresholds set.

In general the following conclusions could be made:

- Vehicle impact velocity is of major influence on the level of injury. For instance, HIC depends linearly on impact velocity by good approximation: HIC-levels at 80 km/h are roughly four times as high as those at 30 km/h, see Figure 9.
- Injuries rose with rising car speed and mostly decreased with increasing bicycle orientation angle. (=> a cyclist heading under and angle of 45 deg towards a car ran higher risk of obtaining injuries than a cyclist heading away under an angle of 45 deg)
- Influences of car speeds, bicycle orientations and bicycle – cyclist combination were found bigger than the influence of the cars geometry
- Small Female on hybrid bicycle obtained higher accelerations than average Dutch male on granny bicycle
- Lower bonnet leading edge (BLER) and lower cars in general resulted in lower pelvis and head accelerations
- No influence on obtained injuries was found for different bonnet – windscreen angles and bonnet lengths
- Most severe injuries were obtained for the tibia instead of the head. Head injuries though are considered to be more fatal than leg injuries which are mainly cost-intensive (Figure 9)
- For car speeds ≥ 50km/h the chance on obtaining severe head injuries got higher than 50 % (Figure 9)
- Least severe injuries were obtained for the chest (Figure 9)

Remark:
Please note, that lower mass people in general show higher accelerations but can typically also withstand more. However, biomechanical data quantifying the relationship between injury threshold and a specific variation is not available. Therefore, the criteria described in section 3.1.4 are taken for both, Dutch average male and small female.

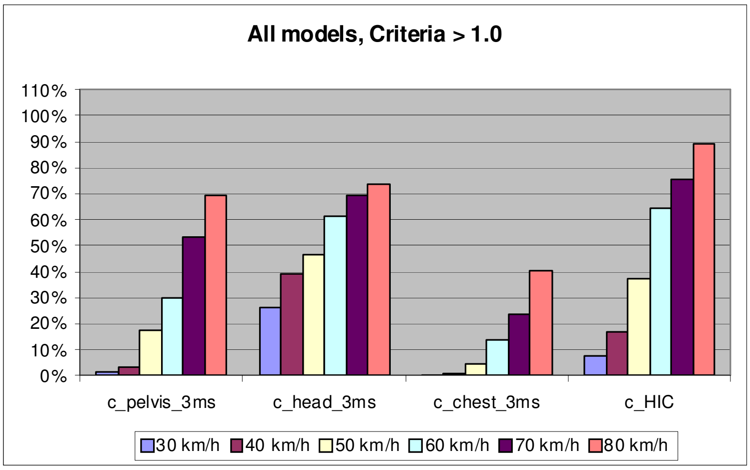


Figure 9 - Percentage of normalized HIC, head -, chest - as well as pelvis 3ms acceleration over car speed; whole study

When looking at the different body parts separately, the following could be found:

Head:

- In cases were the cyclist hit the edge between roof and windscreen, HIC values were found significantly high also for low car speeds.
- Mean HIC < 1000 for car speeds < 50 km/h
- If the car speed rises from 40 km/h to 50 km/h the chance on obtaining severe head injury rises with approximately 20%
- For car speeds ≥ 60 km/h severe head injuries are likely to occur
- Large bonnets peak at 0 deg with respect to HIC. Heading away from the car results in lower HIC values than heading towards the car
- Highest normalized head 3ms accelerations are found for all models between -15 and 15 deg
- For each model at least 75% of all HIC values obtained from car speeds ≤ 40 km/h were found below the threshold for adults (Figure 10)
- For elderly people the chance of obtaining serious head injuries was already high for car speeds > 30 km/h (Figure 10)

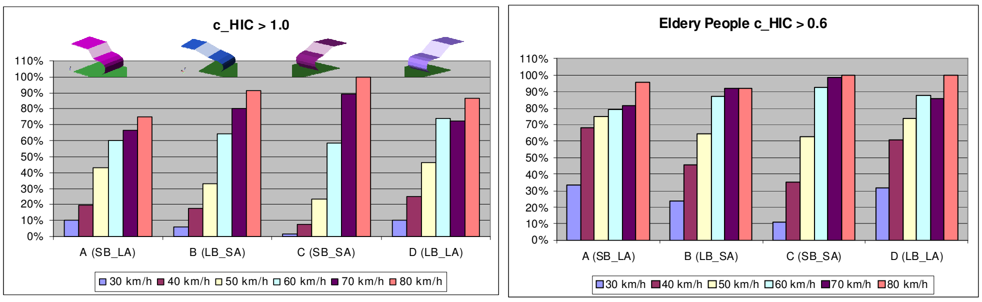


Figure 10 - Percentage of normalized HIC per model and car speed that was found above the critical threshold of 1000 for adults and 600 for elderly people

Torso:

- Chest injuries were found to be least severe injuries
- Large bonnets resulted in a mean normalized chest 3ms acceleration < 1
- Smallest mean chest acceleration was obtained for Model D (LB LA)
- Mean normalized chest acceleration always stayed below 1 no matter which bicycle orientation or car model
- All models: 94% of the normalized chest 3ms < 1 if car speed ≤ 50 km/h (Figure 11)

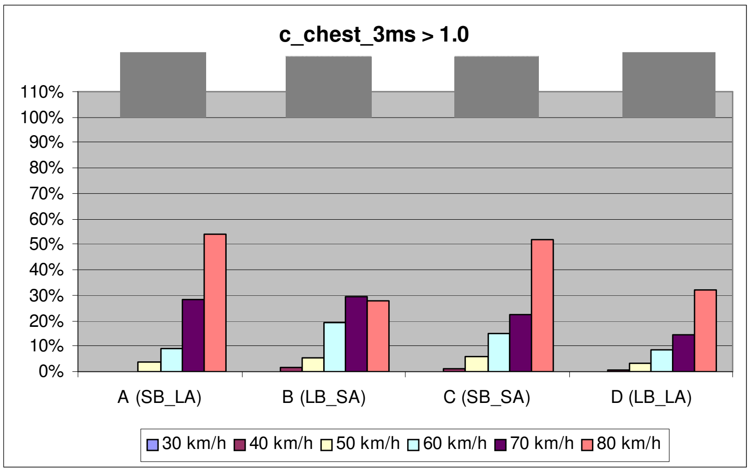


Figure 11 - Percentage of normalized chest 3ms acceleration per model and car speed that was found above the critical threshold of 60 G

Pelvis:

- Smallest mean pelvis acceleration was obtained for Model D (LB LA)
- Mean normalized chest 3ms accelerations were in general slightly lower than the mean normalized pelvis 3ms accelerations
- Only mean normalized pelvis 3ms acceleration of - 45 deg bicycle orientation was found ≥ 1
- Large bonnets were found safer for car speeds around 50 to 60km/h with respect to pelvis injuries
- For small bonnets chance of significant pelvis injuries rose app. 20 % from 40 km/h to 50 km/h

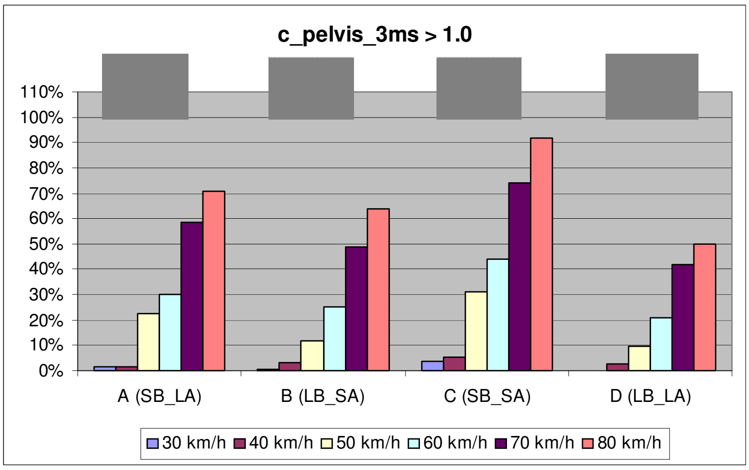


Figure 12 - Percentage of normalized chest 3ms acceleration per model and car speed that was found above the critical threshold of 60 g

Tibia:

- For car speeds > 30 km/h severe tibia injuries were most likely to occur (Figure 13)
- Tibia injuries were found to be the most severe injuries occurring, which is in line with literature

Please note:

For the simulation set up the worst case scenario was chosen for the position of the cyclist’s legs. The right leg which is located on the side of the impact was always stretched out downwards so it would make first contact with the car during the impact. If that leg was positioned differently, other injury values would be likely to be obtained.

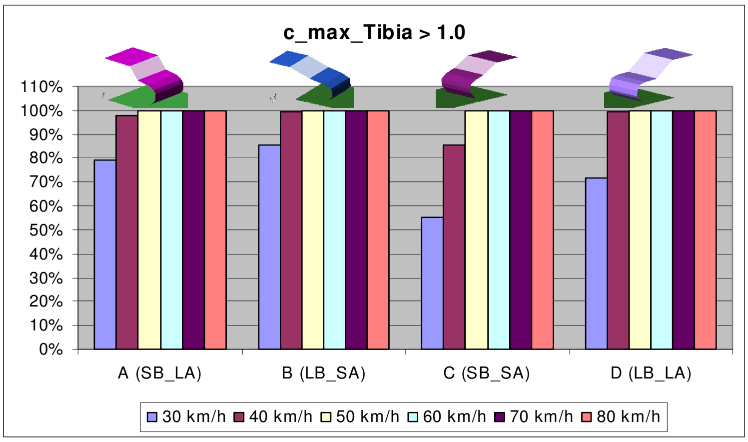


Figure 13 - Percentage of normalized maximum Tibia 3ms acceleration per model and car speed that was found above the critical threshold of 150 g.

3.2.3 *Impact locations*

In Appendix B tables are provided per car model, stating the percental number of hits of the cyclists head, torso and pelvis on different parts of the car. Tables are provided for different car speeds as well as bicycle orientation. Also, each table is split with respect to . the cyclist – bicycle combination, so conclusions can be drawn for differences in seating position and size of the cyclist. Only the first contact of the appropriate body part with the car structure is listed.

As stated in section 3.2.2, most severe head injuries were found in cases, where the head hit the edge between windscreen and roof. Please note, that due to the simplicity of the car model, this hit point cannot be determined automatically and is therefore not further mentioned throughout the following conclusions.

In general it was found, that contact with the car is made significantly different for a cyclist compared to a pedestrian. Not only do cyclists hit the car structure under different angles, but they also hit higher than pedestrians. In contrast to pedestrians who mostly hit the bonnet and the bumper of a car, the main impact location for cyclists was found to be the windscreen. It was not only hit in a significant amount of cases by the cyclists head, but also by the torso and for large bonnet – windscreen angles even by the average Dutch males' pelvis.

It can also be stated that the cyclist anthropometry as well as seating posture were found to be of significant influence with respect to the contact locations between cyclist and car. Tall or upright sitting cyclists hit the car structure in general higher than small or bent sitting ones. Also, higher hits were being obtained for rising car speeds as well as decreasing bicycle orientation. Figure 14 and Figure 15 exemplary show the impact probability of head on different car parts separately for all cyclists – bicycle combinations as found for Model B (LB SA).

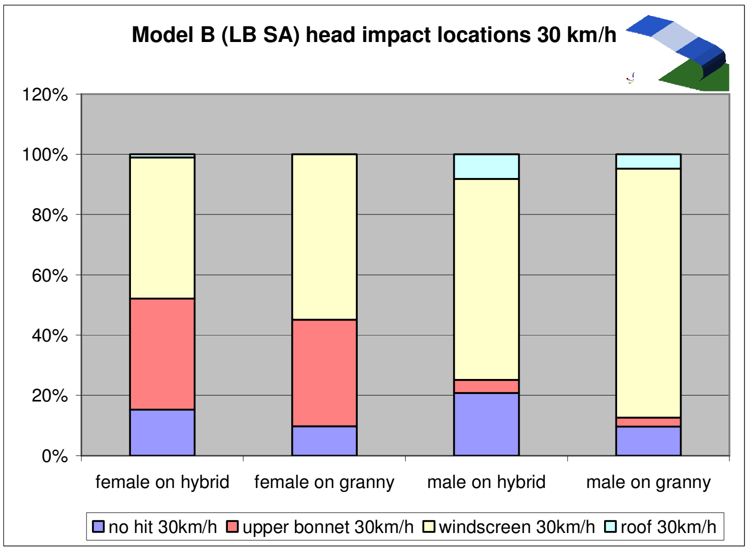


Figure 14 - Impact location of the head on the car structure for different cyclist – bicycle combinations at a car speed of 30 km/h exemplary for Model B (LB SA)

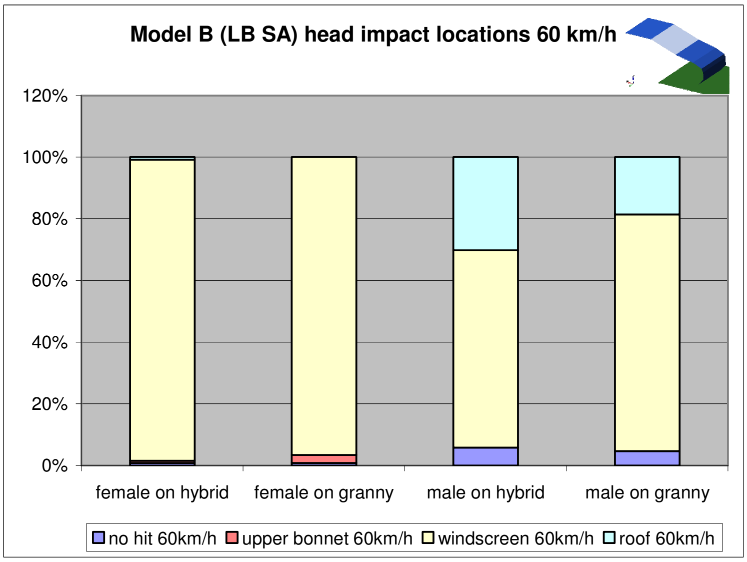


Figure 15 - Impact location of the head on the car structure for different cyclist – bicycle combinations at a car speed of 60 km/h exemplary for Model B (LB SA)

When looking at different body parts separately, the following could be found:

Head:

For the head, 3 different impact locations could be distinguished:
- Upper bonnet
- Windscreen
- Roof

When looking at Figure 16, it can be concluded that the windscreen is most likely to be hit by a cyclists head in a bicycle to car accident for all car models and cyclists.
The upper bonnet was almost only hit by the head of the small female mainly in the 30 km/h condition and mainly for large bonnets. For these cases, the choice of the bicycle only has an influence for Model D (LB and LA) where the upper bonnet is hit more often by the female on the granny bicycle.
The roof is hit almost only by the average Dutch male. If that cyclist is riding the granny bicycle, the chance of hitting the roof is in general higher than on the hybrid bicycle. For Model A (SB LA) the chance that the head will hit the roof is even 43 % when riding the granny bicycle.

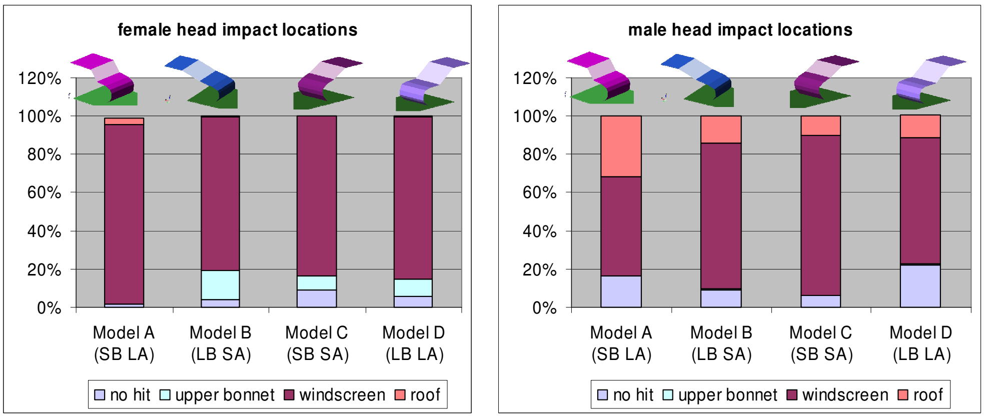


Figure 16 - Head impact locations on the car for all four models for average Dutch male (right) and small female (left)

Torso:

For small bonnet – windscreen angles in general lower hits were obtained compared to big bonnet – windscreen angles. The torso of the tall male in most cases hit the windscreen. The small female also hit the windscreen significantly often, but also a large number of hits on the upper bonnet could be found.

For both cyclist models and all car models a significant number of simulations was found – especially for cars with a large bonnet – where no contact of the torso was made with any of the car parts. For most of these cases the torso is well protected by the cyclists' arms and therefore contact only occurred between the arms and the car and not between the actual torso and the car.

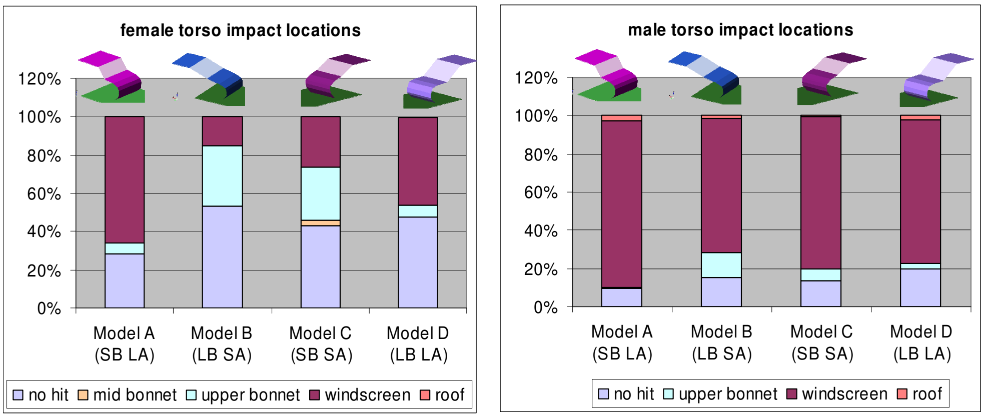


Figure 17 - Torso impact locations on the car for all four models for average Dutch male (right) and small female (left)

Pelvis:

It was found that the pelvis of the small female is most likely to hit the mid or upper bonnet for all car models. Except for Model A (SB LA) the pelvis of the average Dutch male most likely hit the upper bonnet. In Model A for more than 40 % of the simulations the pelvis made first contact with the windscreen. For the other model with large bonnet windscreen angles (Model D) the windscreen was also hit quite often by the pelvis (app. 24%) compared to the models with small angles (app. 6%).

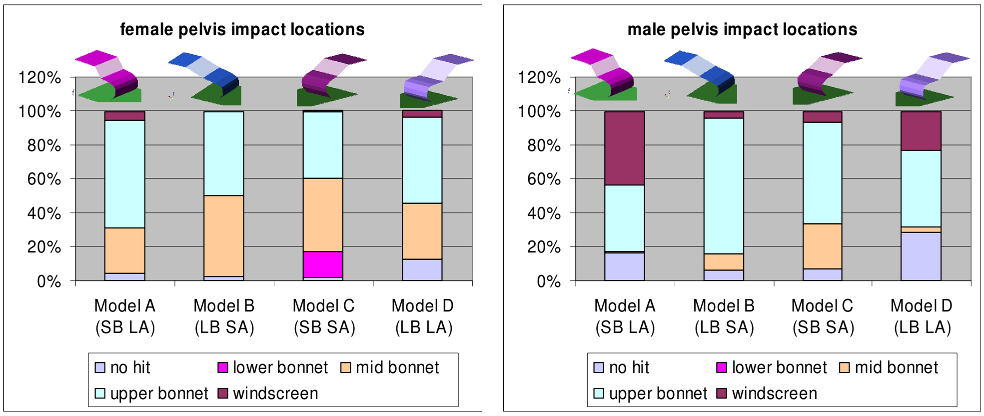


Figure 18 - Pelvis impact locations on the car for all four models for average Dutch male (right) and small female (left)

4 Assessment Methodology

4.1 Introduction

Alike advanced technologies, current regulations have been developed with main focus on pedestrians assuming that it would cover also cyclists' safety. Pedestrian impact requirements are the subject of two existing regulations in Europe and Japan. Though these requirements differ, there are efforts to introduce a Global Technical Regulation to communize them. The European regulation was approved in 2003 by European Parliament and Council as Directive 2003/102/EC [3]. The directive states that new vehicle introductions must have a specified level of pedestrian impact performance starting in 2005. Apart from regulations tests, the most common consumer test in Europe is EuroNCAP pedestrian test (EuroNCAP, 2004) which is based on the EEVC WG17 report (1998). There are differences between EC and EuroNCAP (see Table 8) requirements, however in 2010 the EC requirements should comply with requirements set in the EEVC report. The EC requires only adult head-form tests while in EuroNCAP both adult and child head forms impact are carried out. The headform used in the EC directive is 3.5kg with an impact velocity of 35 km/h while in the EuroNCAP tests 4.5 kg for adult and 2.5 kg for child headform, both with the impact speed 40km/h, are used. The lower legform impact configuration is similar for both protocols. Only different injury limits are applied. The upper legform impact is mandatory only for the EuroNCAP protocol. Since the EuroNCAP protocol is based on EEVC recommendation, the aim of this part of research is to propose changes to the EuroNCAP protocol such that also the bicyclist safety is taken into account.

4.2 Proposal for adaptation of the current protocol

4.2.1 Head impacts

Based on literature review and analysis of the simulation study results it is apparent that to improve cyclist safety additional head impact locations are needed, with different impact angles and a similar impact velocity. To estimate the impact angle and velocity current simulations have been reviewed and analysed based on the assumption that a typical cyclist-car impact configuration is as follows:

- Impact speed 40 km/h
- Bicycle is oriented perpendicular to longitudinal car axis
- The bicyclist is an adult male.

The analyses of such cases demonstrate that the head impactform should be impacted against upper and middle windshield and also on roof-windshield edge. On average the impact velocity against the windshield was 10-11m/s and impact angle was 50-60 °.

4.2.2 Leg impacts

The lower leg impact form is also effective for cyclists. The impacted cyclist leg initially contacted the bumper and in the next stages the bonnet leading edge. It should be remembered that in the current simulations the impacted leg was straight and in real life it might be bent. The impact velocity was dependent on the car and bicycle velocity and for 40 km/h cases it was similar to the one used in the regulations. The current regulation and injury criteria for lower leg impact form aim to protect pedestrian against knee injury. In case of cyclist this regulation would protect against the tibia injury which is more common among cyclists. The secondary lower leg impact against bonnet leading edge is in general covered by the pedestrian upper legform impact requirements. This requirement also should protect the cyclist lower non-struck leg against injury. Currents simulations showed that this leg impact location is mainly on the bonnet and its impact angle and velocity are varied and hard to predict.

4.2.3 *Pelvis impacts*

Bicyclist pelvis in most cases impacts the bonnet with an impact velocity 5±0.2 m/s. The impact velocity is low comparing to pedestrian regulation for upper legform impact, moreover the impacted area for the bicyclist pelvis is the bonnet which is softer than the bonnet leading edge. As such it seems that there is no need to modify current pedestrian regulation in this aspect. There are concerns about the torso injury in cyclists. Current study showed that torso impact velocity was 5 m/s and the main impact location was the bonnet or the windshield. In most of cases the torso was protected by the arm. It has been decided that further study would be needed with more detailed models to fully assess the severity of such impact to suggest a new impact form which minimizes the torso injury risk.

4.2.4 *Conclusion*

Overall the current study and the literature review show that to improve cyclist safety the most important subject is adding to current regulation/safety tests an additional impact area for headform impacts with slightly modified impact angles. The impact area should include the windshield area, particularly the windshield/roof and A-pillar area.

Table 8 - EC and Euro NCAP requirements for pedestrian testing.

		Current EC	**Euro NCAP**	**Additional requirements for cyclists**
Adult head impact	Impact area	bonnet	bonnet	**windshield and roof**
	Impact speed	35km/h test	11.1±0.2m/s	**10-11±0.2m/s**
	Impact angle	65°	65°	**50-60 °**
Lower leg impact form	Impact area	bumper	bumper	Bumper/bonnet leading edge
	Impact speed	11.1±0.2m/s	11.1±0.2m/s	11.1±0.2m/s
	Impact angle	0°	0°	0°
Upper leg impact form	Impact area	Not required	bonnet leading edge	Bonnet
	Impact speed	Not required	11.1±0.2m/s	5±0.2m/s
	Impact angle	Not required	n/a	0-5° relatively to bonnet surface

5 Advanced protection systems of vulnerable road users

5.1 Introduction

In the following section, potential safety measures on cars that are considered to improve cyclist safety in bicycle to car accidents are presented. Safety systems for vulnerable road users should be effective for both pedestrian and cyclists or at least should not be dangerous for the other group. Although this study showed that cyclist and pedestrian accident were in several aspects different it is worth to evaluate current systems and where possible to suggest improvements or add additional components which are effective for cyclists instead of developing a completely new technology. Most of advanced systems were developed focusing on pedestrian safety. Attention is paid, that possible modifications to the car would not have negative consequences for other vulnerable road users such as pedestrians. Only options are presented that are on the market or appeared to be feasible in the near future. Therefore, the list of proposed safety measures in this report does not claim to be complete. It should be noted, that there are most likely also other feasible possibilities to improve cyclist safety that are not reported here.

5.2 Vulnerable road user detection and warning systems combined with brake assist and/or autonomous braking.

The literature review and parameter study both indicate that decreasing the impact velocity is the best way to reduce the severity of the injuries of pedestrian and bicyclist. However, braking by the driver is in many cases not present or not efficient enough to reduce the speed. There systems are under development that support the driver's braking action or that brake the vehicle autonomously, without driver interference.
A typical warning/braking system combines pedestrian detection, trajectory estimation, risk assessment and driver warning/braking procedure. Several detection system have being developed and tested. An example is the APVRU system (McCarthy, 2004). The aims of the APVRU project was to developed and test an on-board sensor system that is capable of detecting a vulnerable road user and distinguishing them from the road environment. The system that consisted of passive infrared sensor for "hot body" detection and radar for accurately ranging the target was concluded to be the best solution. The system was tested for detection of human volunteers in static case and the dedicated dummy in dynamic case. Further simulations were performed in a denser environment and it was concluded that the APRVU system may provide basis for future systems which would decelerate the vehicle to reduce impact speed or to activate an active safety system such as pedestrian airbag and/or active hood.
Another example is the so-called SAVE-U system (Munder S, 2002, SAVE-U), which calculates in a matter of seconds the movement of pedestrians within the `capture zone´ which can be up to 30 meters away from the vehicle. The camera tracks the pedestrian movement and the information is correlated with the data received from the radar network (speed of and distance to object). SAVE-U can consequently identify any pedestrian or cyclist coming within the trajectory of the vehicle and after analyzing the situation, warn the driver or apply automatic braking if there is a risk of collision. SAVE-U protection system was installed on two demonstrator vehicles, a Volkswagen Passat and a DaimlerChrysler Mercedes- Benz E-class.

To apply these systems to bicyclists, the capture zone, decision making module and trajectory estimation module should be modify as cyclists are moving with higher speed than pedestrians and also the cyclist's position is higher above the ground than the pedestrian position. If detection system uses cameras also this module should be altered.

5.3 Hood and A-pillar airbags

A frequent injury cause in a collision between vulnerable read users (pedestrians, bicyclists) and vehicles is the impact on the vehicle front structure like engine hood, A-pillars or windscreen. Apart from the above mentioned hood lifting systems the airbags outside of the car offer an effective solution to reduce the injuries in case of an accident. Due to the nature that airbag systems are not reversible, the biggest problem at the moment is availability of sensors and control systems which can reliably detect a collision.

5.3.1 Hood airbag

Airbags that cover bonnet or scuttle reduce the severity of the head impact against bonnet and on the edge bonnet-windshield. The airbag is disposed in a region between the front end of the bumper and the rear end of the hood. The sensor, radar and/or crash sensor, detects or pre-detects a collision between a pedestrian and the vehicle, and generates a collision signal. The inflator receives the collision signal. The airbag expands forward, inclined upwardly, to cover an upper surface of the bumper and a front end of the hood (see Figure 19).

Figure 19 - Autoliv airbags concept for a SUV. Front edge and bumper airbag

5.3.2 *Cowl and A-pillar airbag*

Figure 20 - Autoliv A-pillar airbag.

The bonnet airbag should be complimented with an A-pillar airbag to protect the head of the pedestrian from the hard surfaces of window frames and pillars. An example of such design is described in several patents (DE 100 14 832 A1, US 6 415 883 B1), moreover it has been applied by Autoliv (2008) and Ford Motor (2008). In Ford concept the first airbag system covers the area of the area between the headlamps and extends from the top of the bumper to several inches above the hood surface. The folding pattern and cross-section of the air bag are engineered so that the deploying airbag conforms to the profile of the vehicle's front end. The second airbag system consists of two airbags that each extend from the centreline of the vehicle to the corresponding A-pillar. Its deployment is delayed compared to the first system about the time it takes the pedestrian to travel across the hood area toward the windshield. When fully inflated, the two airbags cover the full width of the vehicle along the windshield base, from A-pillar to A-pillar. This covers the critical "hard points," such as the windshield wiper spindles and hood mounts, as well as the base of the windshield glass. However, the bag does not completely block the driver's view. Autoliv supplemented their active hood (described in 5.4) with pedestrian protection airbags (PPA), which are comprised of an airbag at each A-pillar. The same sensor that triggers the active hood also sets off the PPA system

Figure 21 - Ford airbag system

5.4 Hood lifting systems

‘Pop-up’ bonnets (Autoliv, Honda, Citroen, Toyota and others) are designed to reduce severe injuries and fatalities from pedestrian head contact with rigid engine parts located beneath the bonnet surfaces. For some vehicle types, for example sports cars, it is difficult to create enough space between the engine and the hood. In order to increase the deformation path for a head impact, the hood is lifted by active systems. Sensors in the vehicle bumper detect the impact and send a signal which raises the rear half of the hood. The engine hood can be activated with the help of pyrotechnical solutions, feather/spring mechanism and/or by pneumatic actuators. The pivot of the hood lies in the area of the front edge whereby the lifting takes place in the cowl zone area. This leads to a maximum increase of the deformation path. This raised and therefore more energy absorbent surface, results in lower accelerations for pedestrians’ head impacts. This lower acceleration levels reduce the chances of fatality and injury.

Figure 22 - Bonnet with protection system in activated, lifted position,

5.5 Bicycle safety dedicated study

Maki study (2002) focused directly on bicyclist safety. He suggested applying a controlled bumper airbag together with an A-pillar airbag. His philosophy was based on differences in kinematics between side and frontal bicycle collision. It was observed that the head contact velocity in frontal vehicle to bicycle impact was lower than in side impact when there was knee-front vehicle contact. It was concluded that the main reason for lower severity in frontal impact is the hip upward movement due to force applied to bicyclist’s knees during the contact with vehicle front structure. The head – vehicle contact occurs later in frontal than side impact. Upward movement of the pelvis decreases the head vertical and relative velocity at time of head-vehicle impact and in consequence lower injury severity. It is thought that the lumbar region’s upward velocity of a bicyclist is maintained because the thighs rotate in the vehicle's reverse direction, having as their fulcrum the knees that collide with the grille. Accordingly in order to get same behaviour for side impact, an airbag was installed such that the airbag deployed at an upward slant of approximately 30 deg. and it was also rotated in the vehicle's reverse direction after the bicyclist collided with the vehicle. To protect the head during final stage when contact between head and A-pillar is probable, Maki

(2002) suggested to use an A-pillar airbag with modified deployment time. The system was tested and showed high potential to reduce injury for both cyclists and pedestrians.

5.6 Résumé

Based on above review two strategies to improve bicyclist safety have been chosen. The first advisable solution is a detection system combined with brake assist and/or autonomous braking. The detection systems have been tested for pedestrians only however it is possible to apply them for the cyclists after a few modifications. This way it would be possible to avoid an accident or mitigate its severity. The aim of the second advised technology is to mitigate the injury severity in case when the accident was unavoidable. The literature review showed the most frequent as well as the most severe injury for bicyclists is the head injury and the most frequent impact locations are the windshield and also the roof. The current computational results also have showed that bicyclist head impact locations are typically windshield, roof and to a lesser extent the bonnet. According to the above, the main focus should be on protecting the head particularly when it impacts the windshield area. The best solution for cyclist would be built in airbags such as presented by Ford. Particularly care should be taken of A-pillars area (Autoliv concept) as well as on windshield-roof edge (patent DE 100 14 832). The head impact area for children and small female bicyclists is lower on the hood, but somewhat similar to those of adult pedestrian hence the hood airbag or ‘pop-up’ bonnet are advised. The bicyclist leg is higher than pedestrian leg however the safety measure such as active bumper or bumper airbag are also beneficial for bicyclist to reduce the risk of tibia injury. The bicyclist pelvis in most cases impacts the bonnet rather than the typically stiffer bonnet leading edge so the extra measures are not pressing, particularly if active bonnets or bonnet airbags are used. The bicyclist torso which hits the bonnet or windshield would benefit from hood airbags as well as windshield airbags which are advised to reduce the pedestrian and cyclist head injury. Overall the most urgent is the bicyclist head protection and the advisable solutions are the windshield area airbags.

5.7 Window airbag for bicyclists / numerical investigation

In order to tone, whether an exterior airbag is also likely to have a positive influence on cyclist’s injuries, a small preliminary numerical investigation was done. As presented before, the Swedish company Autoliv has developed a prototype of an exterior airbag for pedestrian safety combined with a so called “pop-up bonnet”. This airbag would catch the head of the pedestrian during an accident and is able to reduce HIC quite significantly (see Figure 23). Therefore it can be assumed, that a similar set up adapted properly towards cyclists will be able to reduce head injuries in bicycle to car accidents as well.

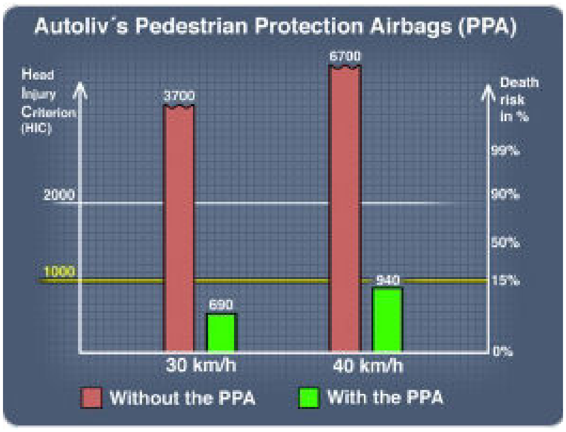


Figure 23 - HIC reduction with the Autoliv exterior airbag for pedestrians for different car speeds as provided by Autoliv

The airbag provided as generic numerical LS-Dyna model by Autoliv is coupled with the following MADYMO set up:

- Midsize family car (TNO Report, Hassel (2006)) extended with A pillars)
- Average Dutch male on granny bicycle
- Car speed: 40 km/h
- Bicycle speed: 18 km/h
- Bicycle to car orientation: 0 deg

As the midsize family car model used throughout the previous study on cyclist safety (TNO Report, Hassel (2006)) provides much more detail as the scalable car model that was used throughout the current parameter study, this car model is chosen for the airbag investigation. The set up is chosen in such a way that the cyclist sustains significant head injuries due to impact of the head on the A pillar in case no airbag is present.

Position and shape as well as characteristics of the provided airbag so far are only optimized for pedestrian safety for a specific car model. From the literature study as well as the numerical parameter study it was found that cyclists hit higher on a car than pedestrians do. Modifying the shape and construction of the numerical airbag model is out of the scope of this project. Therefore, the exterior airbag is moved up approximately 18 cm along the windscreen for the simulation though of course such a position is not possible and suitable in reality. A picture of the complete simulation set up including exterior airbag is provided in **Figure 24**.

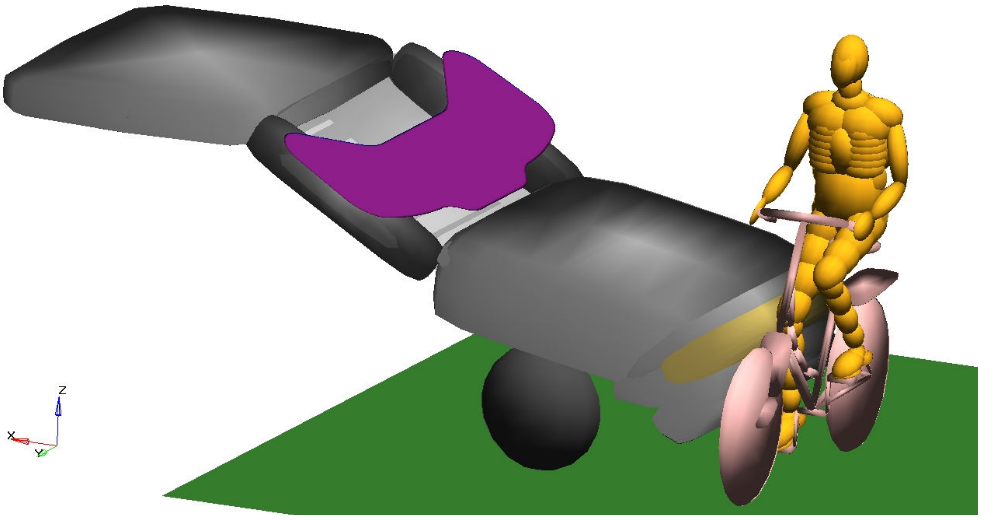


Figure 24 - simulation set up: midsize family car from the previous study including A pillars and exterior airbag; average Dutch male on granny bicycle

Results

The simulation was one run with and one without the airbag. Without airbag, the cyclist would hit the A pillar of the car resulting in a HIC of 2030 which would most likely result in serious head injuries. When using the prototype airbag model as provided by Autoliv, it was found that the airbag was able to catch the head of the cyclist (**Figure 25**) but only minor reduction of HIC was established.

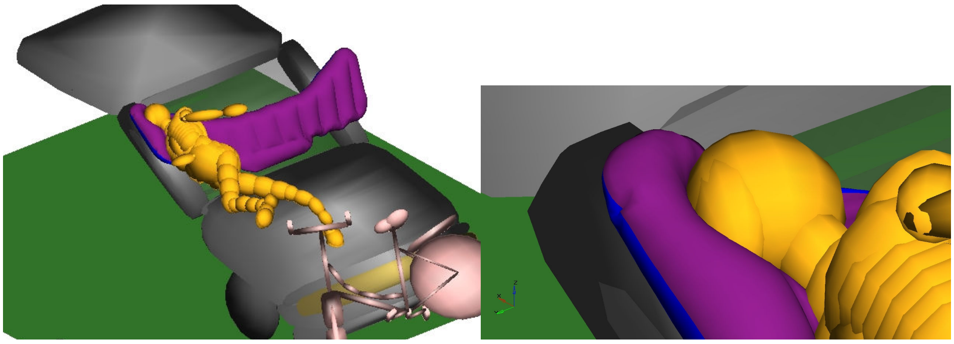


Figure 25 – Head captured by airbag: general view (left); close up (right)

When checking the acceleration signal of the cyclists’ head in both simulations, it was found that the head would just go through the airbag without being really captured. This indicated, that the properties of the airbag such as triggering time, mass flow, gas outflow or gas temperature were not suitable for the selected car geometry, with differs from the design specifications. Therefore the simulation was run again, once with increased mass flow and once with increased gas temperature to briefly check possible influences. Please note, that no airbag optimization was performed as this would have been out of the scope of this project. It was found that both increased mass flow and increased gas temperature resulted in significant improvement with respect to the cyclists’ risk of head injuries:

Table 9 – HIC values for different airbag simulations

	No airbag	Initial airbag	Improved Gas temperature	Improved Mass flow
HIC	2030	1869	428	492

Compared to a situation without airbag it was possible to reduce HIC by more than 75% with an improved set up going from most likely dangerous to moderate risk of injuries.

Altogether it can be stated, that an exterior airbag can be regarded as promising measure to reduce head injuries not only for pedestrians but also for cyclists. However, upcoming design phases therefore would not only have to optimize towards pedestrians but also towards cyclists. A cyclist for instance hits the car structure much higher than a pedestrian does. It could also be shown, that airbag parameters such as mass flow or gas temperature are of significant influence on obtainable injury reductions. Therefore, upcoming design processes of exterior airbag should also consider the differences in head impact between cyclists and pedestrian to guarantee optimal protection of both.

6 Conclusions and recommendations

Cyclists are no pedestrians; most studies about the safety for vulnerable users mention countermeasures to increase the safety for pedestrian and bicyclists. However most of these studies are based on pedestrian's safety only. This study shows that not all safety measures for pedestrians are efficient for bicyclists. Attention for the specific kinematics of bicyclists in future regulations and during the development of safety systems is needed.

From literature it was found, that bicycle safety is an issue that is more serious in the Netherlands than in other countries of the European Union. The Netherlands are the only country were each year the number of fatal cyclists accidents exceeds the number of fatal pedestrian accidents.

From both literature and parameter study it was found that most dominant injuries occurring in bicycle to car accidents were head injuries. Also, they were most often causative for cases with fatalities. Lower leg injuries tended to be the most severe injuries, however they were not life threatening. Elderly people run a higher risk of obtaining serious injuries than younger people.

From the parameter study it was found, that the general car geometry parameters as bonnet length or bonnet – windscreen angle have no influence on obtained injuries. It was only found, that lower cars and lower bonnet leading edge heights tend to result in lower pelvis and head 3ms acceleration. No car height or bonnet leading edge reference height can be recommended though, as the reduction with respect to obtainable injury was found to be highly depending on car speed, bicycle orientation, cyclist – bicycle combination and the combination of these parameters.

The speed of the car at time of impact is the core parameter with respect to obtained injuries, impact velocities, and impact location. Therefore, the most effective way to reduce cyclist injuries in car to bicycle accidents is to make sure cars do not drive faster than allowed and necessary.

Integrated safety systems such as brake assists and autonomous braking are not only effective for pedestrian safety but also for cyclist safety.

Current regulations for pedestrian safety are less effective for cyclists. Though small cyclists as the small female of the parameter study and young children are still covered to some extend for car speeds $\leq$ 30 km/h, average adults and car speeds > 30 km/h are not covered anymore. Therefore it is proposed to extend the current head impact protocol towards the windscreen.

Exterior airbags as under development by Autoliv were shown to be very effective for cyclists as well, showing a potentional HIC reduction of about 75%. Special attention though will have to be paid to the impact location of a cyclists' head as it hits much higher than a pedestrian head.

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8 Signature

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A Influence of vehicle braking on cyclist injuries

In this document, the influence of a car braking on obtainable injury results is investigated for a test set-up representing a lateral impact of a medium family car into a 50th percentile male and 5th percentile female cyclist. Three different lateral impact simulations are performed per bicycle – cyclist combination:
Situation 1: car speed: 40 km/h, bicycle speed: 18 km/h, no car deceleration
Situation 2: car speed: 40 km/h, bicycle speed: 18 km/h, car deceleration = 5m/s²
Situation 3: car speed: 37.12 km/h, bicycle speed: 18 km/h, no car deceleration

It was found, that the head impact of a decelerating car takes place at approximately 160 ms. Therefore, a car velocity of 40 – 0.160*5*3.6 = 37.12 km/h was chosen for the third simulation.

In Table 10 the simulation results are listed. All accelerations are given in m/s², velocities are given in km/h. Bicycle 1 represents the hybrid bicycle, bicycle 2 the granny-bicycle, respectively. Ped_No 05 refers to the 5th percentile female which is also chosen to represent a 12 year old child and Ped_No 50 to the 50th percentile male, respectively. The 50th percentile human male currently used is 50th percentile for the western population. This model will be replaced by a 50th percentile Dutch male for the actual parameter study. Since here only an indication on the influence of a car braking or not on the injury response should be given, the Western 50th percentile male is considered suitable for this simulation study.

Table 10 - simulation results

Car_vel	Break_acc	Ped_No	Bike	HIC	Pelvis_3ms	Chest_3ms	TibiaR_3ms	TibiaL_3ms
-40	0	50	1	2364.3	332.03	252.44	2665.8	976.87
-40	5	50	1	2066.2	229.83	241.1	2658.5	970.28
-37.12	0	50	1	1899.6	185.6	238.52	2494.8	941.58
-40	0	5	1	1317.3	368.41	379.89	2567.9	894.4
-40	5	5	1	1017.1	362.45	377.7	2563.1	881.46
-37.12	0	5	1	931.39	352.21	335.73	2381	856.76
-40	0	50	2	1490.3	246.47	260.45	2656.1	1275.1
-40	5	50	2	1411.3	221.65	259.98	2639.1	1262.2
-37.12	0	50	2	1591.9	162.39	255.76	2347.5	1184.9
-40	0	5	2	1863.8	306.61	364.41	2540.5	1242.8
-40	5	5	2	1939.9	305.13	385.86	2537.9	1236.6
-37.12	0	5	2	1723.6	296.16	356.3	2345	1178.1

It can be seen, that in general the injury measures are highest in situation 1 (40 km/h, non-braking) and lowest in situation 3 (37 km/h, non-braking). The only exceptions are found for HIC of the male cyclist on the granny-bicycle and for the chest acceleration and HIC of the female on the granny-bicycle. As can be seen from Figure 26, for the simulations of the 50th percentile human male on the granny bicycle, the head impact does take place earliest in situation 1 but the impact velocity and acceleration is highest in situation 3. Therefore, for this case a lower car velocity leads to a higher HIC.

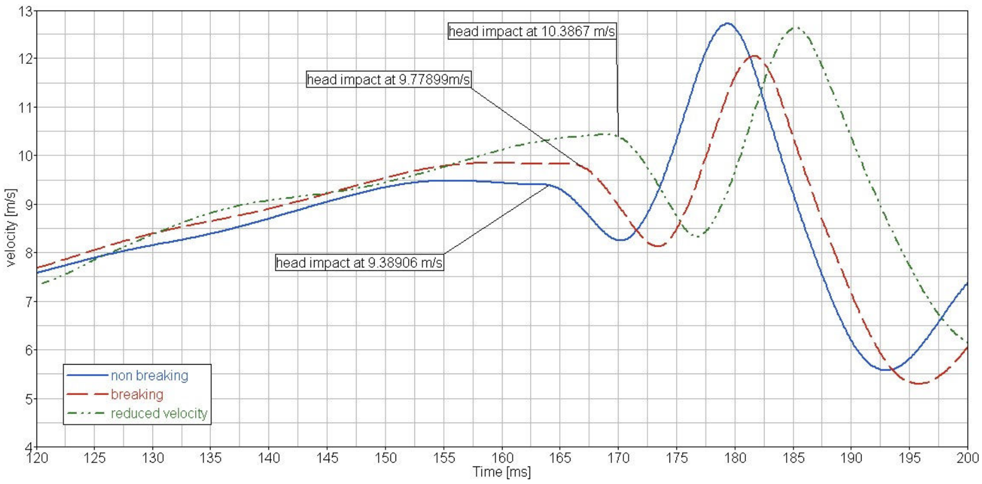

Figure 26 - head velocity of the 50th percentile male on the granny-bicycle

As can be seen in Figure 27, for the 05th female on the granny-bicycle the position of the arm changes if the car is braking. This leads to a slightly earlier shoulder impact resulting in slightly higher chest acceleration and HIC.

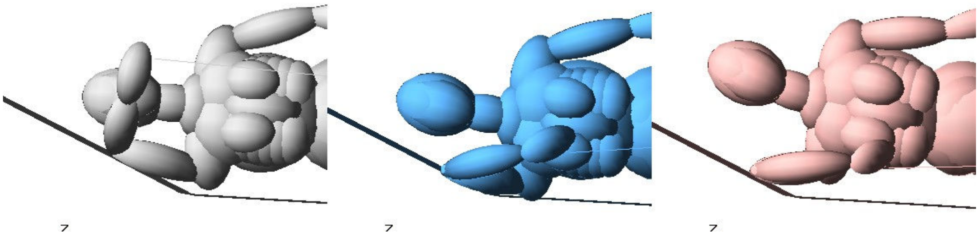

Figure 27 - Scenario 1 (left, gray), 2 (middle, blue) and 3 (right, rose), 5th female on granny-bicycle, shoulder impact

For all other set ups, the cyclists behave similar for all 3 situations. Only that the impact with the car occurs with delay for situation 2 and 3 with respect to situation 1.

Comparing the 40 km/h braking and the 40 km/h non-braking simulations it can be seen that braking leads in general to lower injuries for the upper body. In addition it can be seen that the 40 km/h braking situation can not be modelled with a non-braking situation at lower velocity. However since the impact velocity is varied widely (30 km/h – 80 km/h), the influence due to braking is only limited. In addition, it was also found from literature, that in lots of cases the car would not brake prior to a car-cyclist accident. Therefore, it is recommended not to include braking into the current study.