Vehicle Safety Institute

Analysis of real world car to bicycle accidents

Master Thesis

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STATUTORY DECLARATION

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ABSTRACT

When considering all means of transport, bicycle accidents comprised the third largest group in Austria in 2014. As bicycle to car accidents are already a significant point for vehicle safety, safety solutions to improve cyclist protection can be of even greater importance in the future, due to predictions of continuously increasing bicycle traffic. This thesis focuses on parameters that can be found in real world car to bicycle accidents. Bicycle to car accidents in Austria have been reconstructed and the CEDATU, an Austrian in-depth accident database, has been supplied with the information gleaned. With this foundation of accident information and additional accident data from national statistics, an analysis has been established. Results show that most accidents with injured and killed cyclists happened at cross sections, where both vehicles are approaching at right angle to each other without turning. Accident reconstruction furthermore demonstrated that 80% of all car damages were in the front region of the car, and 49% of the first impact points were with the right third of the car front. Impact regions have been analyzed for three different vehicle geometries. Head impacts were mainly distributed on the windshield and roof and thorax impacts on the windshield and hood. Injuries of the head revealed as most frequently causative for the death of the cyclist, where the windshield represented the highest percentage of head injury causing car parts. For cyclists as well as for car drivers, inattentiveness and ignoring of priority were the most frequently met definitely causative factor for accident occurrence. Moreover analysis of accident location and time, showed a high proportion of injured and killed cyclists in the evening from 5 to 6 p.m. and on urban roads. Other analyses mentioned in this thesis address age and gender of injured and killed cyclists, injury distribution, impact angles, helmet usage and more. Thus this thesis presents a wide spectrum and overview of bicycle accident parameters, which can be further inspected in future researches.

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2 MOTIVATION AND GOALS

2.1 Introduction

Great efforts have been made to establish safe traffic for each individual since the invention of the car. However, increasing individual traffic due to the rising level of motorization leads to a higher risk of being involved in a traffic accident [1]. Every single road accident results in large economic costs (6,7 billion euros 2011 in Austria [2]). In order to reduce the number of traffic accidents or mitigate their consequences, strict safety requirements are imposed on current vehicles. Likewise, high safety standards must be provided by infrastructure, with the level of safety increasing continuously. However, there are also efforts undertaken to raise the awareness of road users in order to allow safe coexistence in traffic. A substantial proportion of accidents involve pedestrians and cyclists – the so-called vulnerable road users. These traffic participants deserve special attention, since they have no physical safety protection, as opposed to vehicles.
The objective of this thesis is to provide an overview of car to bicycle accident: With its parameters, physical processes, pre-accident circumstances (including causative factors) and influencing parameters for the injuries of the cyclist.

The purpose of the following chapters is to clarify the importance of discussing and analyzing bicycle accidents. Therefore, the role of bicycle traffic as compared to other means of transport will be stated, as well as the percentage of bicycle accidents out of all means of transport both in the past and for future perspectives. Furthermore, crash safety legislation for impacts of vulnerable road users with a passenger car and their consideration of bicycle accidents should be discussed. The value of bicycle accidents and the motivation for this thesis will be examined and relevant goals and points will be introduced, which will be focused on later.

2.2 Accidents regarding types of transport

Figure 2-1 introduces fatalities and injured road users in percent for all means of transport in Austria in 2014. These numbers from Statistik Austria show that in 2014, 47670 injured cyclists and 439 cyclist fatalities were registered on Austrian roads [3]. The highest amount of injured occupants and fatalities were passenger car occupants with 55% (n=25998) and 43% fatalities (n=189). This category was followed by vulnerable road users – including motorized one-track vehicles, bicycles and pedestrians. Together, this group comprised 40% of all injured occupants (n=19179) and 46%

fatalities (n=202). In fact, the passenger cars and the vulnerable road users made up 95% of all injured occupants and 89% of all fatalities. Bicycle accidents played the third biggest role, making up 14% (n=6654) of all injured road users and 10% (n=45) of all fatalities.

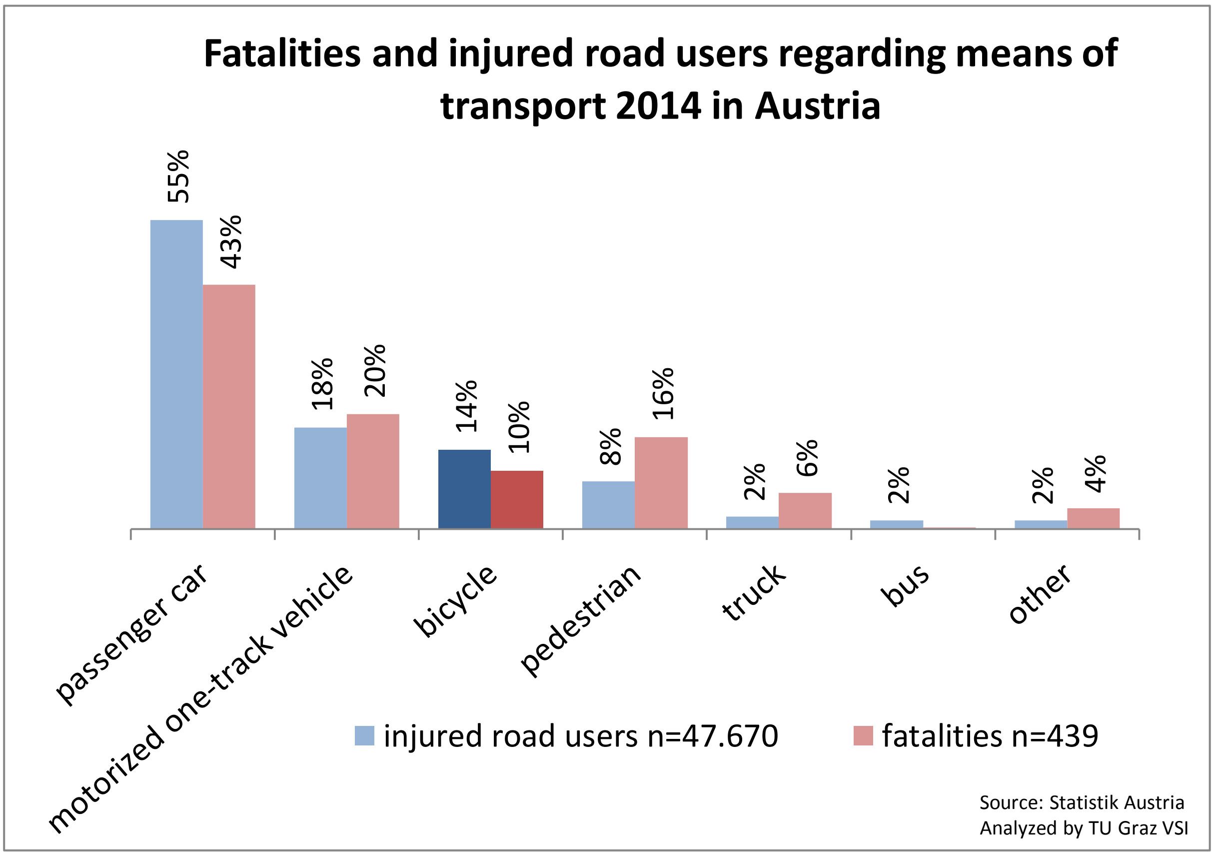


Figure 2-1: Fatalities and injured road users in percent regarding means of transport 2014 in Austria [3]

Another aspect that should be taken into consideration is the percentage distribution of collision partners of bicycles, which are causative for the cyclist's injuries. Numbers of injured cyclists from Statistik Austria point out that in 2011, the highest percentage of injured cyclists, by far, was caused by crashes with a passenger (54%, n=3001). In second place was the single bicycle accident, where no other vehicle was involved, with 23% (n=1318). Bicycle to bicycle and bicycle to truck follow with much lower percentages. When neglecting single bicycle accidents and only considering crashes with at least one other vehicle, about 70% of accidents involved the passenger car as the collision partner of the bicycle. [4] [5]

2.3 Development of bicycle accidents

An analysis of numbers from a Statistik Austria publication showed an average increase of 0,27% per year in bicycle accidents when considering all types of transport, from 10,19% in 2002 to 12,66% in 2011. A similar trend was observed during the years of 2012 to 2014 with an increase of 0,81% in bicycle accidents out of accidents from all means of transport. [6]

It is of crucial importance to compare the number of accidents with usage in order to make proper conclusions. Figure 2-2 gives a closer look into the development of bicycle traffic as a percentage of all means of transport from 2006 to 2011, and shows the predicted goal until 2025 [7]. In 2006, bicycle usage comprised 5% of all means of transport and increased to 7% in 2011. Importantly, in 2011, bicycle accidents comprised 8% of fatalities and 13% of injuries of all means of transport [4]. This reveals a higher percentage of accidents involving bicycles than usage.

A project from the „Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft“ in Austria is aimed at promoting bicycle traffic for ecological and health reasons, mainly through bicycle infrastructure upgrades and extensions. Previously, they published plans to improve bicycle traffic under the project name “Masterplan Radfahren”, in which a goal of 10% bicycle traffic in all of Austria within 4 years until 2015 was set [8]. While the results have not yet been published, the next part of “Masterplan Radfahren” is available and sets a goal of 13% bicycle traffic until 2025 [7].

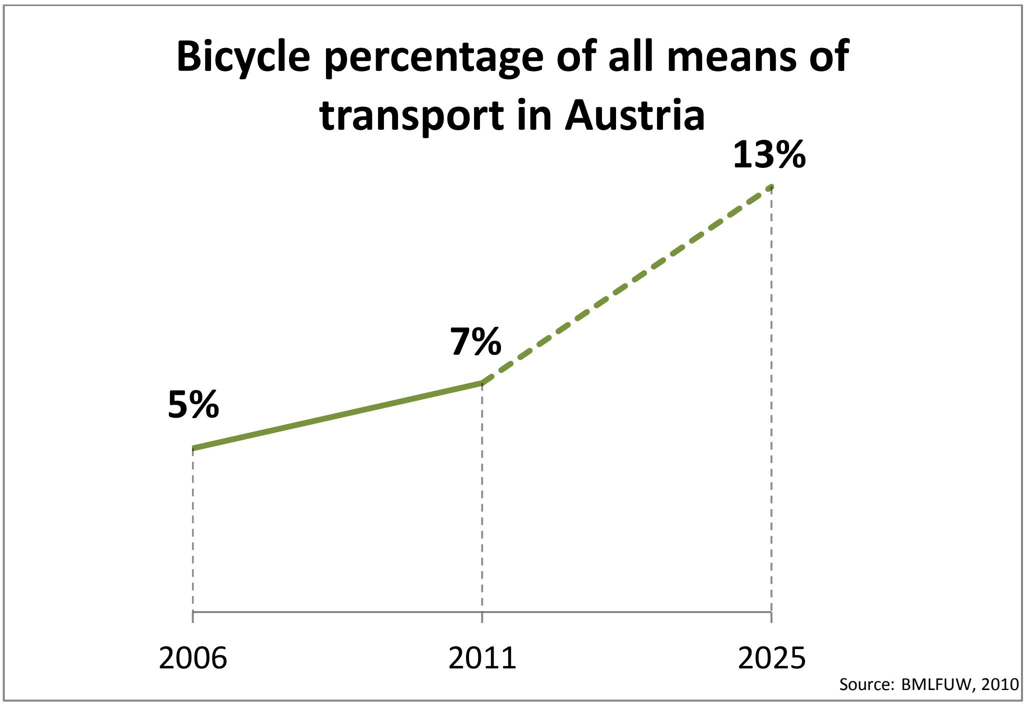


Figure 2-2: Bicycle percentage of all means of transport in Austria [7]

A more specific development example represents the bicycle traffic in Graz, the second biggest Austrian city, shown in Figure 2-3 (1982-2008). Within 26 years the bicycle traffic doubled and there is still the intention to increase this percentage to 20% until 2021 [9].

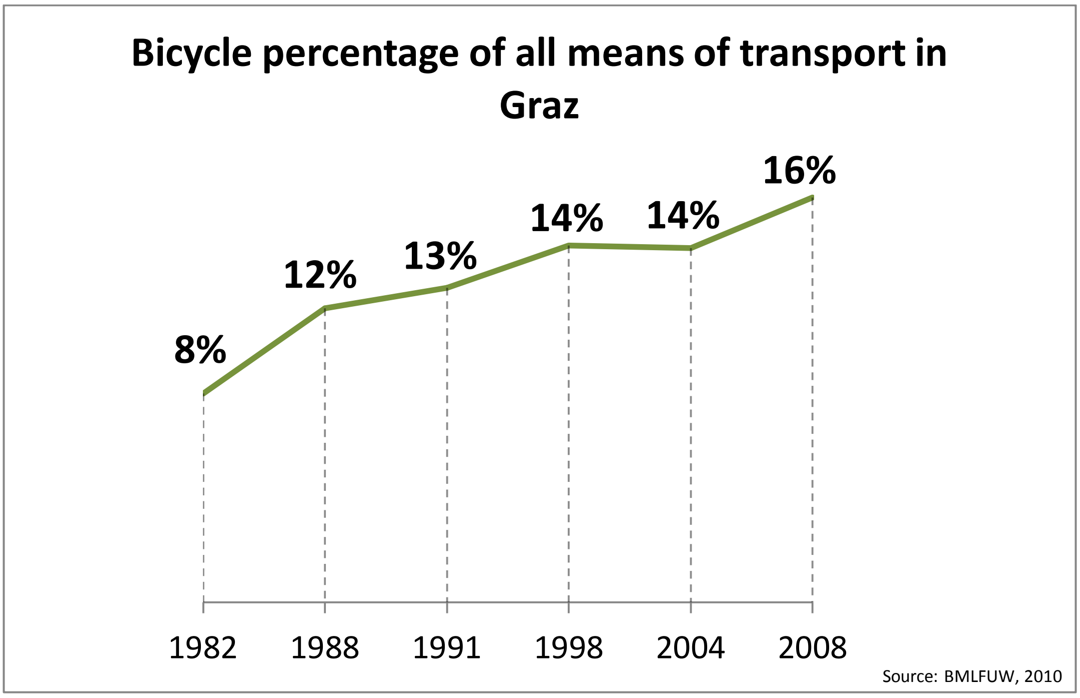


Figure 2-3: Bicycle percentage of all means of transport in Graz [7]

2.4 Crash safety legislation and Euro NCAP

Crash safety legislation

In 2003 the European Parliament in cooperation with the Council of the European Union founded the directive 2003/102/EC (phase I) to reduce pedestrian injuries in car to pedestrian accidents [10]. Since 2005, every new car must pass a test according this directive to be able to enter the market. In this test, the impacts of several body parts - legs, pelvis and head - are simulated by mechanical impactors and accelerations, impact forces and moments are measured and checked, to ensure that they are within a specified limit.

In 2010, this directive was replaced by a newer version, 2009/78/EC (phase II), which includes additional impactors for more detailed testing (see Figure 2-4) [11].

The current legislation (phase II 2009/78/EC) requires following test to be executed on the vehicle front:

- Leg form to bumper
    - Either lower leg form to bumper or
    - Upper leg form to bumper
- Upper leg form to bonnet leading edge (monitoring purpose only)
- Child/small adult head form to bonnet top
- Adult head form to bonnet top
- Adult head form to windscreen (monitoring purpose only)

Limits for results of this test and more detailed requirements can be found in the directive 2009/78/EC [11].

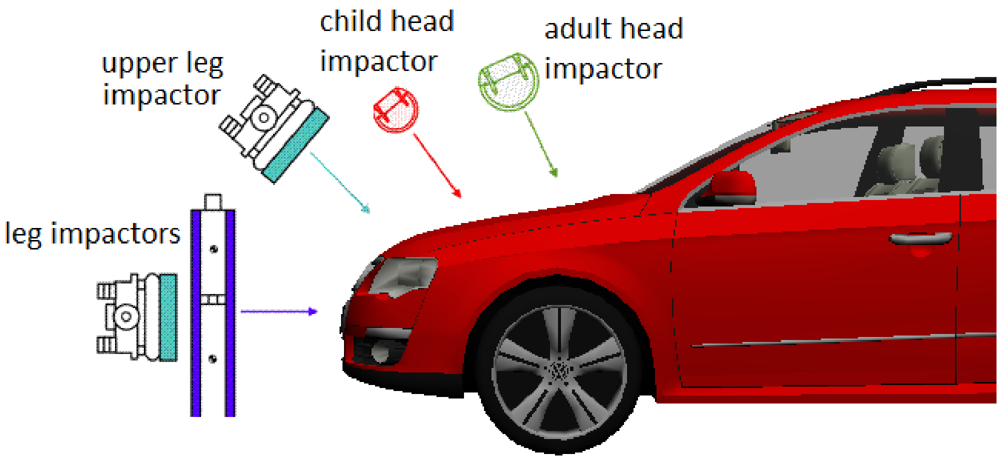


Figure 2-4: Component test phase II according to 2009/78/EG (adapted from [12])

Even though the mentioned directive includes pedestrians and other vulnerable road users, as written in the title, it focuses only on pedestrian impacts. Until today there is no specific legislation regarding bicycle impact testing. There is an assumption that pedestrian component tests also aid bicycle safety, since during accidents, both are generally in contact with the front of the car. Nevertheless, there are fundamental differences between the kinematics and injury occurrence of cyclists and pedestrians. Compared to pedestrians, cyclists have a higher point of gravity and their feet are not on the ground at the moment of impact. Moreover, the traveling velocity of the bicycle is usually higher than that of the pedestrian, which has consequences on impact positions. [13]

Euro NCAP

In contrary to the European legislation, the Euro NCAP (New Car Assessment Programme) does not check vehicles for predefined impact limits, but rather represents an evaluation of the vehicle with respect to their occupant's safety and pedestrian safety. The goal is to make it easier for customers and businesses to compare vehicles and to identify the best choice for individual needs. Each tested vehicle is rated by stars, which reflect their safety performance (a maximum of five stars can be achieved, which represents the best overall result). [14]

For the evaluation of pedestrian safety various tests are performed, which are similar to the legislation mentioned previously and are described in detail in the Pedestrian Testing Protocol by Euro NCAP [15]. Basically following impact forms are used (type and mass corresponding to directive 2009/78/EG mentioned before):

• Lower leg form

• Upper leg form

• Child/small adult head form

• Adult head form

Impact points for the child and adult head form are chosen regarding WAD (Wrap Around Distance): Points located from 1000mm to 1500mm WAD are assigned to the child/small adult head form. Points from 1700mm to 2100mm WAD are assigned to the adult head form. [15]

18 different collision points get selected and tested (6 for each head form, 3 for lower leg and 3 for upper leg form). Each impact test can be awarded by maximum 2 points, which results in a total number of 36 points as the maximum value. Individual values of the impact areas are visualized by different colors, ranging from red (poor) to green (good) (see Figure 2-6). [14]

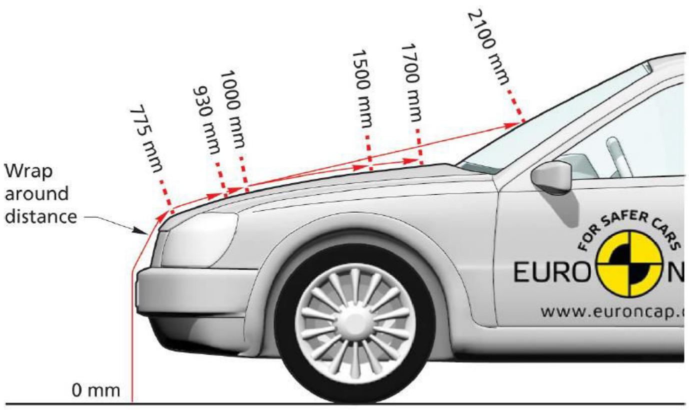


Figure 2-5: Wrap around distance Euro NCAP [15]

Figure 2-6: Pedestrian protection evaluation Euro NCAP [14]

Like for the legislation mentioned before, also for the Euro NCAP no specific test for cyclist impact exist. A study from Germany found out, that this tested WAD could be observed in a big amount of pedestrian accidents, but in much lower number for cyclist accidents: The WAD of 1500mm covered 18% of pedestrian accidents and only 8% of cyclist accidents. The WAD of 2100mm covered 74% of pedestrian accidents and only 51% of cyclist accidents. Generally the average WAD of cyclist was higher than of pedestrians. [16]

2.5 Goals

This thesis aims to focus and specialize on bicycle accidents, state essential parameters and to discuss and set them into relation with each other.
Summing up the following points should be set as objective:

- Analyzing relevant parameters of bicycle accidents and their linkage to each other
- Analyzing relevant scenarios and their differences in injury severity
- Analyzing injured body regions and injury-causing parts at the vehicle
- Selecting and preparing car to bicycle accidents for further FEM analysis

By reviewing literature, accident kinematics should become clear, and common influencing parameters and injury patterns should be found. Afterwards results of a real world car to bicycle accident analysis will be introduced, compared and discussed.

3 REVIEW OF LITERATURE

Within this chapter, fundamental kinematics, scenarios, terms, parameters and injuries will be described, to build up a foundation for results and discussions to follow.

Studies which are reviewed here have used various methods to analyze, evaluate and predict car to bicycle accident parameters. The most commonly used methods are listened below:

- FE (finite elements) simulations
- Multi-body simulations
- Crash Dummy and other physical experiments
- Statistical analyses of recorded accident data

FE and multi body simulations found application for accident reconstruction and also for generic accident simulations.

The types of literature used for this review are mainly research articles, conference proceedings, as well as dissertations and master theses.

3.1 Kinematics of bicycle accidents

When reviewing literature, recurring kinematics were observed and therefore described in detail in Figure 3-1, which is based on kinematical frontal-side crash motion as mentioned in literature [17] [18]. A side collision of cyclists with the front of a car presents the most common constellation, as it comprises a large percentage of car to bicycle accidents (60% of all bicycles colliding with the left or right side of the bicycle and 75% of cars colliding with the front) [19].

A Chinese accident analysis, based on accident reconstruction of car to bicycle accidents (reconstruction of 24 real-world accidents, limited on cyclists with body high above 150cm, car velocity greater than 20km/h and only impacts on the lateral side of the bicycle) divided the kinematics of a side collision into 4 time steps, each 45ms [17]:

- **0ms**

  This time step shows the moment right before the collision with the front of the car. The lower leg, knee and upper leg of the cyclist are positioned to impact with the bumper. The knee can be seen as pivot in this moment, for the upcoming rotation of the upper body.

- **45ms**

  During the phase from 0-45ms the legs obtain a movement in the driving direction of the car, while the upper body stays almost stationary. The tibia gets bended medially until the knee or upper leg hits the bonnet leading edge, continued with an impact of the pelvis with the hood of the car. The bicycle frame is jammed between the cyclist's legs.

- **90ms**

  After minor sliding of the upper leg on the bonnet of the car, the lower extremities start to rebound from the bumper and a rotation of the upper body around the pelvis towards the windshield occurs.

- **135ms**

  Finally the head impacts with the lower part of the windshield

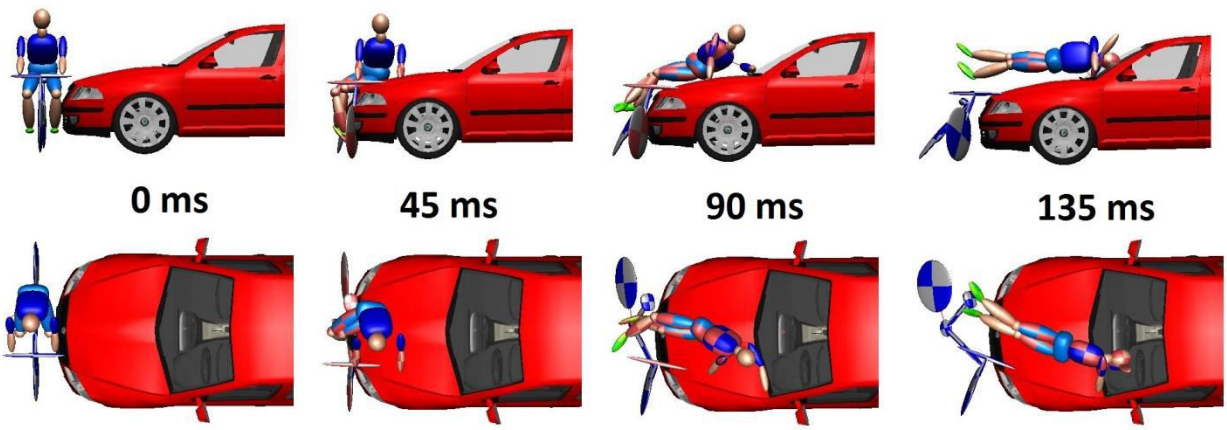


Figure 3-1: Overall kinematics during side impact (adapted from [17])

Another study (simulation of a similar constellation with a sedan car impact velocity of 40kph) additionally remarks a rotation of the upper body at about 120ms along its longitudinal axis, which leads to an impact of the cyclist's back and finally occiput on the surface of the car. This rotation towards the back however, cannot be transferred to simulations using another vehicle geometry (SUV). [20]

3.2 Accident Scenarios

After understanding what happens during an impact of a cyclist on a car, it is also fundamental to focus on the cause and the pre circumstances of the accident. With the aid of damages, skid marks, injuries and further material it is possible to reconstruct accident scenarios.

Beginning with the damaged car parts it is possible to determine the impact areas of the cyclist and may lead to conclusions about the impact direction as well. A German study which is based on contents of insurers' claim files from 2002 to 2010 describes impact distributions of injured cyclists (n=356) on the car [21]: As mentioned in the previous chapter, the highest proportion of impacts were found at the front area of the car: 84% of all impacts occurred at the front (including left and right wing). Only 12% of all bicycles collided with the side of the car and even less (4%) impact with the rear of the car. [21]

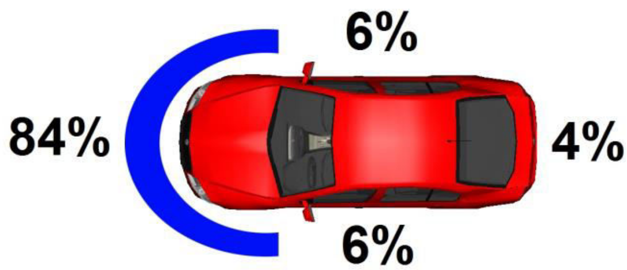


Figure 3-2: Areas of impact n=356 (adapted from [21])

Figure 3-3 shows four different constellations (A, B, C, D) of a front collision from the literature mentioned above. 276 accidents were taken into consideration with restriction to accidents where both vehicles were moving at the moment of the crash. The highest percentage was observed at bicycle direction A, which displays that in a frontal collision 42% of all bicycles approached from the right side of the car, while the car is following the road, turning left or turning right. 34% of all bicycles came from the left side, and 24% drove on the same road in the same or opposite direction as the car. [21]

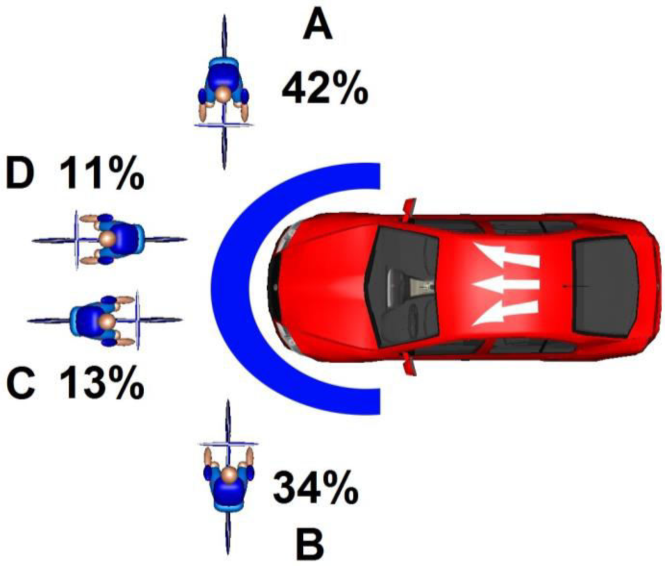


Figure 3-3: Impact constellations n=276 (adapted from [21])

Furthermore A and B constellation, which comprise 76% of all bicycle to car accidents, are further divided into driving directions of the car (turning left A1, B1; going ahead A2, B2; turning right A3, B3). Figure 3-4 illustrates these subcategories and their frequency, and gives one typical example for each case.

The lowest percentage was recorded for accidents where the car was turning and the bicycle followed in the same target direction as the car.

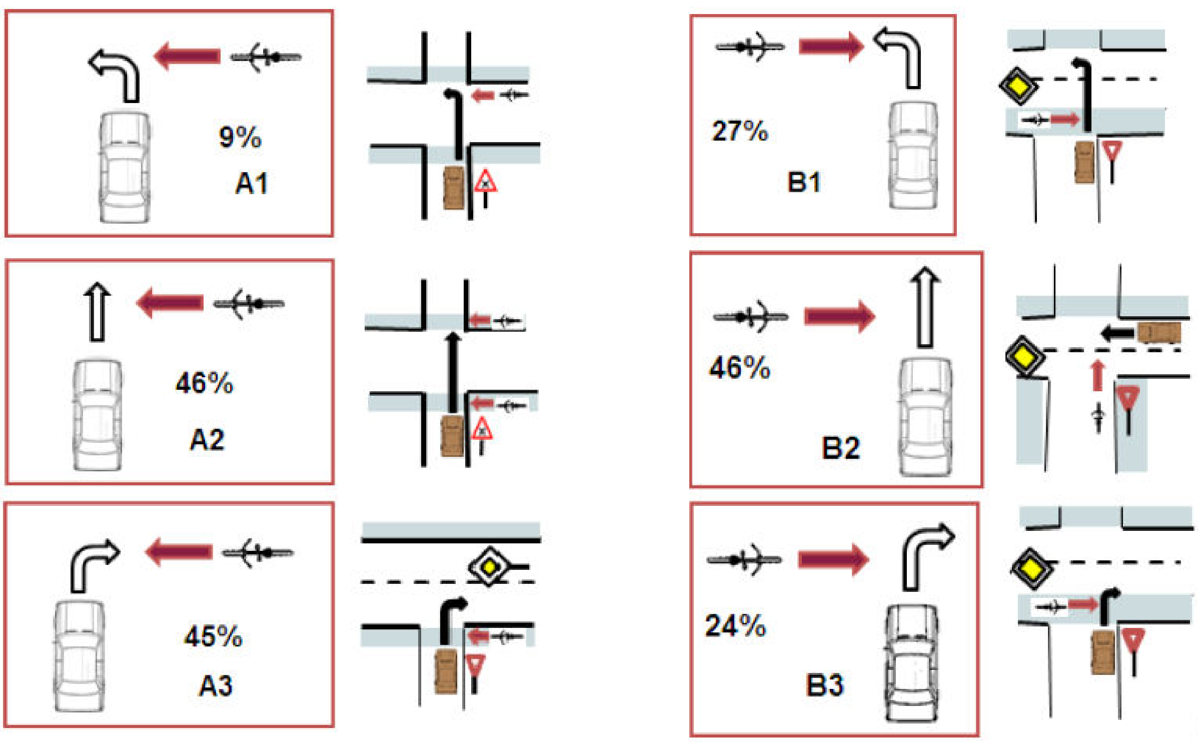


Figure 3-4: Distribution of accidents into car behavior [21]

3.3 Car parameters

This chapter introduces the main car parameters that will be further used in this research. Influences of these parameters should be stated and variations that supported the accident reconstruction and analysis of this thesis should be described.

3.3.1 Car velocity

Vehicle velocity is the most important factor for pedestrian accidents, regarding reducing injuries and their frequency [22]. For cyclists the probability of serious injuries and the risk of death increases with the impact speed of the vehicle as well [17] [23] [24] [25]. However, another study from Germany discovered that impact velocity does not necessarily influence the head acceleration drastically: Crash child-dummy tests revealed a slightly higher peak head acceleration for frontal impacts when reducing the car velocity from 40kph to 30kph. This can be explained by a change in the region of impact, which can offset the benefits of reduced car velocity by impacts on harder car structures [26]. As simulations from another study show, higher car speeds can radically affect the area of impact for the head of the cyclist [24]. With females (average Dutch 1.53m, 50.2kg), there was a high increase of head to windshield impacts and a decrease of head to upper bonnet impacts when car velocity was increased from 30kph to 60kph. For males (average Dutch 1.82m, 83.7kg), there is a gain of more than 100% of head to roof impacts when changing the impact speed of the car from 30kph to 60kph.

According to data from an APROSYS project, most bicycle accidents happen within a speed limit of 50kph [22] [19]. Based on 139 accidents from German data (German In-Depth Accident Study – GIDAS), an average impact speed of 36kph could be found [27]. Moreover, another study from the UK found that most cyclist fatalities happen within a speed limit of 48kph (53%), with the second highest percentage of fatalities occurring within a speed limit of 97kph (25%) [28]. While the percentage of bicycle accidents within a 48kph speed limit may be high, the percentage of MAIS 3+ for low impact speed is little: only 5% below 30kph. On the other hand 90% MAIS 3+ are above 70kph [29] [30].

3.3.2 Car front geometry

The car front geometry plays a crucial role when it comes to pedestrian and bicycle accidents. It has influences on kinematics and therefore dramatically affects injury severity as well [13] [20].

According to a Czech study from 2013, the relation between the point of gravity of the cyclist and the front edge height of the car is essential for further kinematics in the moment of the impact. The lower the height of the impacting edge in relation to the point of gravity of the cyclists, the higher the rotation of the upper body will be. This rotational movement, which was also described previously in chapter 3.1, is typical for impacts with the front of a Sedan, where the car front edge height is below the cyclist's center of gravity. For the MPV front geometry, the steep hood and the close distance to the windshield restricts rotational movement [23]. Figure 3-5 gives an overview of impact locations on the front of a Sedan, SUV and MPV at 40kph car velocity and 1.74m standing height of the cyclists.

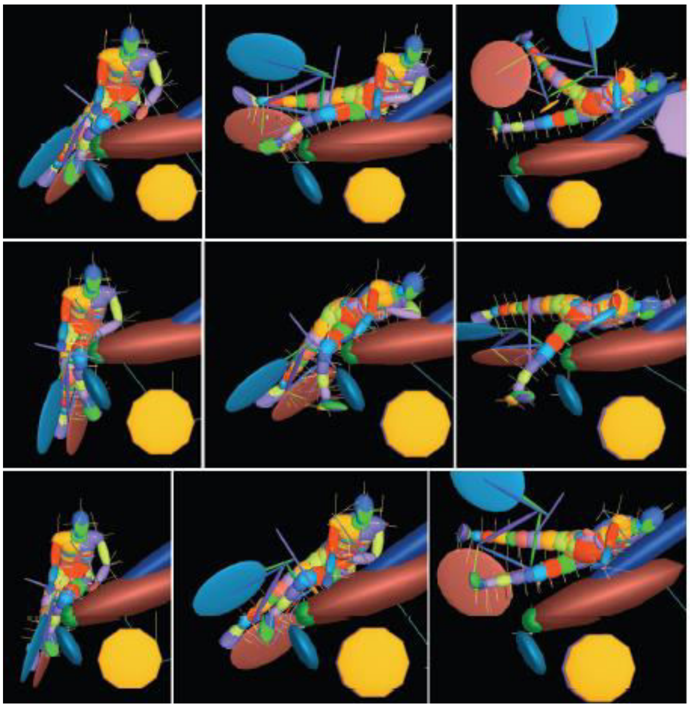


Figure 3-5: Comparison of Sedan, SUV and MPV impact [23]

Similar conclusions in literature (Multi-body/FEM simulations, physical dummy Test) can be found, when looking at the impact location differences between Sedans and SUVs. Head impact points are more concentrated on the hood than on the windshield for SUVs, compared to Sedans [13] [20] [23]. For Sedans, the pelvis can slide onto the hood, which allows travelling of the head until the windshield, which in contrast is restricted by the impact of the pelvis at the front of the car in SUV cases [20]. For the head trajectory and the final impact point, the length of the hood is another influencing factor: the longer the hood of the car, the harder head impacts on the windshield occur [23]. The length of the hood as an influence of the impact point is also reflected by another study, which executed multi-body simulations with an average Dutch male cyclist and differentiated four different car fronts (see Figure 3-6). The highest proportion of head and torso to roof impacts were associated with a front geometry of a small hood and a large windshield angle. All four geometries are common in that there were very few head impacts on the hood. Most impacts of head and torso occurred on the windshield. Impacts of the torso on the upper hood had their highest percentage for long hood and small windshield angle. [24]

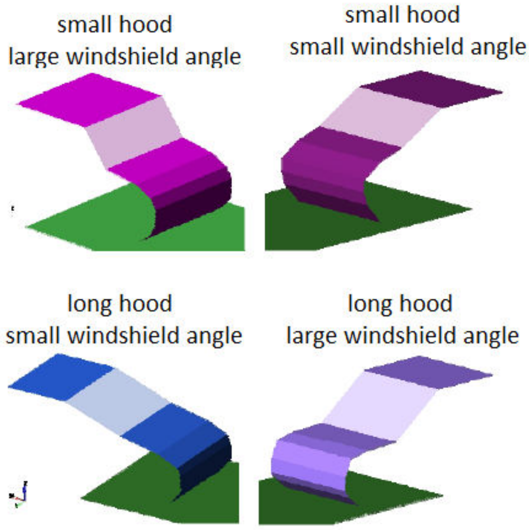


Figure 3-6: Car front geometry differentiation [24]

With the support of simulating generic finite element accidents, a Japanese study came to the conclusion that head impact points are distributed mainly over the windshield for Sedans and for SUVs impact points are distributed mainly from the upper part of the hood to the lower part of the windshield. Moreover, another result shows that if the front edge of the car is low, head peak accelerations are low as well (also Sedan and SUV front comparison). [20]

A similar approach was made within another study with the help of multi-body simulations (see Figure 3-5). A variation of car velocities (35kph, 40kph and 65kph) were applied on a Sedan, SUV and MPV and head accelerations were calculated. The results show the highest acceleration for the SUV and the lowest for the Sedan, and this was independent of changing velocity. Furthermore, an increase of head acceleration in a bicycle to Sedan case can be also noticed for increasing length of the hood [23].

3.4 Bicycle parameters

This chapter introduces those bicycle parameters, which are used as a basis for further research. Influences of the following parameters will be displayed and variations supporting accident reconstruction and analysis of the thesis will be described.

3.4.1 Bicycle velocity

According to the KfV (Kuratorium für Verkehrssicherheit), the average speed for a conventional bicycle in Austria is 18.5kph. For racing bicycles it is 24.2kph. 75% of conventional cyclists ride below 20kph, in contrast to only 20% of racing cyclists that do so. However, high velocities seem to be quite frequent for racing cyclists - about 6% of them ride above 30kph. With conventional bicycles this happens three times less. [31]
Based on analysis from German accident data (German In-Depth Accident Study – GIDAS) an average bicycle impact speed of 14kph could be found [25] [27].

3.4.2 Cyclist position

Impact speed and impact location seems to be the most influencing parameter for injuries [24]. Besides car front geometry, the posture of the cyclist on the bicycle affects the kinematics after the primary impact remarkably, especially due to differences in head height over the car surface. Moreover, it affects the impact areas of the different body parts and in fact, it causes different accelerations and impact velocities [23].
Figure 3-7 displays the three main sitting positions according to literature [23]:
A – Mountain position
B – Road position
C – Trekking position

Through multi-body simulation it was found that the most reasonable indicator for the impact velocity is the height of the cyclist's head above the hood. Therefore, the trekking bicycle, with the cyclist sitting upright, caused the greatest HIC (Head Injury Criterion). This dissimilarity from the other two sitting positions increased with higher vehicle velocity: a car velocity of 65kph resulted in a two times higher HIC value, compared to the other two positions. Road and mountain position showed similar HIC values for all simulated car velocities. However, the road position, with its slightly lower head height, had overall lower head accelerations than the mountain position. [23]

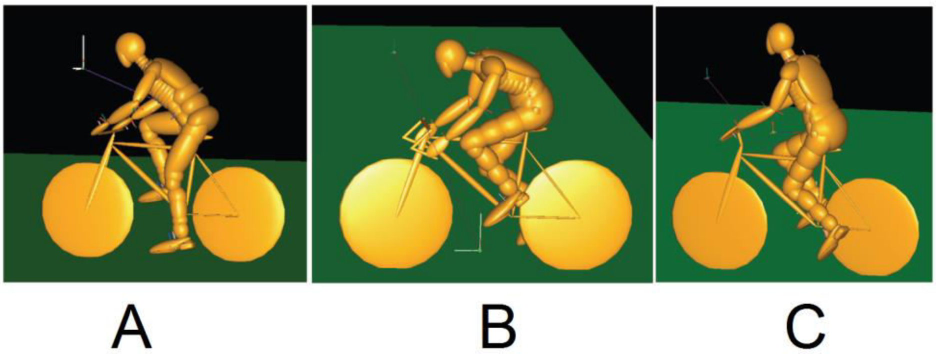


Figure 3-7: Bicycle sitting positions [23]

Another study investigated impact locations in relation to body height (male, female) and frame type (according to sitting position): Figure 3-8 shows a multi-body of an average Dutch male on a granny bike and a hybrid bike as well as a small female riding on a granny bike and a hybrid bike (with the seat height adapted to the body height).

It has been observed that the cyclist's anthropometry, as well as the sitting position, had a significant influence on the impact areas on the car front. Simulations of a side collision (comparable to the constellation in Figure 3-1) were made, with varying car velocity (30kph and 60kph). The results reveal additional information to what has been mentioned above [23]: The higher the head above the ground, the higher the impact region on the car. This means that that granny bikes, with an upright body position, tend to have a higher percentage of windshield impact, or even roof impact, than hybrid bikes. What seems to have an even stronger influence than sitting position and bicycle frame type is the height of the cyclist. Simulations of a car velocity of 30kph showed a percentage of about 30% bonnet-to-head impacts for small females, where it was not even 10% for male. Roof impact for small females was below 1%. [24]

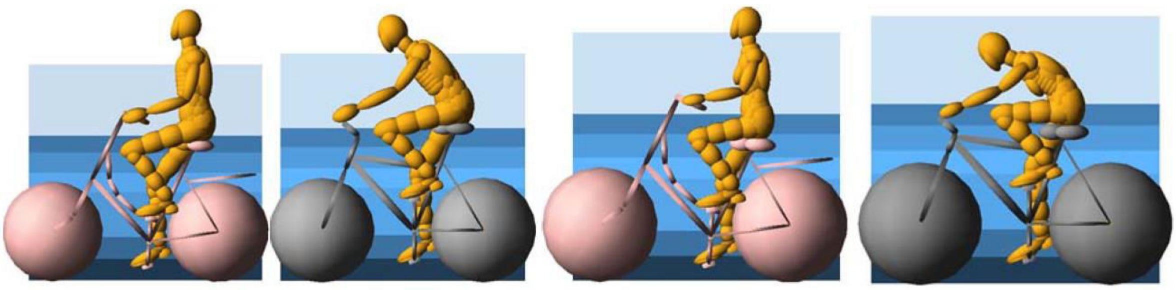


Figure 3-8: Bicycle sitting position according frame type [24]

3.4.3 Injuries

Chapter 6.5.1 will focus on the point of injured body parts and the distribution of injuries for fatal car to cyclist accidents. When reviewing literature, similar approaches can be found. A German study based on data recorded by GIDAS (German In-Depth Accident Study) from 2000 until 2012, analyzed 4245 bicycle accidents: Figure 3-9 presents the percentage of injuries to body regions, differentiated regarding car collision speed. A common trend seen is that an increase in speed is accompanied by an increase in the incidence of injuries. The lower extremities were the most frequently injured body parts, irrespective of the collision speed. The head, neck, thorax and abdomen are the most speed-dependent, with the percentage of accidents affecting these areas doubling from below 40kph to above 40kph. In contrast, the upper and lower extremities have quite stable behavior when increasing the velocity of the car. [32]

Overall the legs and the head are the most frequently injured body parts, followed by the upper limbs and thorax [17] [32].

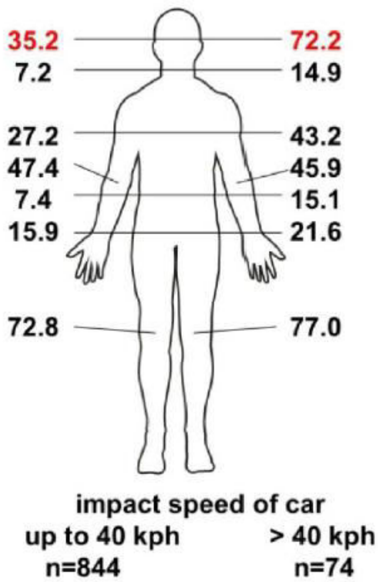


Figure 3-9: Percentage of injuries to body regions differentiated regarding car collision speed [32]

Table 1 shows the most frequently recorded injuries registered by hospitals from 2005 until 2008(EU Injury Data Base - EU IBD [33]). According to this reference about every third injured cyclist involved in accident, obtains a fracture. Also very common are contusions and open wounds.

Table 1: Types of injuries in cyclists [33]

Type of injury	Percentage
Fracture	34%
Contusion, bruise	31%
Open wound	13%
Distortion, sprain	6%
Concussion	6%
Luxation, dislocation	3%
Other specified brain injury	2%
Injury to muscle and tendon	1%
Abrasion	1%
Other specified types of injury	3%

A study based on Swedish insurance claim reports, where in 308 cases of detailed injury description were available, stated that the highest amount of injuries was not of serious nature: 667 AIS 1 and only 119 AIS 2+ injuries could be registered. From these 119 AIS 2+ injuries the most common ones were fractures (76%), predominately of upper/lower extremities and thorax. The second most frequent injuries were brain injuries (10%), with a high amount of concussions. Injuries of the lower extremities were documented most often (18%) in the AIS 2+ category, followed by the upper extremities (16%), thorax (14%) and head (9%). [34]

One study from Australia considered the cases of only seriously injured cyclists (AIS 3+) from 2001 to 2009 (hospital admissions of 1859 cyclists), and found out that the proportion of cyclists with head injuries was the greatest (about 14%) followed by the lower extremities (about 9%), thorax (about 7%) and abdomen (about 7%). [35]

An analysis of GIDAS data (German In-Depth Accident Study) from 1999 until 2008 showed an increase in percentage of severe head injuries for fatally injured cyclists (81% n=59) compared to severely injured cyclists (31% n=213) [24]. Additionally Japanese statistics demonstrated that for fatal accidents, the head is the most frequently injured body region (63%) ([36] in [20]).

Finite element simulations (800 contact points) demonstrated a high proportion of impacts on the windshield where the highest HIC values are represented by impacts with the windshield frame [20]. This goes hand in hand with accident reconstructions from another study (24 cases), which also showed a high proportion of windshield impacts and a distribution of all AIS 3+ injuries around the windshield frame and roof edge [17].

Based on the damaged car parts and accident reconstructions from Finland (23 cases), it has been shown that the principal cause of death resulted from impacts with the windshield (35%), followed by the windshield frame (22%) and the hood (9%) [37].

However, the impact with the ground following the first impact with the car cannot be negated. The proportion of injuries caused by ground impacts should be considered as well: 20% of all severe injuries are caused by the secondary impact to the ground, according to GIDAS data from 1999 to 2008 [24] and 14% of all AIS3+ head injuries (GIDAS 1999-2010) [27].

3.4.4 Helmets – head injury prevention and usage

To test the impact differences associated with wearing a bicycle helmet, several experimental and simulative approaches have been performed. Drop tests of dummy heads and human cadaver skulls, equipped with and without helmets, showed that linear head accelerations and HIC values can be drastically reduced by the use of helmets for all drop heights used in the tests [38] [39] [40] [41], which strongly implies lower risk for brain injuries [39] [40]. Drop tests of a Hybrid III dummy head form performed on three different head locations (lateral, front and crown), for example, showed a reduction of the HIC value up to 70% for the helmed head form. For angular accelerations of the head, a reduction could also be observed when a helmet was used. However, the angular acceleration reduction was much less evident than linear accelerations. A multi-body simulation of a rear end collision of a car into a bicycle resulted in significantly higher angular head accelerations of helmed cyclists, compared with a cyclists without a helmet (linear accelerations lower with helmet) [42]. Moreover, another study using a front collision of a helmeted Hybrid III dummy head against a variation of foams (velocity ranging from 5 to 10 m/s), came to a similar conclusion: For four of nine the foams (varying in stiffness), the angular head acceleration was higher for the helmeted head form (linear accelerations lower with helmet for all foams) [43].
Another study focused more on head impacts (head form with child helmet) on the surface of the car. Results show a higher HIC value for impacts without helmet with the hood, roof header and especially a-pillar. On the other hand impacts with the windshield caused a higher HIC value for child helmet equipped head forms, compared to no helmet use. This was explained by the different glass fracture patterns, which were observed for helmet and no helmet. [44]

The KfV (Kuratorium für Verkehrssicherheit) observed 2009 in total 19.306 cyclists, considering their helmet usage in all provincial capitals of Austria at 2 different locations each (see Figure 3-10). The result of these observations is that 33% of females and 37% percent of males used a helmet. When differentiating into 5 different age groups (below 6 years, between 7 and 15 years, between 16 and 30 years, above 60 years), it was seen that a high percentage of both male and female children below 6 years used helmets (89%), without gender differences. With increasing age, the number of helmet using cyclists decreased and the differences between male and female became more evident. [45]

Since 31.3.2011, children below 12 years must wear a helmet according to Austrian law *("§ 68 StVO Verhalten der Radfahrer (6)")*.

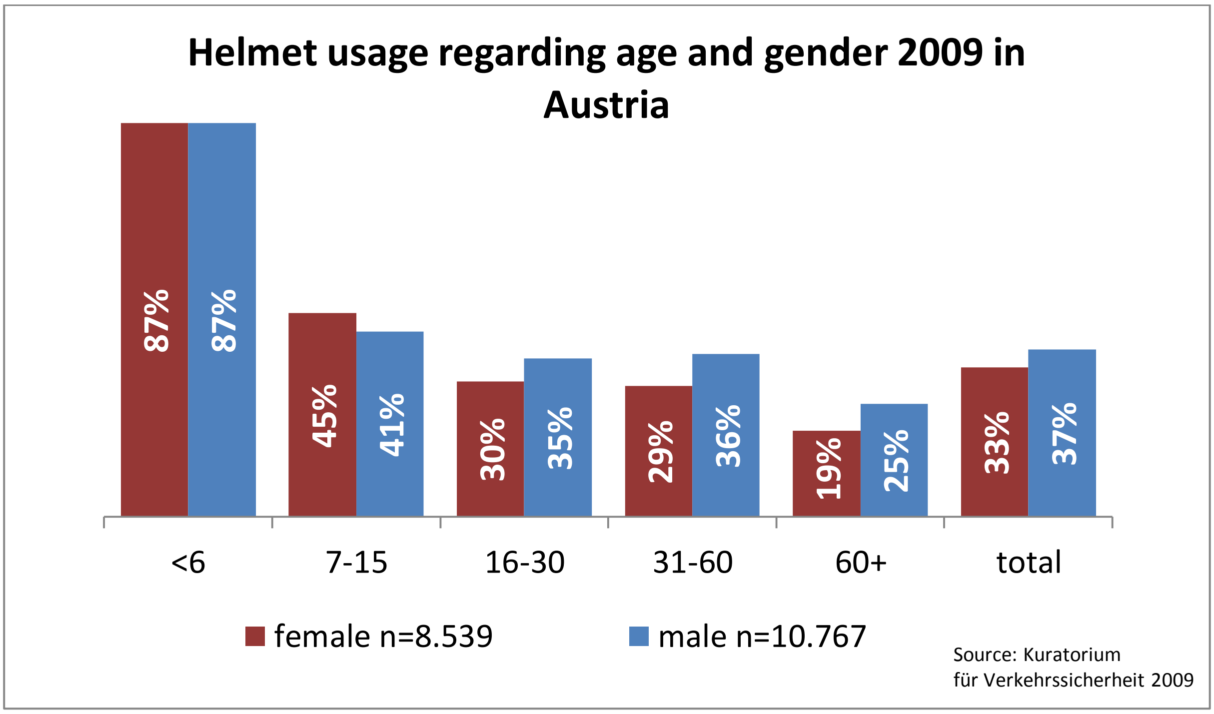


Figure 3-10: Helmet usage regarding age and gender 2009 in Austria [45]

The percentage of helmeted cyclists was not always as high. As mentioned before, in 1994 it was only 6% and then increasing year by year to 22% until 2006. [45]

4 METHODOLOGY

The foundation of this study rests on the documentation of 49 fatal car to bicycle accidents occurring in Austria between 2003 and 2008, for accident reconstruction and further analysis, plus 41 additional cases that have already been reconstructed (90 accidents in total: 63 fatal and 27 non-fatal). Another part of this analysis deals with a higher quantity of national bicycle accident documentation from Statistik Austria [4], which also includes not fatally injured cyclists. So 55.641 bicycle accidents from 2002 until 2011 could be taken into consideration.

Supported by national accident documentation, car to bicycle accidents have been reconstructed. The available material and the gained information from reconstructions (using a multi-body accident simulation tool – PC-Crash) represents together the input for an in-depth database (CEDATU). The next step was creating analysis out of this database. The results will be demonstrated in the next chapter.

Moreover 7 out of the 49 reconstructed bicycle accidents have been selected for further Finite Elements simulations.

4.1 CEDATU

The CEDATU is a Central Database for In-depth accident study developed and still extending at the Vehicle Safety Institute in Graz. Currently it contains about 3000 accident cases, starting from 2003 and still expanding at a rate of up to 200 cases each year. About 4% of these cases include bicycle accidents, wherein more than 90% of these are fatal. This database provides a retrospective accident analysis of road accidents based on court documents; including vehicle data, infrastructure, participant data, injury, etc. This fundamental information also includes accident data acquired from reconstructions (e.g. pre-crash velocities). Furthermore input fields relating to Statistic Austria [4] are available, to offer linked analysis to national statistics. In total, more than 800 input fields are available for each case. [46]

With this acquired data from court files and accident reconstructions, a creation of new statistics and analyses is viable. Accordingly, this thesis makes use of this data and from additional specialized data acquired from a reconstruction of 49 accidents out of the CEDATU.

4.2 Accident reconstruction

Upon arriving at the scene of an accident, it is challenging for police to find out what exactly happened, who is the malpractice participant and why this accident actually happened. Therefore, skid marks, as well as further measurements and information get collected and participants get interviewed. With this information pool, accident reconstructions can be built up and give conclusions to unclear scenarios. For virtual reconstructions of the accidents the software PC-Crash^{TM} has been applied. Within this software a multi body system of the cyclist and the bicycle supported the simulation of realistic kinematics and hence, displays accurate real end positions.

4.2.1 Reconstruction process and required material

Figure 4-1 illustrates schematically the process of a bicycle to car reconstruction with PC-Crash^{TM} and the necessary input.

Depending on the accident, there is more or less documentation available. Listed below is the content that effectively supports the reconstruction [47]:

- Pictures of the scene of accident
- Overview and detailed pictures of the car damages
- Sketch of the end positions and skid marks
- Liquid marks (oil, fuel)
- Broken glass fragments and other broken material (windshield, lights)
- Record of interrogation

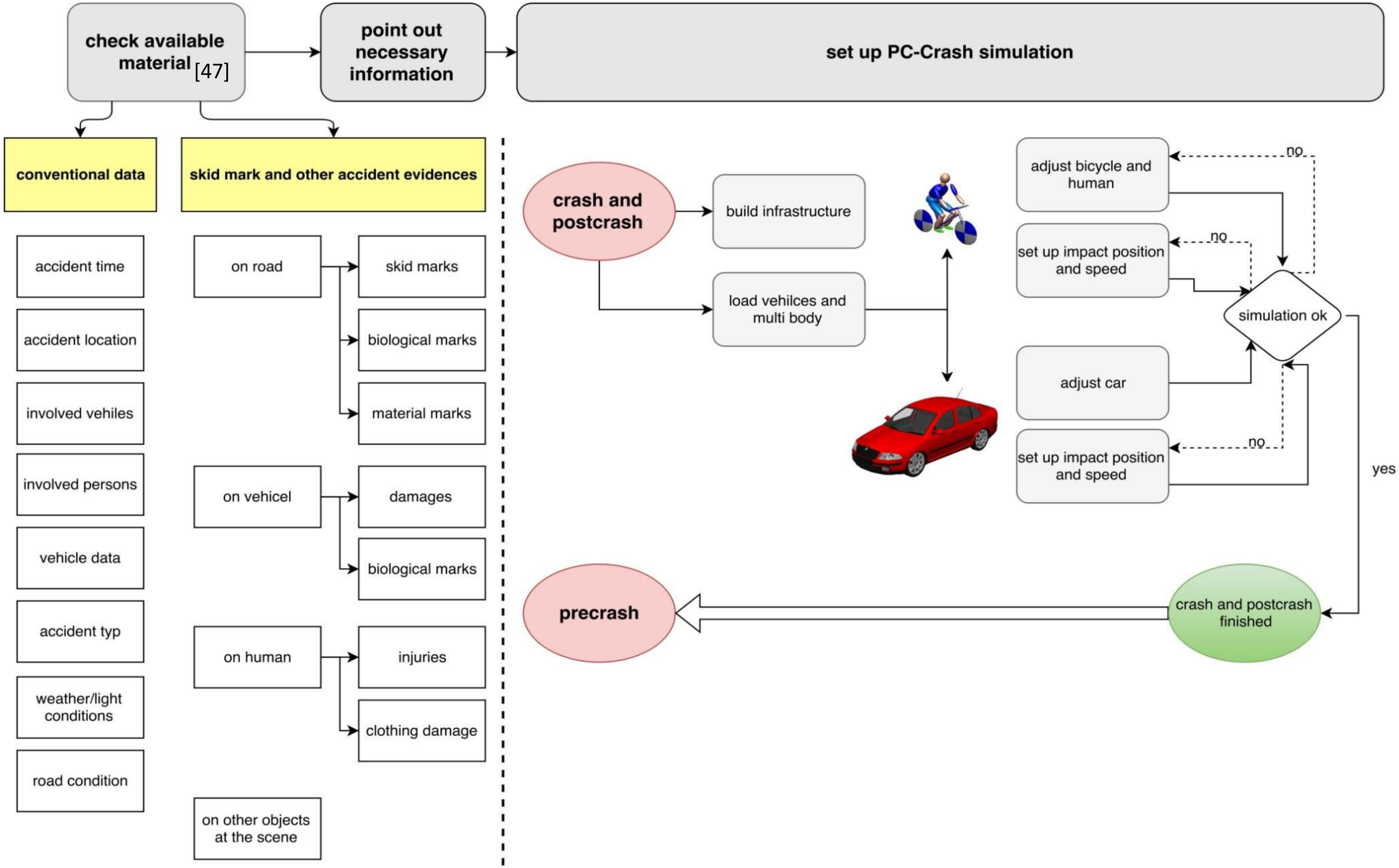


Figure 4-1: Reconstruction process flow and reconstruction material

4.2.2 PC-Crash™ and the multi-body model

PC-Crash™ is a numerical simulation software, used frequently for traffic accident reconstruction. With its extensive database of car models - including individual DXF car surfaces for simulating pedestrian, cyclist and motorcyclist accidents - it offers numerous accidents the possibility for realistic reconstructions. Proper infrastructure is created with the help of streets with a three-dimensional variation (including embankments), friction coefficients and graphical surroundings that can be adapted to the real accident case. In the reconstruction of bicycle accidents, there is the option to work with multi-body systems for the crash phase and an abstracted version of the cyclist is available for pre-crash phase or accident analysis, where an accurate kinematic impact is not required.

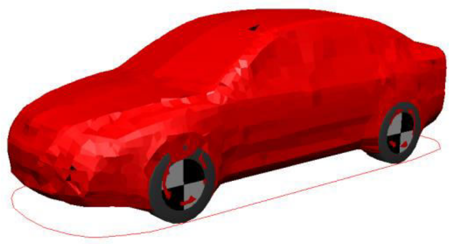


Figure 4-2: Vehicle DXF surface

When it is necessary to simulate the dynamic motion of a cyclist crash, then it is no longer adequate to use a rigid system for the cyclists anymore. Then the multi-body system finds application instead, which consists of unmovable parts, represented by ellipsoids and linked with twistable joints (e.g. spherical joint for pelvis or hinge joints for the knees). The multi-body system allows assigning injured body parts of the cyclist to areas of the car. Moreover, certain sitting positions can be adjusted and body proportions and body part dimensions, as well as weight, can be set up individually. Friction coefficients (part-car and part-ground), moments of inertia and body part stiffness are other features that can be used for individualization of the multi-body system. The possibility to change the weight, height, sitting position of the cyclist and geometry of the bicycle, can be useful for accurate simulations of bicycle accidents. Standard values of body part proportions of the human multi-body model are based on a German anthropometric study with the title "Internationaler Anthropometrischer Datenatlas" and can be applied if there is no specific body measurement available [48]. [49]

Figure 4-3: PC-Crash abstracted bicycle model, graphical model and multi-body system

4.3 FEM case selection

For further detailed analysis by finite elements, specific, already reconstructed accidents have been selected.

As the multi body system, used for this thesis, can only be seen as an abstract model of the human body, a FE model is expected to deliver more accurate and realistic results. Using human body models like for example THUMS (total human model of safety) enables a more detailed analysis of the response of the bicyclist to the impact. Injury metrics like strains in the bones or brain tissue can be analyzed and correlated with the real world injuries to gain a better understanding in injury mechanisms of bicycle crashes. These FE model simulations should be executed with limitations, choosing only relevant accidents and accidents that are feasible to simulate. Accordingly it was planned to select at least 5 relevant accidents from the 49 reconstructed ones. Afterwards a preparation for the simulations has been accomplished, by providing collision parameters (found through multi body reconstructions and accident analysis), which are necessary for the FE simulation set up.

The following filter criteria were used for the selection:

- Medical report available (information of resulting injuries is required)
- Year of manufacturing of the car greater or equal than 1990
- Cyclist age lower or equal than 70 years
- Collision velocity of the car less or equal than 70kph
- Car front collision

This limitation resulted in a reduction to 8 car to bicycle accidents. One of these included a pre conflict of the cyclists, where the cyclists fell from his bicycle in a curve because of too high velocity and collided after sliding on the ground with the lower front of the car. Thus 7 accidents remained to be valuable for FE simulation.

The following parameters were provided for each accident:

- Car model, velocity and pre brake conditions
- Bicycle model/dimensions, velocity and impact angle
- Human height and weight
- Pedal Position and body posture
- Coordinates of bicycle and car
- Multi body impact region results
- Pictures of car damage

- Cyclist’s injury list
- Related statistics

A detailed selection list and descriptions of these 7 accidents can be found in the appendix.

4.4 Introduction of analyzed parameters

4.4.1 Car front geometry and impact regions

As mentioned previously the car front geometry plays a crucial role when it comes to pedestrian and bicycle accidents.

Car front classifications used in this study are derived from an APROSYS [22] classification and therefore divided into:

- Supermini/Small MPV Cars (e.g. Renault Clio IV)
- Large and Small Family Cars (e.g. VW Golf VII, VW Passat 2012)
- SUVs (e.g. BMW X5 F15)
- MPV/1-Box (e.g. VW Sharan II)
- Roadsters (e.g. BMW Z4 E89)

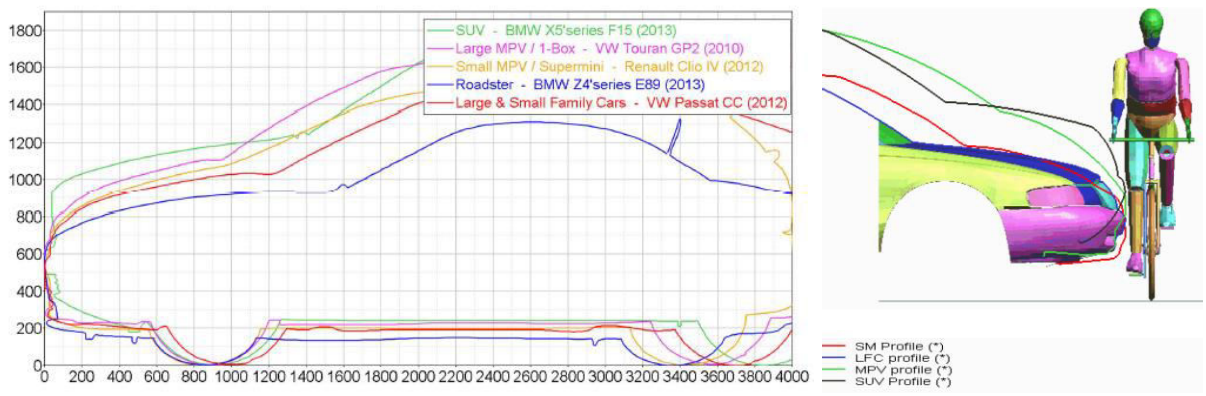


Figure 4-4: Car geometry classification [22] [13]

Reconstructed car to bicycle accidents were analyzed using the impact regions of the cyclist on the car front. Accordingly the front of the car has been divided into six regions ranging from the bumper to the roof of the car. Starting from the top, the divided regions can be explained in words as followed:

- Roof
- Upper half windshield (including a-pillar)

- Lower half windshield (including a-pillar)
- Upper half hood (including fender)
- Lower half hood (including fender)
- Vehicle front (including bonnet leading edge and bumper)

Moreover, a differentiation between the left middle and right front of the car is given (divided into thirds).

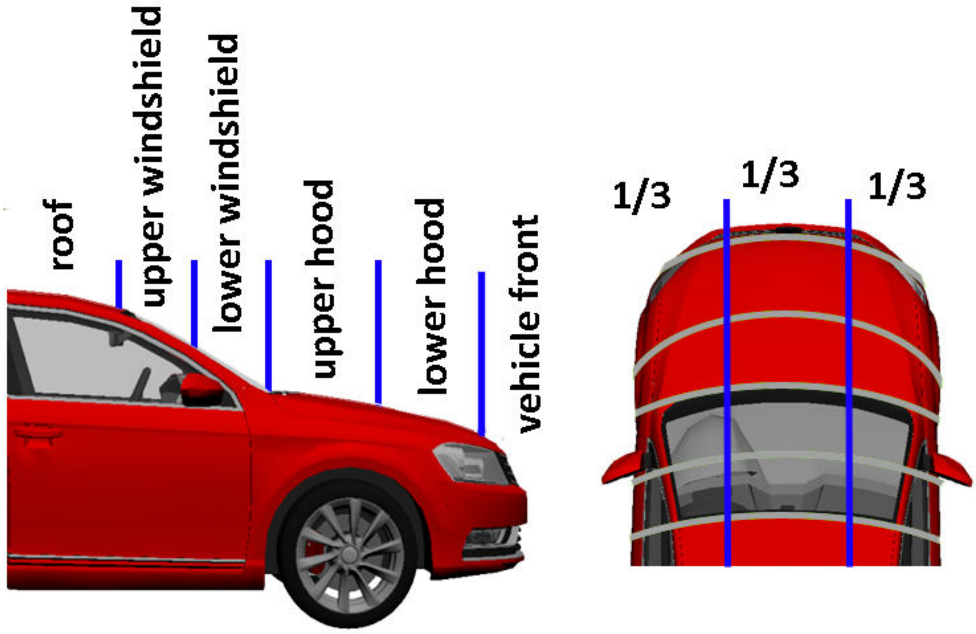


Figure 4-5: Car impact region separation

4.4.2 Bicycle frame

Figure 4-6 visualizes four main bicycle frame types according to literature [50]. These types have already been applied to previous projects of the Vehicle Safety Institute in Graz (Hainisch, 2015 [51]) and will be also used for differentiating bicycles in this thesis.

A distinction has been made between:

A – Diamond Frame

B – Trapeze Frame

C – Swan's Neck Frame

D – Wave Frame

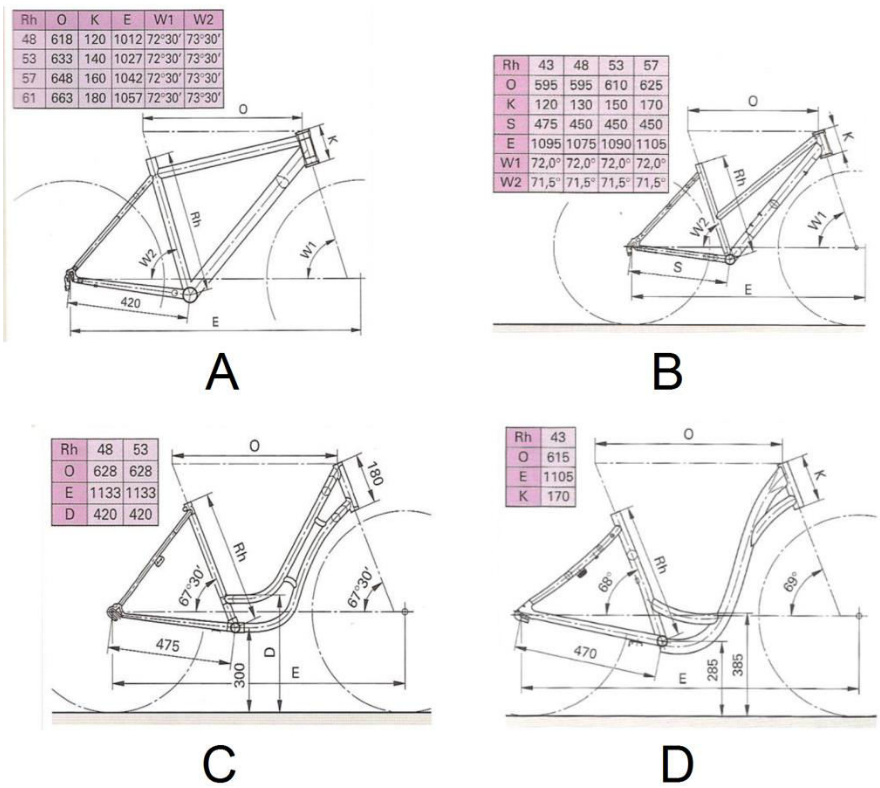


Figure 4-6: Bicycle frame types [50]

4.4.3 Collision Deformation Classification - CDC

The CDC indicates the region and the maximum extent of vehicular penetration, when involved in an accident. It can be expressed by a 7-digit code. Like the AIS, the CDC provides a standardized system for describing accurate car surface damage, and therefore, will be also used later in chapter 6. One example of a CDC code is given below. Figure 4-7 illustrates and explains the following numbers and letters from the example. [52]

Example:

12FDEW3

11 = **Clock direction of PDOF**

F = **Area of deformation**

Y = **Specific location or lateral area**

M = **Specific vertical area**

W = **Type of damage distribution:** wide impact

3 = **Maximum extent of penetration** on a scale of 1-10:

Figure 4-7: CDC damage example

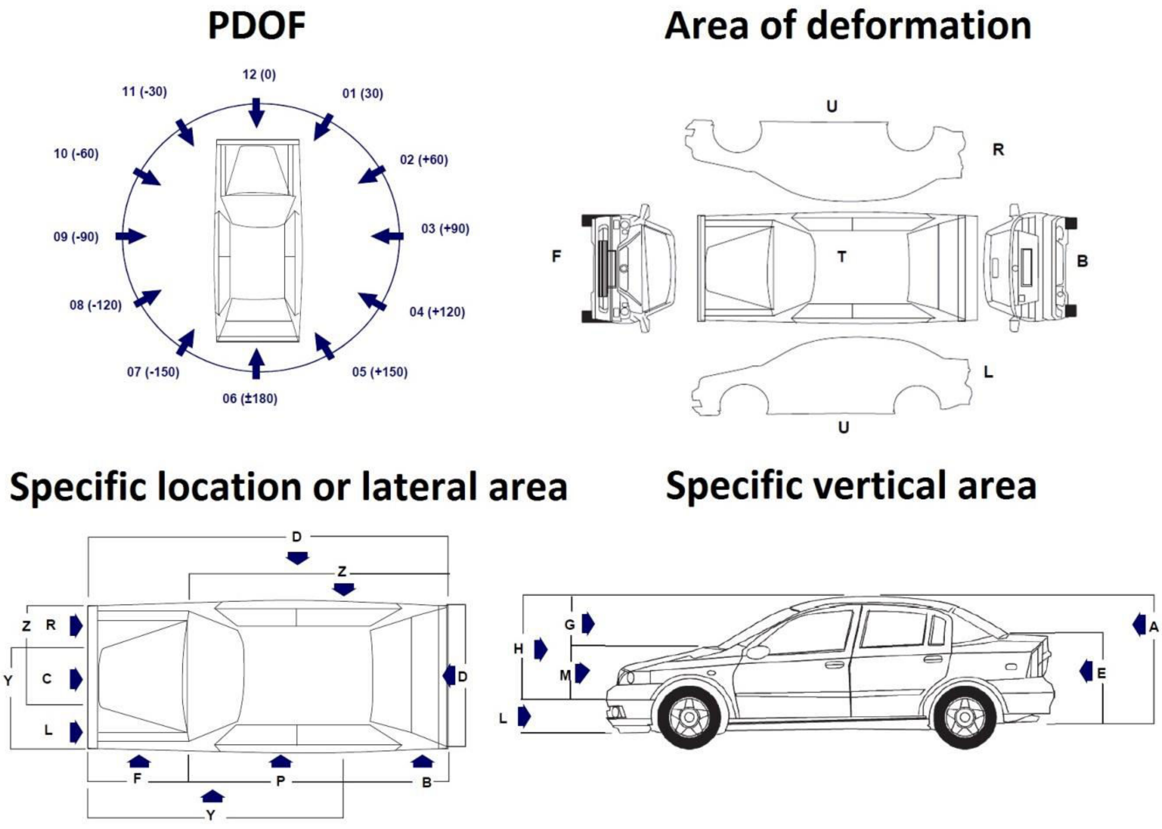


Figure 4-8: Collision deformation classification [52]

PDOF stands for Principal Direction of Force and means the direction of the force that caused the crush and sheet metal displacement. [52]

4.4.4 Abbreviated Injury Scale - AIS

The AIS (Abbreviated Injury Scale) is an internationally used severity classification for single injuries on anatomical aspects for a certain parts of the body. The AIS employs a global ranking system, with the intent of making injuries comparable to each other. The first official AIS codebook was published in 1976 by the "Association for the Advancement of Automotive Medicine" (AAAM), and has since been continually updated (e.g. AIS90, AIS2005). The most recent revision is the AIS2005, updated in 2008, which is a 7 digit code including information about the injured body part, type of injury and severity of the injury. Another value, the MAIS (introduced with the 1980 revision), describes the maximum AIS of one person involved in an accident. [53]

Apart from the AIS, there are other approaches for a standardized injury classification (examples):

- Injury Severity Score - ISS (based on AIS-76)
- Trauma Score - TS

- International classification of diseases - ICD
- Glascow Coma Scale - GCS
- Hannover Polytraumaschlüssel - PTS

Other challenges of the AIS are: considerations of interactions of multiple injuries and their influence on each other and late complications, as well as injury classification in relation to age. [53]

AIS98-Code example:

853422.3 – Tibia shaft fracture open:

8 = Body Region: Lower Extremities

5 =Type of Anatomic Structure: Skeletal

34 =Specific Anatomic Structure: Tibia

22 = Level of injury: Shaft

.3 = Severity score (AIS): serious

→translated into AIS2005: 854222.3

Table 2: Injury severity and injured body parts (AIS90/98, AIS2005/2008) [53]

AIS-Code	Severity Score	AIS-ID	Body region
0	No injury	**1**	Head
1	Minor injury	**2**	Face
2	Moderate injury	**3**	Neck
3	Serious injury	**4**	Thorax
4	Severe injury	**5**	Abdomen
5	Critical injury	**6**	Spine
6	Maximum (currently untreatable)	**7**	Upper extremity
9	NFS (not further specified)	**8**	Lower extremity
		9	External and other trauma

5 LIMITATIONS

As mentioned previously, the CEDATU contains about 4% bicycle accidents, in which 90% of those CEDATU accidents are fatal (including deaths at the scene and deaths during medical treatment within 30 days). The next chapter focuses on the CEDATU data of fatal, severe and slight injuries caused by a crash with a passenger car - accidents with trucks, motorcycles and other vehicles are neglected. This reduces the amount of CEDATU accidents, used for statistics, down to 90 car to bicycle accidents (including 63 fatalities).

For the analyzed injuries it was essential to have documented injury description, diagnosed by a doctor, available in the form of an autopsy or injury report. From the 49 bicycle accidents, which were reconstructed and further analyzed, 26 remained to be acceptable for injury analysis.

The car with the earliest year of manufacturing was registered in 1984 and the latest in 2006. From 2006 to now continuing on into the future, deviations regarding impact zones and injuries can be assumed, due to the ongoing development of car front designs [32]. Moreover, it should be mentioned here additionally, that the reconstruction software PC-Crash™ does not always provide the exactly needed car surface. In these cases similar models were used (in 12% of all reconstructed accidents).

In the occasion that exact bicycle geometric measurements are unavailable, there is often a subjective assignment required, using bicycle frame types (assigned according to picture).

Arrows from the accident types, mentioned in Table 5 (Appendix) and in the chapter of the results, seem to be often quite clear to whom they belong to (bicycle or car). However these statistics do not make any differentiation between car and bicycle, which means that there is no explicit assignment available.

6 RESULTS AND DISCUSSION

Based on the previous content, the chapter "Results and discussion" is dedicated now to deeper analysis of bicycle to car accident, with the support of data from CEDATU and specific data from accidents reconstruction generated from CEDATU cases, along with data from national statistics (Statistik Austria [4]).

Accident parameters, such as the age of cyclists, time and location of the accident, car and bicycle types, helmet usage and malpractice participant are going to be covered first. Afterwards common accidents scenarios will be described in general and split up into cross section and longitudinal accident types as well. Finally this chapter deals with impact regions and injuries. Specific impact regions of the car that are usually involved (specialized on the car front) will be identified, in addition to which injury patterns can be determined and what are sources of these injuries. Discussions can be found for each chapter, to evaluate and compare the discovered content.

6.1 Accident Reconstruction Examples

To obtain a better practical understanding of real world car to bicycle accidents, the pre-crash circumstances and the resulting injuries and car damages of two chosen accidents are demonstrated. For both accidents there was sufficient documentation available to describe them in detail. Concerning impact location, impact velocities, impact constellations, injuries and vehicle geometries they represent a large number of car to bicycle accidents from CEDATU, as well as parameters mentioned in the literature chapter previously.

6.1.1 Example A

Table 3: Basic values real world accident example A [4]

Car		Cyclist	
Model	Skoda Octavia 81kW	Bicycle type	Kids bike
Front geometry	Family Car	Gender	Male
Year of manufacturing	1998	Age	6
Initial speed	45kph	Height and weight	130cm / 29kg
Collision speed	45kph	Collision speed	10kph

Circumstances of the accident

The accident occurred in the evening in May on an urban road. The accused passenger car was travelling at a speed of 45kph, approaching to a residential area. A natural fence restricted the view of the right side of the road, providing limited visibility for the driver (see Figure 6-1). Meanwhile, a mother with her child (without helmet) prepared to embark on a bicycle trip. When the mother turned towards the garage, she left her child unattended. At this moment, the child left the garage entrance on his bicycle and entered the road. When the boy was already about two meters away from the right boundary line of the road, he collided with the right front-side of the non-braked car. 6 meters after this first impact, followed by a wrapping around of the body on the car surface and a final rolling and sliding on the road, the child remained on the ground. Three days later the child died in hospital, due to his severe injuries.

Figure 6-1: 3D model of the infrastructure of accident example A [54]

Kinematics

In this accident the bicycle approaches from the right side, much like 42% of all bicycle accidents (according a German study [21]). Figure 6-2 illustrates a scene of the kinematic motions during the crash and the resulting damaged car regions. The first impact point occurs between the left femur of the child and the right fender of the car. A decentralized impact on the bicycle front causes a rotational moment along the longitudinal axis of the cyclist. Additionally, orthogonal velocity vectors forced the upper body to impulsively come into contact with the upper part of the fender and the right edge of the hood. Thus the thorax of the child impacted at about 80ms after the first contact with the car, resulting in a lung contusion. The friction between the car surface and the upper body, lead to the child being rotated through his longitudinal axis further and colliding finally, after releasing forces on the thorax, with his head on the a-pillar of the car. This impact caused a traumatic brain injury and was causative for the following death of the boy.

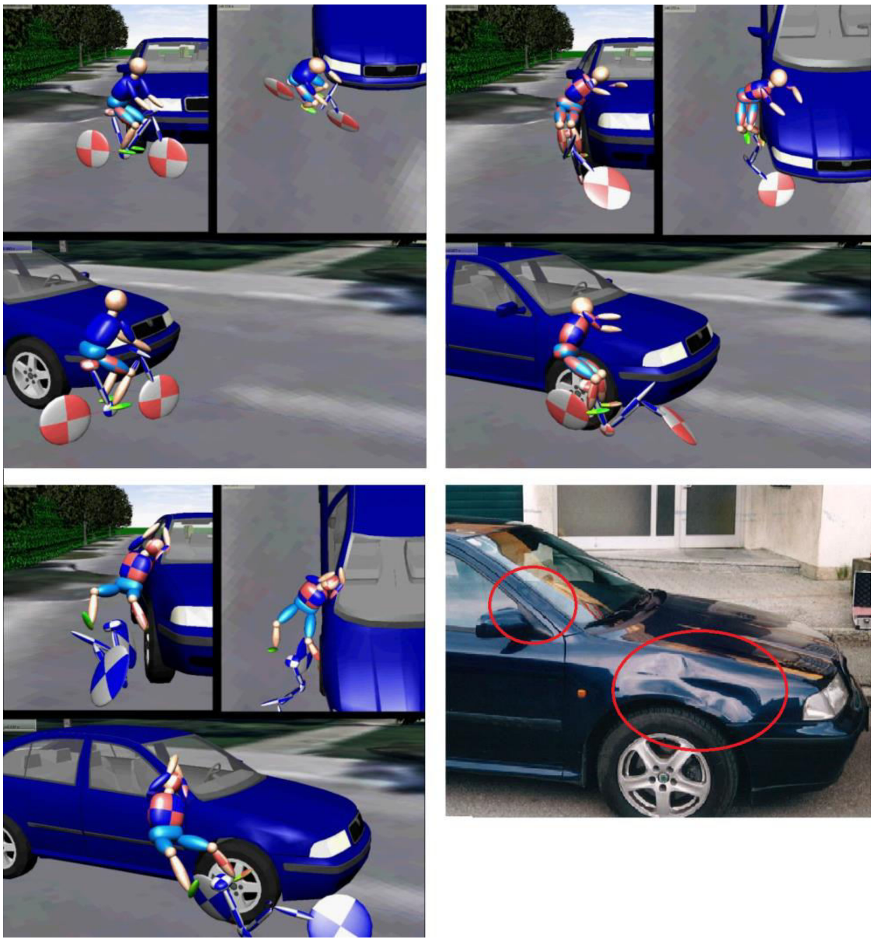


Figure 6-2: Cyclist impact points and damages on the car of accident example A

6.1.2 Example B

Table 4: Basic values real world accident example B [4]

Car		Cyclist	
Model	Honda CR-V 108kW	Bicycle type and frame	Racing / diamond
Front geometry	SUV	Gender	Male
Year of manufacturing	1999	Age	18
Initial speed	30kph	Height and weight	181cm / 75kg [55]
Collision speed	45kph	Collision speed	18kph

Circumstances of the accident

The accident occurred in the afternoon in August on a rural road. The accused passenger car and another vehicle were following a tractor for several minutes at a speed of 30kph. At the end of a bend, 2.2 seconds before the crash, the driver of the Honda CR-V accelerated his car to 45kph to overtake the tractor. The driver didn’t recognize three oncoming racing cyclists approaching with a speed of 30kph and collided with the second one. A skid mark of 8.5 meters from the brakes of the bicycle could be identified, drawing the conclusion that there was an impact velocity of 18kph with a braking deceleration of 2.3 m/s² (assumption of single back brake only, to keep control over the bicycle) [56]. Due the impact on the car front, the cyclist was thrown laterally into the grass next to the road and died afterwards during medical treatment at the scene.

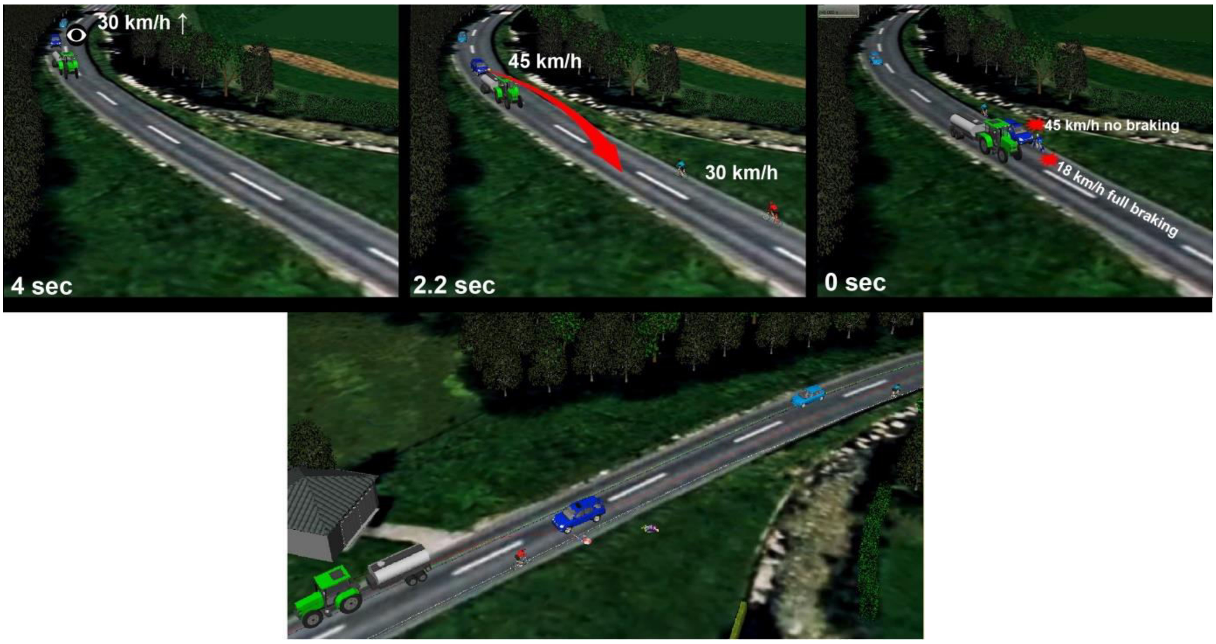


Figure 6-3: Sequence and end positions of accident example B

Figure 6-4: Accident perspectives for accident example B

Kinematics

Accident B is part of the front-to-front collision group, which makes up a percentage of 13% of all bicycle accidents [21]. The first impact point occurred between the left front of the car and the front wheel of the bicycle. Consequently high impact forces caused a deformation of the bicycle rim and torsion of the wheel to the right, in relation to the angle of the handlebar. Afterwards the knees of the cyclist collided with the bumper of the car, followed by a twist of the upper body towards the hood and windshield. Finally the head and the thorax hit the windshield in the left lower corner.

These given impulses threw the cyclist slightly to the side of the road into the grass, where he remained lying with a polytrauma and died during medical treatment.

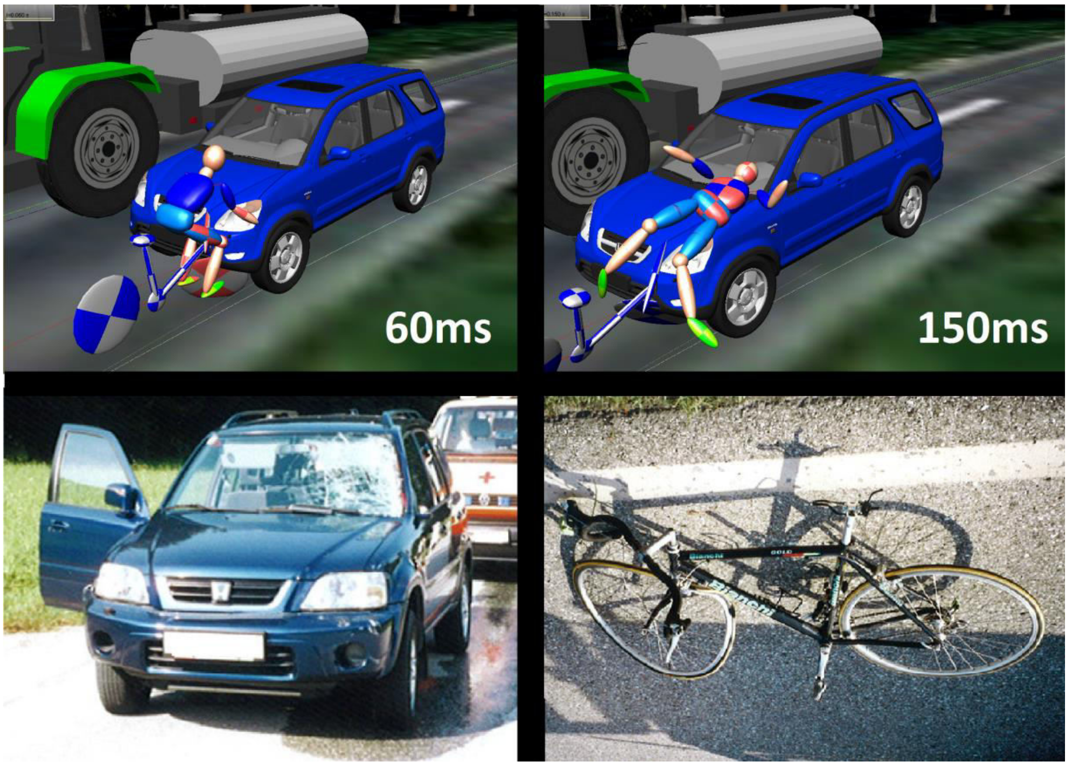


Figure 6-5: Accident crash phase and damages on the vehicles for accident example B

6.2 Parameter Analysis

6.2.1 Age Perspective

In Austria, from 2002 to 2011, 55.140 cyclists got slightly or severely injured and about 501 died at the scene or within the following 30 days. Figure 6-6 and Figure 6-7 divide these injuries into 20 age groups, increasing by five years each. Cyclists from 10 to 14 years of age were by far the largest group (9,8%), with 5.709 males and females injured. This group also has the highest percentage of males, at 71%. In general, males are more often involved (at least slightly injured) in bicycle accidents than females (62% male, 38% female). The second largest injury group is from 40 to 44, followed closely by 45 to 49 year old cyclists. Cyclists older than 49 and younger than 40 are less often injured: a decrease with higher age and lower age can be noticed. Below 5 and above 90 years, cyclists were rarely injured (161). The highest percentage of the population is in the 40 to 44 year age group. There seem to be a relationship between the age of the population and the age of the injured cyclists

- for some age groups with higher deviation and for others, lower. In taking a closer look at the average Austrian population between 2002 and 2011, it can be recognized that very few people exist in this high age category. However, for younger riders, there is a high percentage of the population. For both the younger and older age groups, (beyond 15 and above 80) the percentage of population in comparison to the injured cyclists has a strongly deviates, which should be discussed later on. [4]

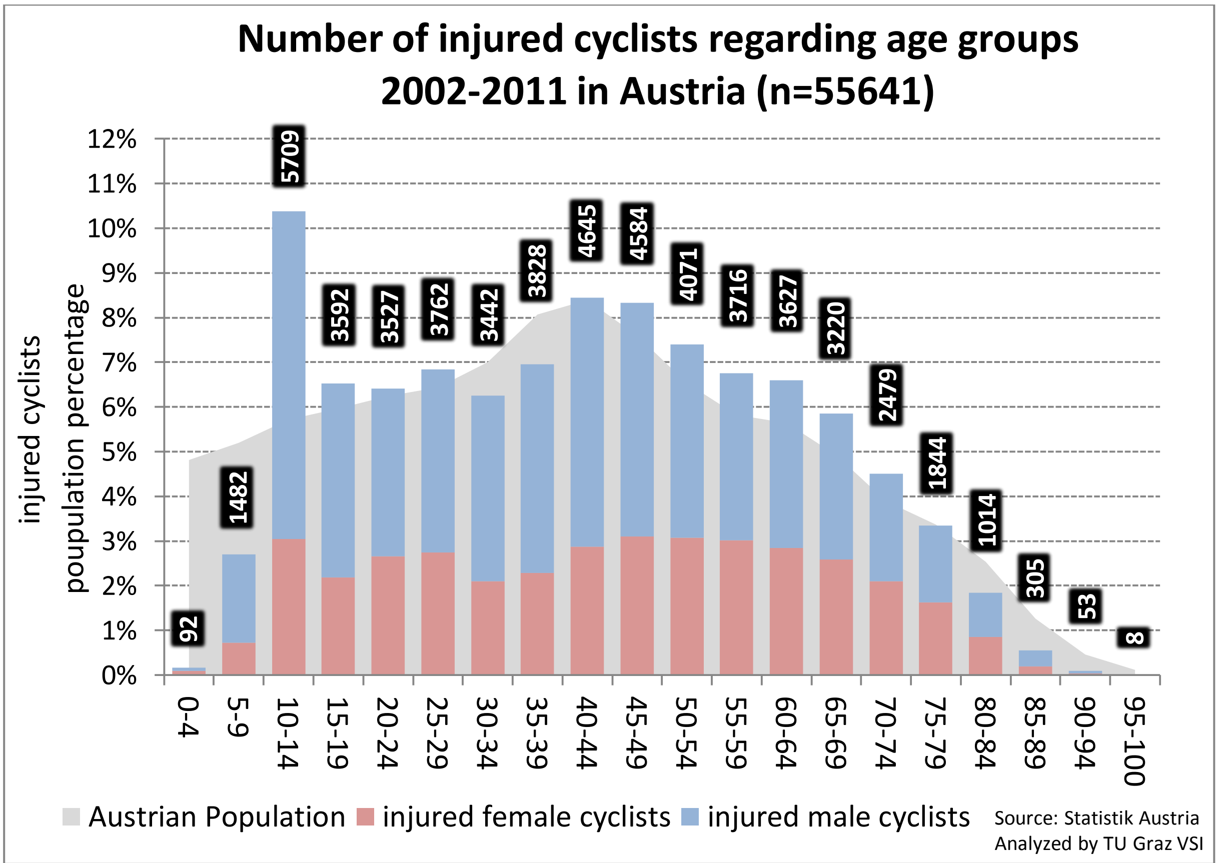


Figure 6-6: Number of injured cyclists regarding age groups 2002-2011 in Austria [4]

There is a completely different picture in regards to fatal injuries, as seen in Figure 6-7. The amount of cyclist fatalities peaks at the age of 70 to 74 with 61 cases, followed closely by 65 to 69 and then by those aged 60 to 64. Cyclists between 60 and 90 make about 56% of all fatalities, were in contrast cyclists under 20 make only 7%. In 71% of all fatalities males were riding the bicycle. [4]

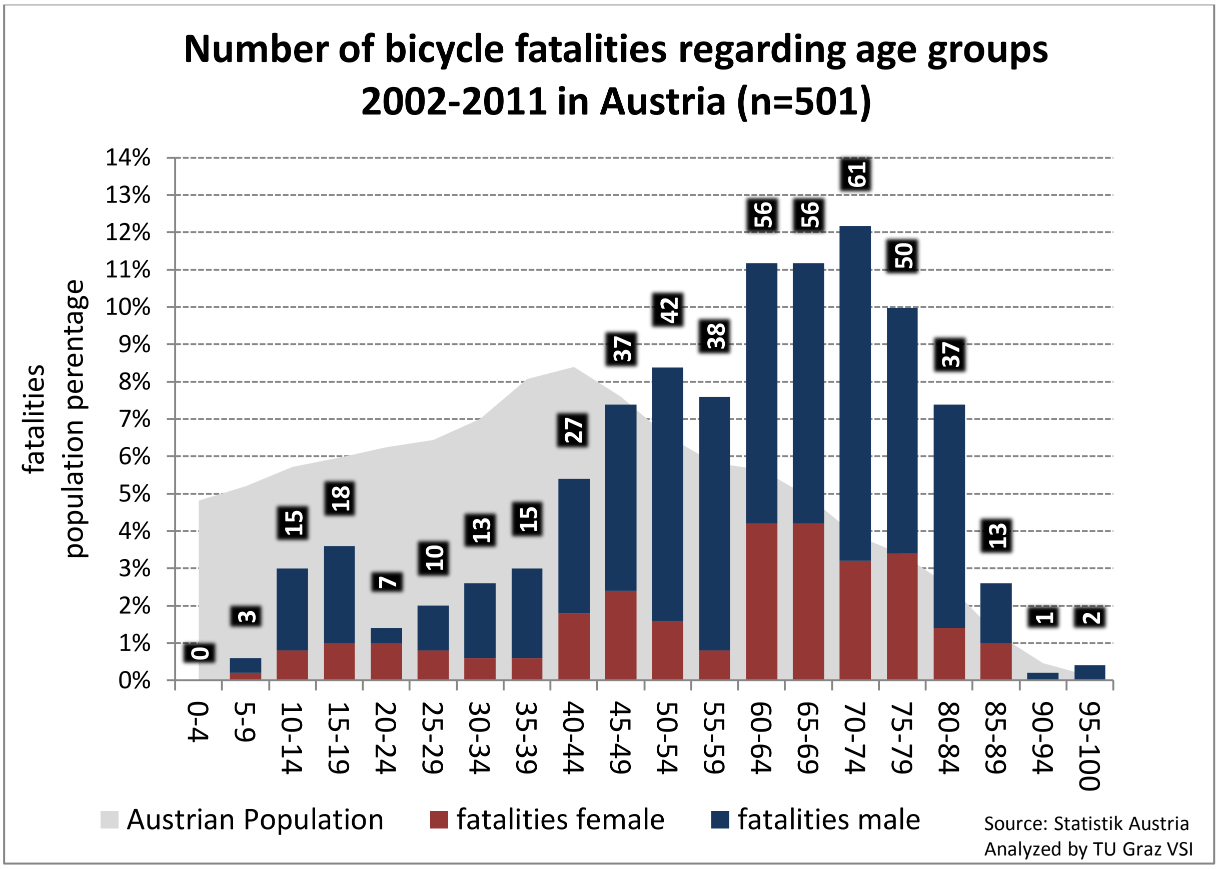


Figure 6-7: Number of bicycle fatalities regarding age groups [4]

6.2.2 Further Parameters

Figure 6-8 illustrates the slightly, severely and fatal injured cyclists, along with their accident location in Austria from 2002 until 2011, with a total number of casualties being 55.641. Generally speaking, about 77% of these occurred in urban areas. The percentage of rural areas accidents increase when comparing slightly injured cyclists (14%) to severely injured cyclists (29,1%). However, fatal accidents in rural areas are much more common, making up more than a half of all incidents at 50,3%. [4]

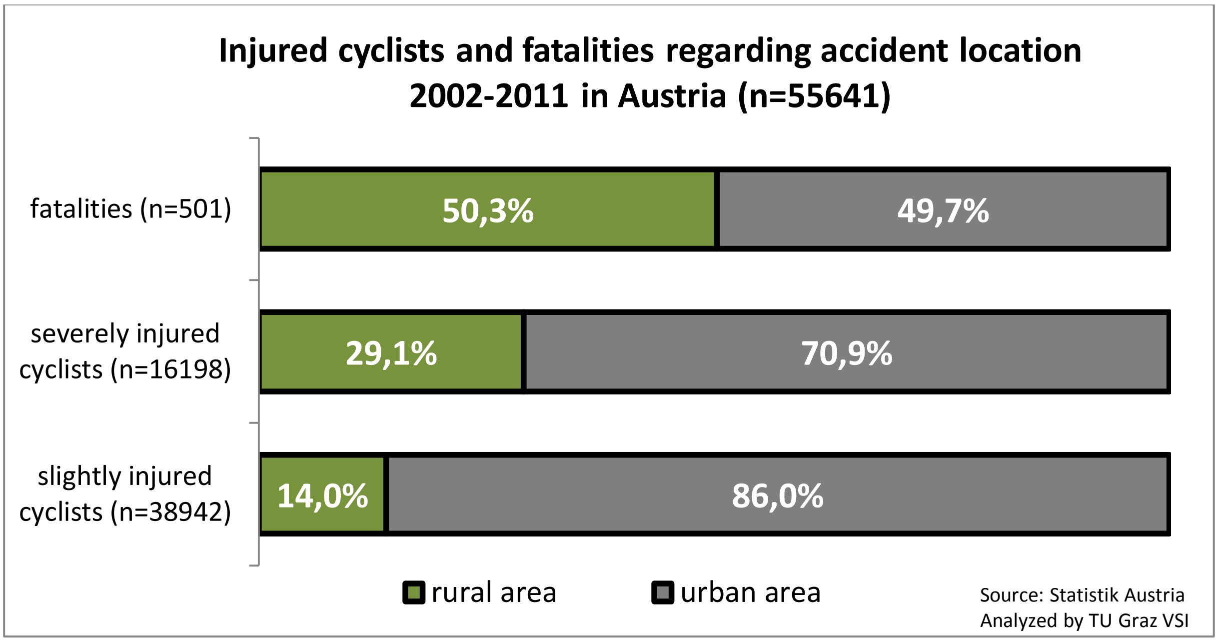


Figure 6-8: Injured cyclists and fatalities regarding accident location 2002-2011 in Austria [4]

Aside from the location of an accident, another interesting aspect is the timing of the accident (Figure 6-9, numbers from the axis are related to a time period of one hour, which means for example the number 7 stands for a time between 7:00 and 8:00). Between 2002 and 2011, almost half of the accidents (43%) occurred in the afternoon and early evening, between 2 p.m. and 8 p.m. The peak is evident around 5 to 6 p.m., in which the maximum injuries and fatalities are also present. This is in comparison to between 3 and 4 in the morning, where the lowest amount of injured and dead cyclists has been registered. Beginning at 4 a.m., an almost steady increase of bicycle accidents is observed until 5 p.m., when the percentage starts rapidly to fall down. During the night (between 8 p.m. and midnight) the percentage of injuries and fatalities diverges: While injuries continue to fall, fatalities begin to raise their occurrence until midnight, when they adapt almost the same percentage like injuries again. [4]

When focusing on the traffic over daytime, it can be recognized that the behavior is similar to the accident behavior. Traffic counting from a street called Lassallestraße from Vienna, showed that bicycle and passenger cars can be observed most frequently in the evening from 5 p.m. to 6 p.m. Both have their minimum (similar to accident rate) in the early morning hours. At around 8 am a little bump can be noticed. [57]

Furthermore color transitions in Figure 6-9 describe the timing of sunset and sunrise over the year. In 2015 in Vienna the earliest sunset could be observed at 16:00 and the latest at 20:59. The earliest sunrise was 4:53 and the latest at 7:46. [58]

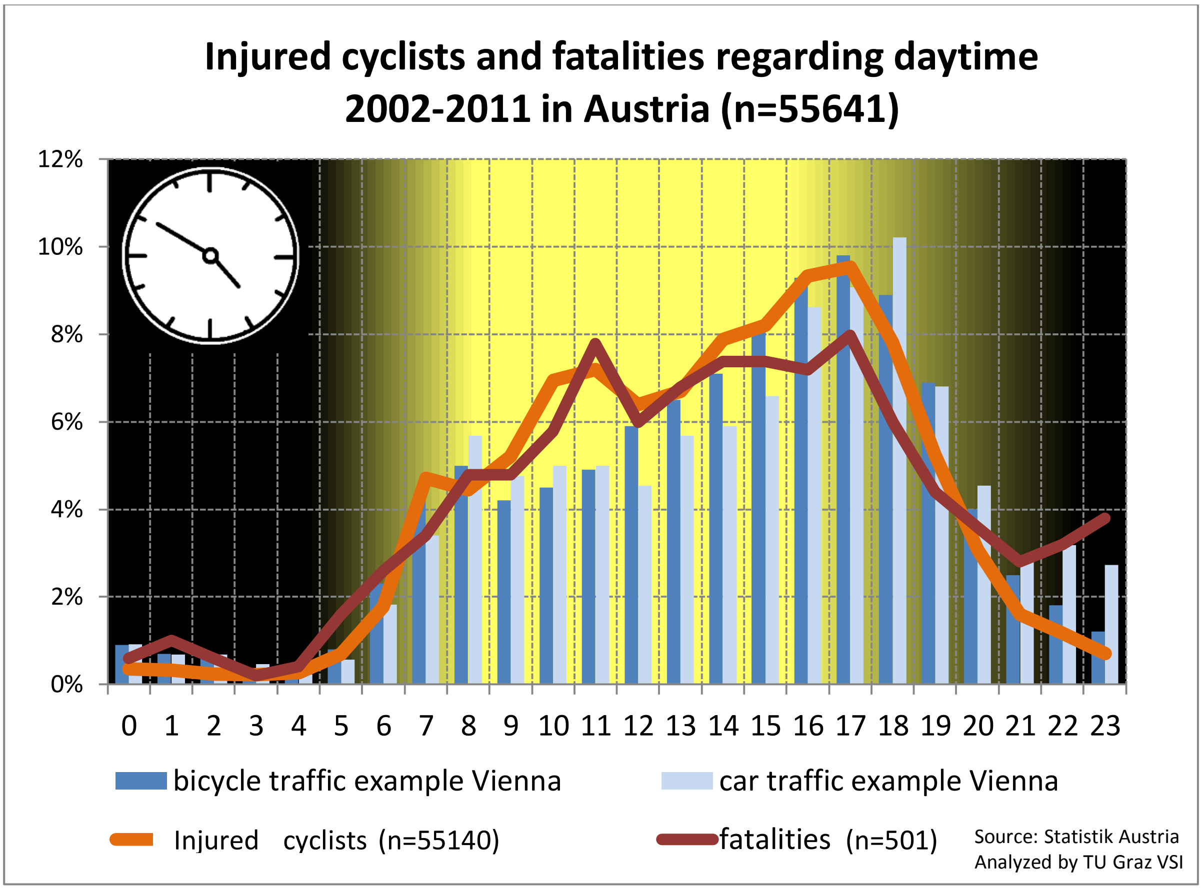


Figure 6-9: Injured cyclists and fatalities regarding daytime 2002-2011 in Austria [4] [57] [58] [59]

Figure 6-10 displays cyclist accidents regarding injury severity (slightly, severely and fatally) and lighting conditions. For injured as well as for killed cyclists the highest percentage represent accidents that happened during daylight. Nevertheless there can be a decrease of daylight accidents observed for increasing injury severity: While in cases of slightly injured cyclists 81,4% of the accidents occurred during daylight, only 67,7% of fatalities can be noticed for this lightning condition. On the other hand accidents occurring during light restrictions (darkness, artificial light and dazzled sun) have a higher percentage for fatal accidents, compared to accidents with slightly injured cyclists. The highest percentage difference in this respect show accidents occurring in the dark (12,2% for fatal compared to 2,8% for injured cyclists).

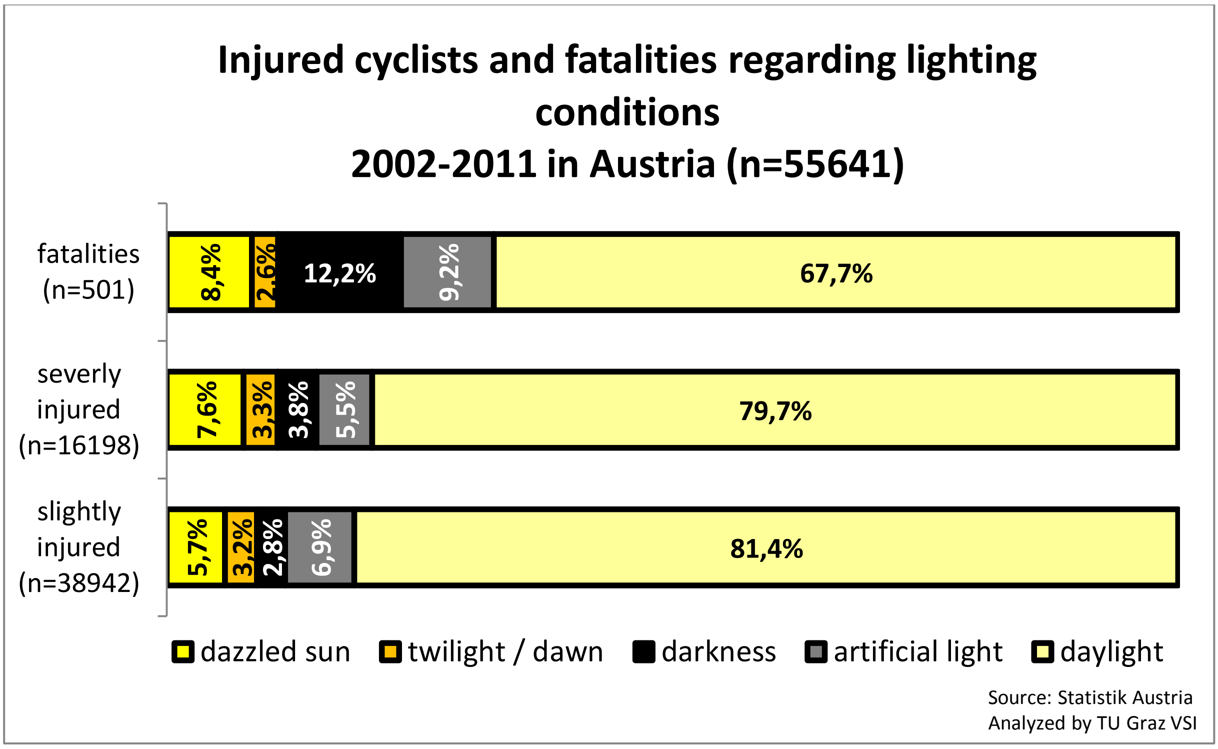
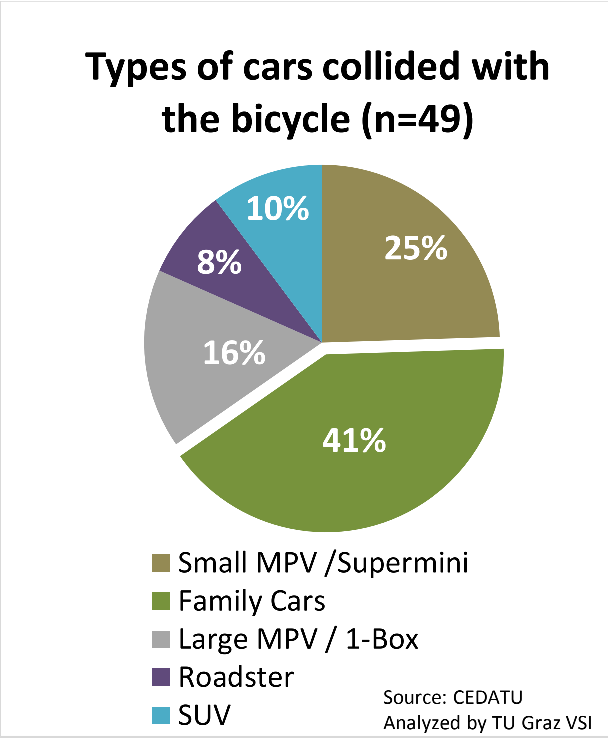


Figure 6-10: Injured cyclists and fatalities regarding lighting conditions 2002-2011 in Austria [4]

For a more detailed analysis of car to bicycle accidents, CEDATU cases have been taken into consideration. The following figures are therefore based on CEDATU accidents and reconstructed cases.

Figure 6-11 presents car geometries and bicycle types which were most frequently involved into a bicycle to car accident. The biggest group of car front geometries were small and large family cars with 41%, followed by small MPV/Supermini with 25%. Roadsters were with 8% only rarely involved in an accident.

Regarding the differentiation of bicycles types, own types were created, which should give a basic overview with the support of conventional terms. In this respect the so called “City Bikes” take the leading participation when it comes to collision with passenger cars, with 41%. The second largest percentage was represented by Trekking Bikes (23%), closely followed by racing bikes (20%). Mountain bikes were in 8% of all cases observed.



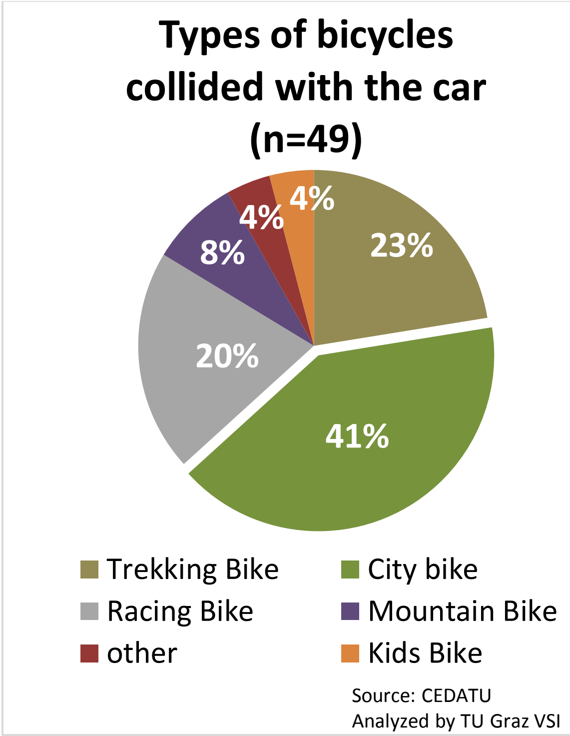


Figure 6-11: Types of involved cars and bicycles

Beside of this own classification of bicycle types, Figure 6-12 illustrates bicycle frames, mentioned previously in the methodology. The graphic points out that almost half of all bicycle frames (47%), involved in the fatal bicycle to car accident, were diamond frames. Trapeze frames made about 23% and swan's neck frames 16%. Wave frames could be observed in 6% of all cases. Some frames could not clearly be assigned to one of the mentioned frames, as they were special kind of bicycles, like child bicycles, folding bicycles or tandem bikes (8%).

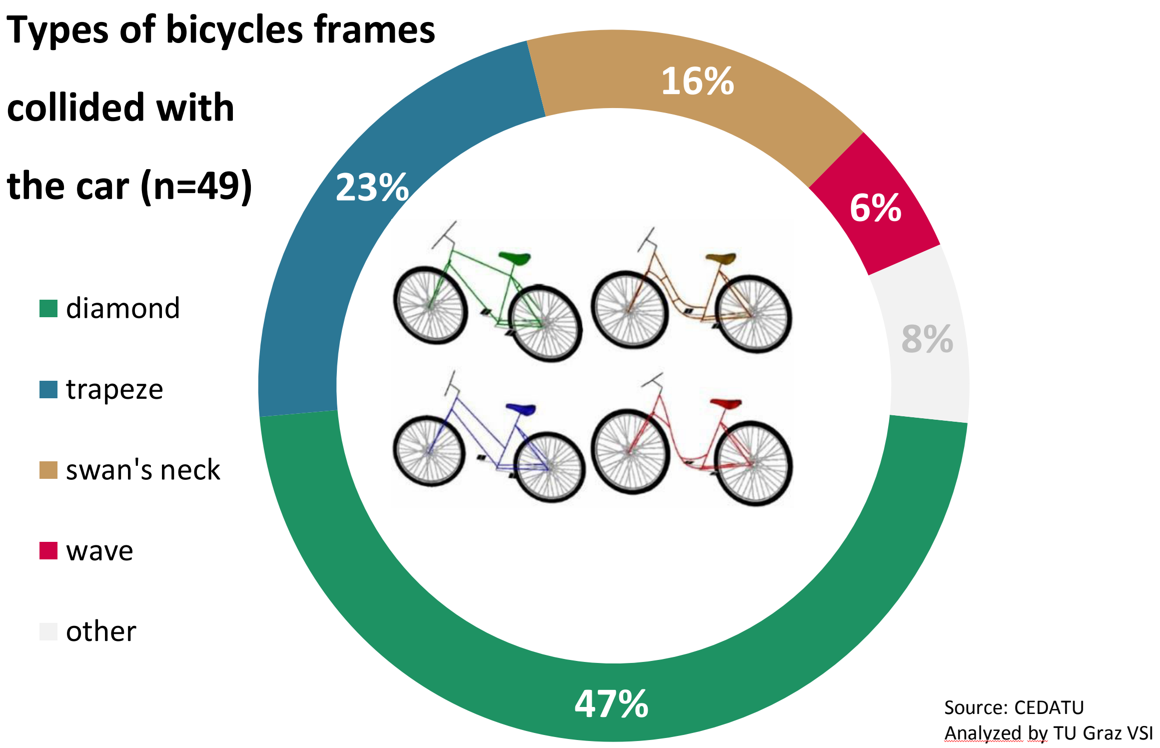


Figure 6-12: Types of bicycle frames collided with the car

The causative aspect in a car to bicycle accident, why the accident actually occurred and by whom this conflict was initiated, may be one of the most essential points for future accident and injury reduction and avoidance. Analyzed data show that it is quite balanced, when it comes to the question of the malpractice participant of the accident: In about 41,6% of all relevant CEDATU cases (77 out of 90 accidents, where the malpractice participant could be clearly identified, could be considered) the cyclist was the malpractice participant and a bit more frequently it was the fault of the car driver, that the accident occurred. Figure 6-13 presents the main risk factors of bicycle accidents, focused on the car driver as malpractice participant. The risk factors are divided into their probability of causation (definitively causative, probably causative and possibly causative). It can be found out, that inattentiveness was the by far most frequent factor for the causation of the accident (where the driver of the passenger car was the malpractice participant). After inattentive drivers, ignoring priority made an outstanding percentage as well with 16% occurrence. In 50% of all cases driver's constitution or experience were possibly causative. When pointing out infrastructure, lighting conditions shouldn't be neglected, as they were in every 20th case definitively causative, in about every 7th case probably causative and in every 4th case possible causative.

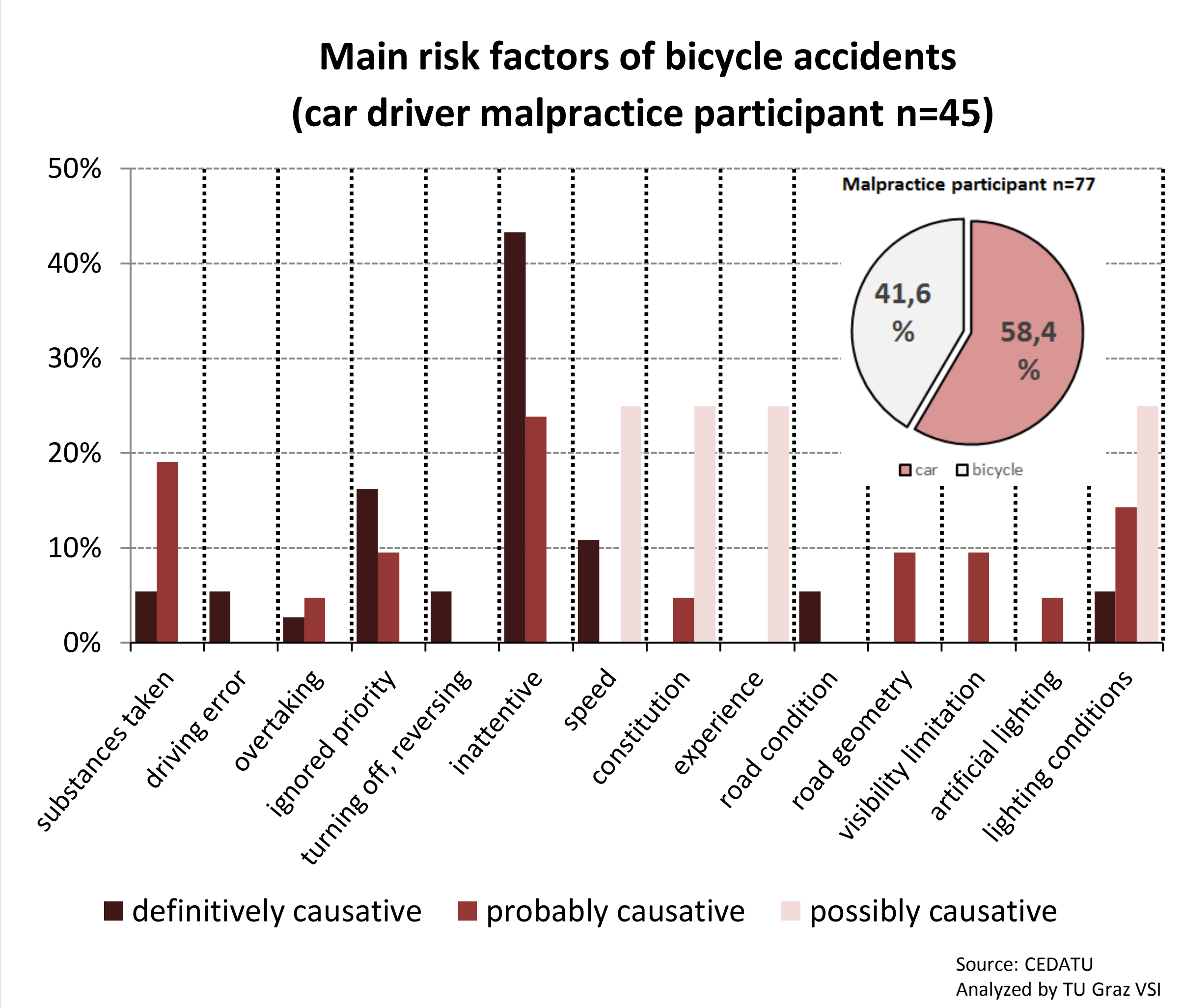


Figure 6-13: Main risk factors of bicycle accidents (car malpractice participant)

Risk factors for the cyclists as the malpractice participant showed a similar picture (n=32). Inattentiveness as well as ignoring of priority were the most frequently met, definitively causative risk factors. Ignoring of priority (mainly at junctions) occurred to an even much higher percentage compared to accidents where the car driver was the malpractice participant. A high frequency with about 30% of probably and possibly causative factors could be recognized for the constitution of the cyclists, more detailed speaking the age of the cyclists (very old or very young). The percentage of taken substances (e.g. alcohol) is much higher for car drivers than for cyclists.

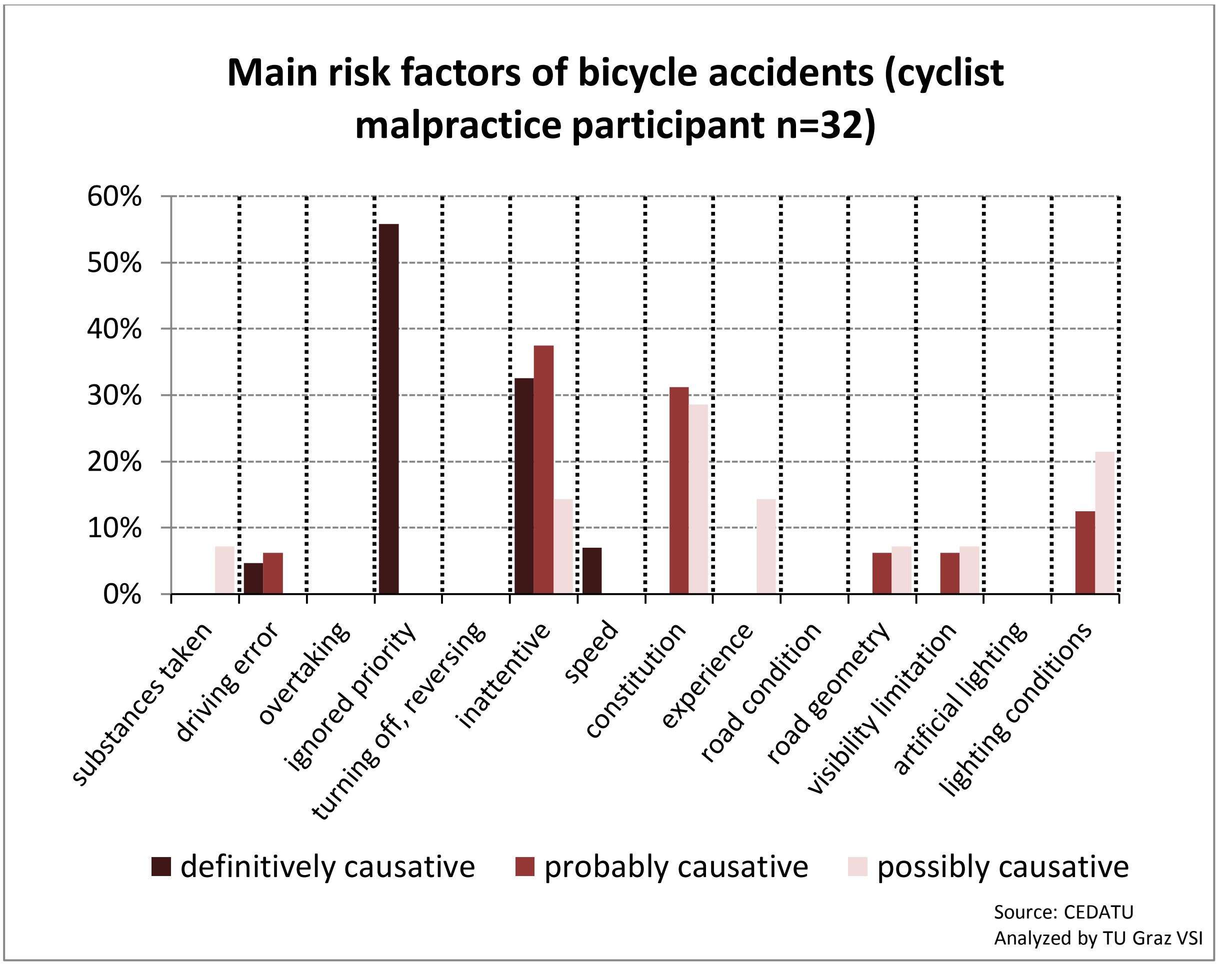


Figure 6-14: Main risk factors of bicycle accidents (cyclist malpractice participant)

In a large percentage of all relevant CEDATU cases excessive speed or inappropriate speed of the car was definitively causative for the accident. Even more than that, inattentiveness influenced the outcome of the accident. Figure 6-15 displays now the pre-crash behavior of the car, and shows that in only 35% of all reconstructed car to bicycle accidents the driver of the car initiated a braking maneuver before colliding with the cyclists. In more than a half of the cases (53%) the driver kept the velocity and in 12% of the cases he even accelerated the car (e.g. overtaking). If no braking of the car was initiated by the car driver, it does not mean that the driver didn’t recognize the cyclist in all cases. Here are also accidents included where the driver maybe recognized the cyclist before the crash, but only tried to avoid the accident by steering of the car without braking.

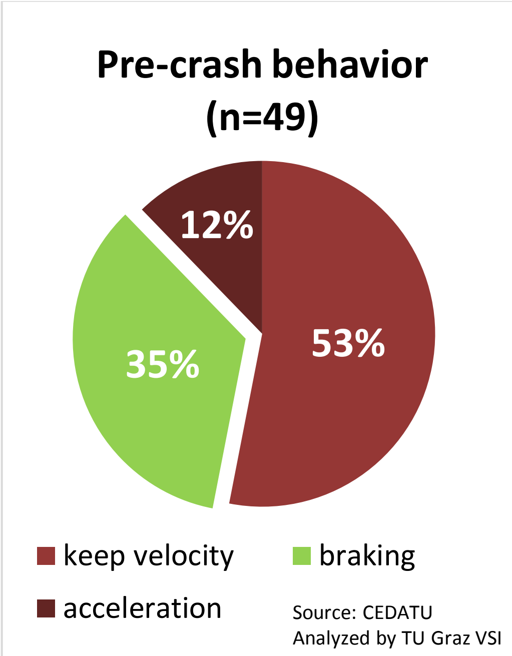


Figure 6-15: Precrash behavior

Documentation of lighting conditions was available in 89 out of 90 accidents from CEDATU. Results show that most of the accidents occurred during daylight (71%). In about 18% of the cases only limited light was provided. Dazzled sun was present in 10% of all car to bicycle accidents.

Regarding road condition a clear majority of dry roads could be found (in 78% of all cases). Only in 10% of all cases the road was wet and there were no cases where an icy road could be observed.

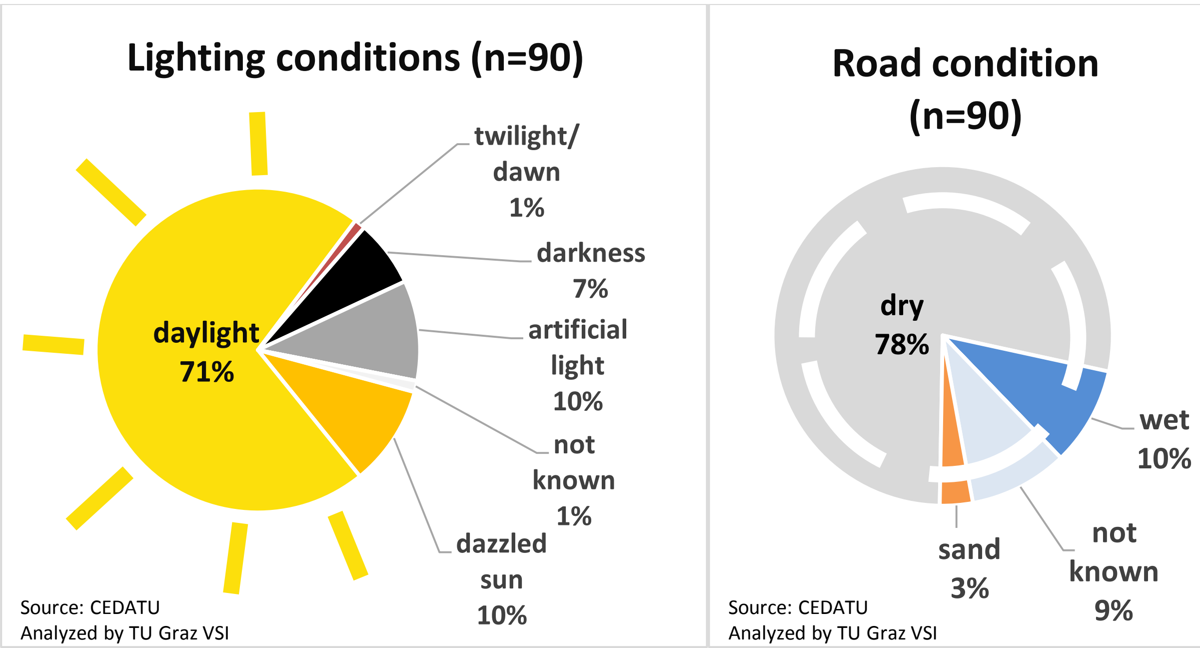


Figure 6-16: Lighting and road condition

The usage of safety equipment may help to prevent accidents and influence the outcome of the accident. Therefore 90 registered car to bicycle accidents from the CEDATU have been analyzed. For 24 cyclists, clothing has been documented quite well and it can be concluded that 79% of these cyclists did not wear high visbility clothing at the time of the crash.

There is a higher frequency of helmet usage; however, overall helmet usage is still low. For 48 documented cyclists (42 out of 90 without information about helmet usage) there is a percentage of helmet usage of 42%. Of the cyclists not wearing a helmet at the moment of the crash, 69% were men. When implementing age steps adapted from previously mentioned literature [45], the highest no-helmet wearing age group is 7-15 with 79%. The lowest percentage of no-helmet usage is the age group of 31-60 (27%). [46]

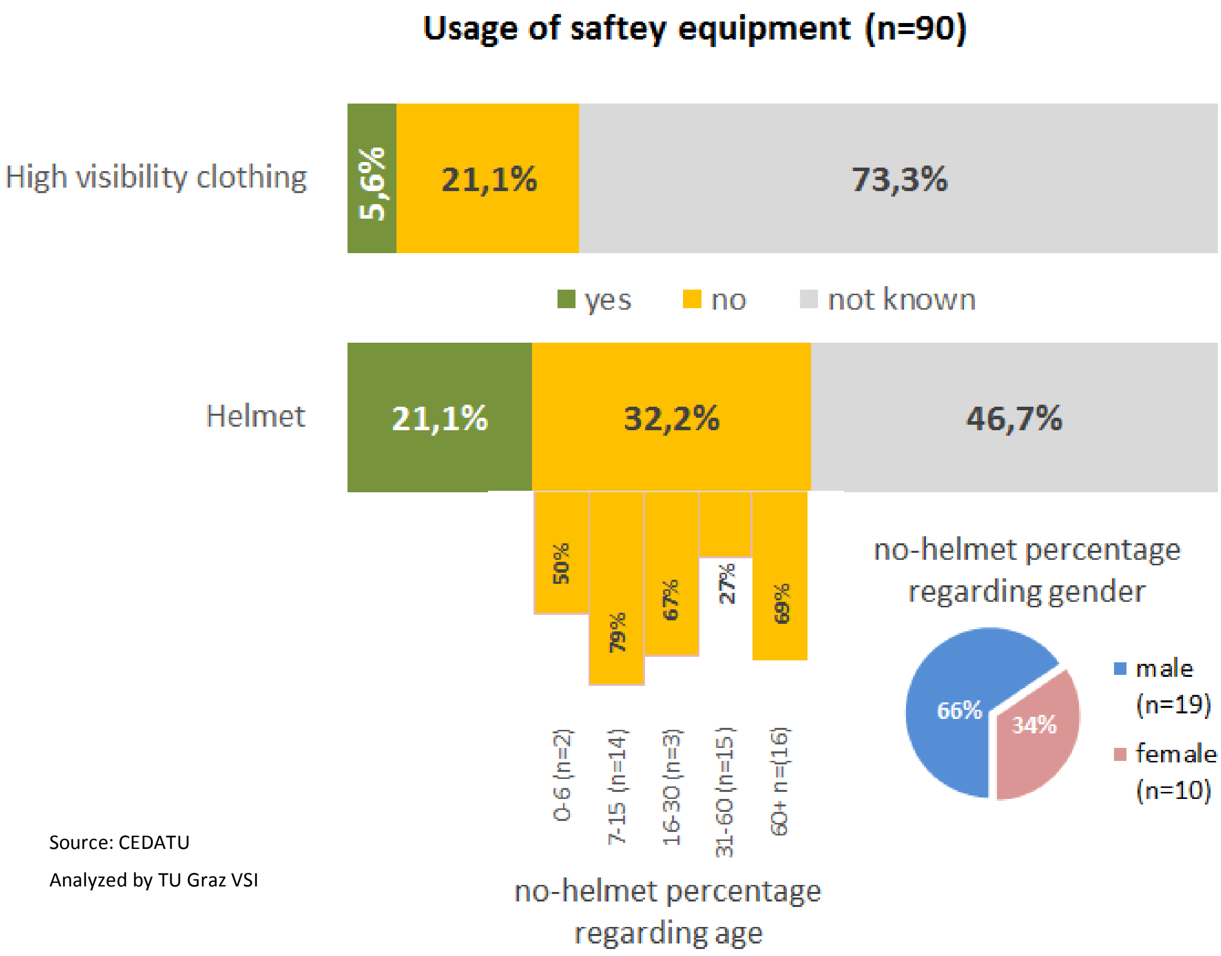


Figure 6-17: Usage of safety equipment

6.2.3 Discussion

Regarding injuries and cyclist age, an important point of discussion is the high population deviation and injuries occurring for cyclists below 20 years. The highest can be observed for the group of 0-4 years old. This can be clearly explainable by the fact that the percentage of bicycle use is much lower for this age group than for older age groups [60]. In Austria it is not allowed to ride a bicycle without a chaperone until the age of 10 years. Afterwards, it is possible to apply for a license to ride without a chaperone. When older than 12 years of age, a license is no longer necessary to ride a bicycle on public roads. This legislation may result in a strong increase of bicycle usage for individuals from 10-14 years old, thus leading to a high in increase of accidents and injuries as well. For the group of 90 years and more, the high deviation between population and injuries can also be explained with low usage percentage. Generally speaking, there is a higher frequency of male cyclists for being injured or killed in an accident. This could possibly be because males more frequently exhibit poor behavior in traffic, or could just be explained by the fact that male cyclists comprise a higher percentage of cyclist traffic than females [61]. With increasing age, the differences in the frequency of killed and injured cyclists between male and female decreases.

The incidence of cyclist fatalities peaks with older age (60-80). The reason for this could be high bicycle use in combination with the loss of strength of the human body against impacts in elderly cyclists (e.g. skeletal strength [62]).

While most accidents with injured cyclists (80,9%) can be found on urban roads, the highest fatality rate can be observed on rural roads. The high number of urban accidents seems to be reasonable, when taking into account that most traffic occurs on urban roads [61]. Due to the much higher fatality rate of rural accidents, accidents on these roads tend to be of a much more of serious nature. As mentioned in chapter 3.3.1, almost half of all fatal accidents mentioned in the study from the UK happened above a speed limit of 48kph [28], which is comparable to the Austria speed limit for urban roads (50kph*,"§ 20 StVO Fahrgeschwindigkeit (2*)"). When increasing the speed of the car, the fatality risk also increases (see chapter 3).

As reviewed previously in chapter 3.4.2, the height of the cyclist's head above the hood has a crucial influence on the head acceleration at the moment of the impact [23]. The proportion of bicycles types and frames where upright sitting positions are typically employed is quite high: When reconstructing 49 accidents, 41% of the bicycles were City Bikes and 45% had a trapeze, wave or swan's neck frame (comparable to the granny bike frame from the literature chapter [24]). Besides resulting in a higher impact point on front of the car, also effects on the injury severity of the head can be expected.

Inattentiveness and ignored priority are the most common risk factors in a car to bicycle accident, from the perspective of the car driver as well as from the perspective of the cyclist. Reconstructed accidents demonstrated that even if the driver of the car recognized a bicycle prior to the crash, 75% did not even brake before impacting with the bicycle. A similar picture regarding accident causation is revealed by a research from the UK for the contributory factors assigned to the cyclist [61]: Most commonly cyclists fail to look properly, followed by failing to judge other person's path or speed and being careless, reckless or in a hurry. Analysis of risk factors showed that driving a car under the influence of substances is quite often the possible cause for accidents. However, the percentage of riding a bicycle while impaired is very low. It must be mentioned that for car drivers, an alcohol test was available in most cases, but for cyclists, proof of alcohol influence was rarely provided.

The failure of a car driver to recognize a cyclist seems to be a critical problem in a car to bicycle accident. Lighting may play a role here (increase in fatality rate after 9 p.m.), as well as the use of high visibility clothing. In almost 80% of all cyclist accidents, where the clothing of the cyclist was known, cyclists were wearing dark clothing. Another frequently discussed factor is the bicycle helmet. From crash dummy tests, it was found that the HIC (Head Injury Criterion) and linear head acceleration can be reduced up to 70%, when using a helmet [38]. The accident helmet usage rate of about 42% (from CEDATU cases were helmet usage has been recorded) seems to be high when considering reviewed percentages from literature (e.g. 37% helmet usage for male and 33% for female). When reconstructing accidents and searching for information about helmet use for each case, pictures often support the search by showing helmets on or next to the cyclists. If there is no picture of the helmet available, it cannot be assumed that there was no helmet used. Thus, a slightly higher amount of helmet usage records may have occurred compared to no helmet use.

The age steps of cyclists not using a helmet have been adapted to age steps in the reviewed literature (see chapter 3.4.4). Results reveal a completely different picture and no common percentages. A possible reason for this discrepancy may be the low amount of cyclists that could be taken into consideration. Age groups with a higher amount of cases display results that are more similar to helmet usage reported in literature.

6.3 Accident Scenarios

This chapter is devoted to accident scenarios recorded by Statistik Austria [4] from 2002 until 2011, which can be seen as a more concrete add-on for chapter 3.2. It deals with specific types of bicycle accidents, including impact directions, types of roads/infrastructure (cross sections, longitudinal traffic), single accidents, turning or no turning, etc. These types are identified by their three digit numbers. The first number describes the main accident group (e.g. collision between two vehicles driving into the same direction) and the second number stands for a more specific sub-type of the accident (e.g. rear-end collision into stationary vehicle on a straight section). An exact description of each accident type that will be mentioned in this thesis can be found in Table 5 in the appendix.

6.3.1 Overview

Figure 6-18 displays the 15 most frequent bicycle accident scenarios with injured and killed cyclists in Austria from 2002 until 2011 (n=55641). The orange bars represent the percentages of injured cyclists and fatalities for each accident type. Accident types are sorted by the overall frequency. Additionally, the red and blue bars describe the separate percentages of injured and killed cyclists respectively. A single vehicle accident (no passenger car involved) due to sideway skidding or forward skidding and overturning of the vehicle on a straight road is accident type with the most injured and killed cyclists, comprising 16,5% of all accidents (88 fatalities and 4202 severely injured cyclists). The second highest percentage is represented by accident type 511 (13,2%), which includes cross section accidents between two vehicles and is therefore the more relevant accident type when considering car to bicycle accidents. It describes a collision at a junction where a vehicle and a bicycle are proceeding at right angles to each other. 62 fatalities, 1760 severely injured cyclists and 5505 slightly injured cyclists (even more than in single accidents) can be contributed to this accident type. The third and fourth largest amount of injured and killed cyclists is caused in the accident types 622 and 411, which are both accidents where one vehicle turns towards or in front of another vehicle.
The third highest percentage of fatalities can be observed in accident type 312, which is a rear end collision. An example would be a bicycle approaching a junction and wanting to turn right. A car behind the bicycle, which is moving straight ahead, collides with the rear of the bicycle, because of failing to brake and not recognizing the bicycle ahead. This is in contrast with accident type 741, which is in the top ten of accident types regarding injuries, but has zero fatalities: A bicycle which is driving on the left side of the road collides with an open door of a vehicle, which is parked or stopped on the right side of the road. Other cases involving high amount of fatalities (18) and severe injuries (464) occurred when vehicles overtook bicycles but did not keep enough distance from the bicycle while overtaking.
The amount of single bicycle accidents is high (21% of fatalities plus injuries, 28% of fatalities and 33% of severe injuries), but because the main focus of this thesis is on car to bicycle accidents, single accidents will not be further discussed. Of much higher interest is the percentage of cross section accidents and accidents in longitudinal traffic between a bicycle and another vehicle. 45,3% of all injured cyclists and fatalities are caused in intersection accidents, 23,7% in longitudinal traffic where

at least two vehicles were involved, and the remaining in single vehicle accidents and others. 35,7% of all cyclist fatalities occurred in intersections and 28,7% in longitudinal traffic (collision of at least two vehicles). Regarding severely injured cyclists, cross section accidents have a 16,1% higher frequency than accidents occurring in longitudinal traffic. [4]

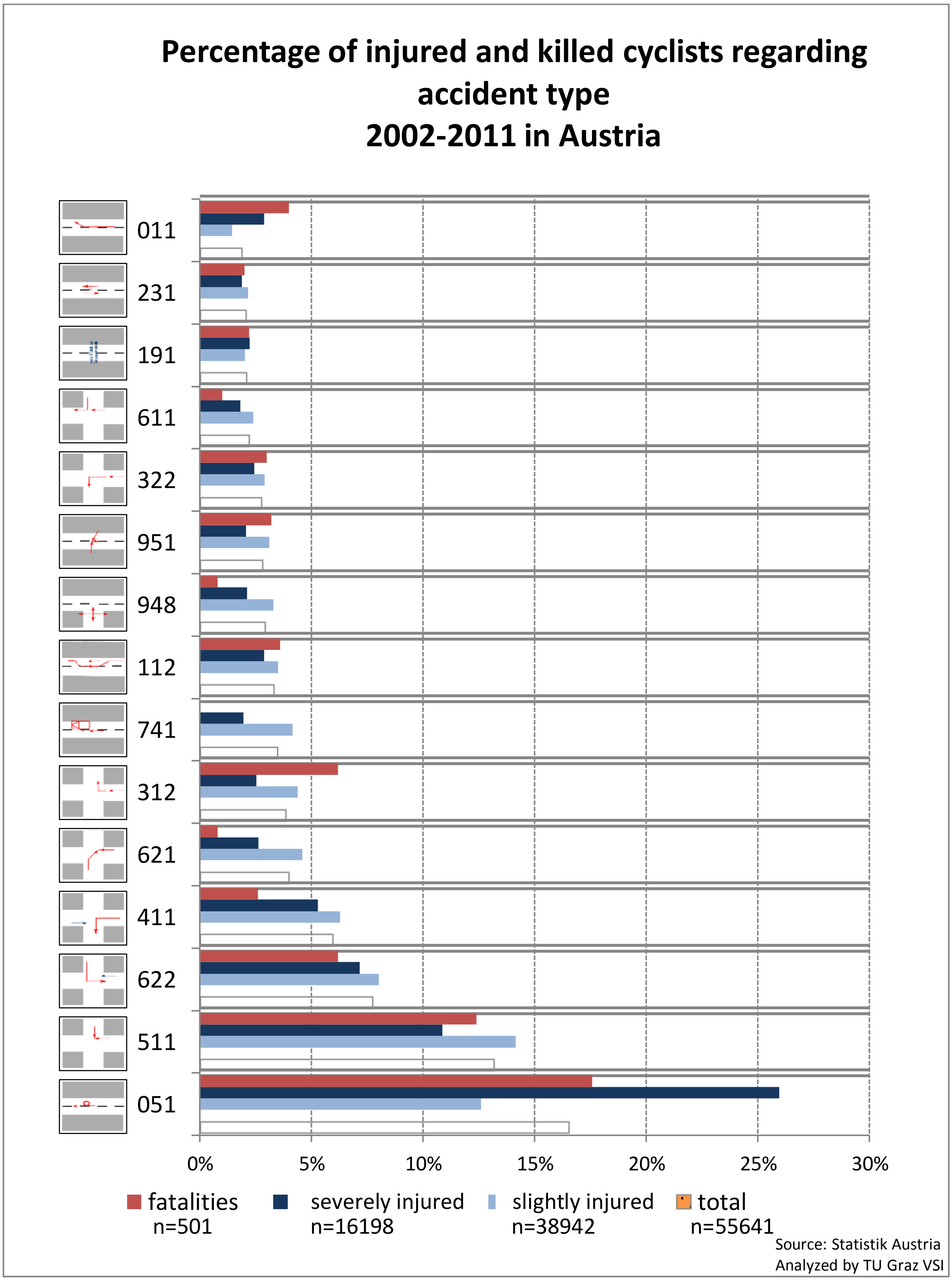


Figure 6-18: Percentage of injured and killed cyclists regarding accident type 2002-2011 in Austria

6.3.2 Intersection accidents

Due to their high percentage, intersection accidents have been analyzed in detail. Figure 6-19 illustrates the 10 most common bicycle accident types, regarding injured cyclist and fatalities, in Austria from 2002-2011. The largest percentage of cross section accidents is attributed to accident type 511, which has already been descripted previously (29%). Concerning fatalities, this frequency rate is even higher (35%). A new bicycle-specific type can be found in this list: 451, a collision of a vehicle, which is turning right, with a bicycle, which is proceeding in the opposite direction on a special track (cycle way). 582 injured cyclists and two fatalities occurred within this scenario. [4]

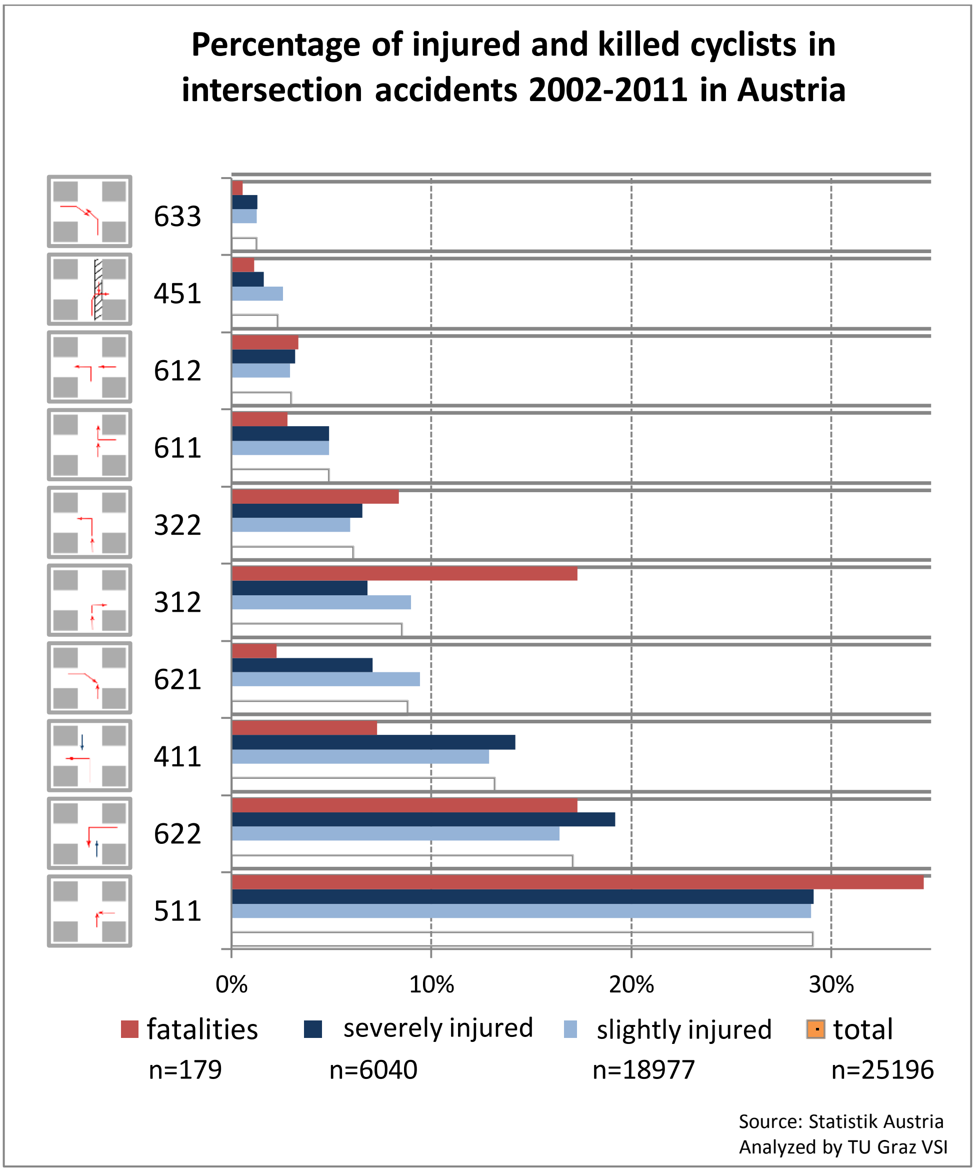


Figure 6-19: Percentage of injured and killed cyclists in intersection accidents

6.3.3 Longitudinal traffic accidents

The highest percentage of longitudinal accidents (in Austria from 2002 to 2011) is attributed to accidents where a bicycle driving on the left side of the road collides with an open door of another vehicle that is parked or stopped on the right side of the road. Of a more serious nature are overtaking accidents, which have the second highest percentage concerning longitudinal accidents. In general, 3,3% of all accident scenarios, with injuries or fatalities as a result, include overtaking of a vehicle. However, if the focus is only on longitudinal accidents, this type of accident has a much larger percentage of 17,6%. The third highest percentage of longitudinal accidents are "not-further specified" accidents, which were unable to be assigned to available types. Grazing collisions with 45 fatalities (in a bend and on straight roads) and front to front collisions (in a bend and on straight roads) with 19 fatalities should not be neglected as well. Accident type 131, a rear-end collision of one vehicle into another vehicle on a straight section, represents the highest percentage of fatalities (and the highest fatality rate of the shown scenarios) by far, with 25,7%. 4,9% of all fatalities are accidents where one vehicle merges into traffic from the left. [4]

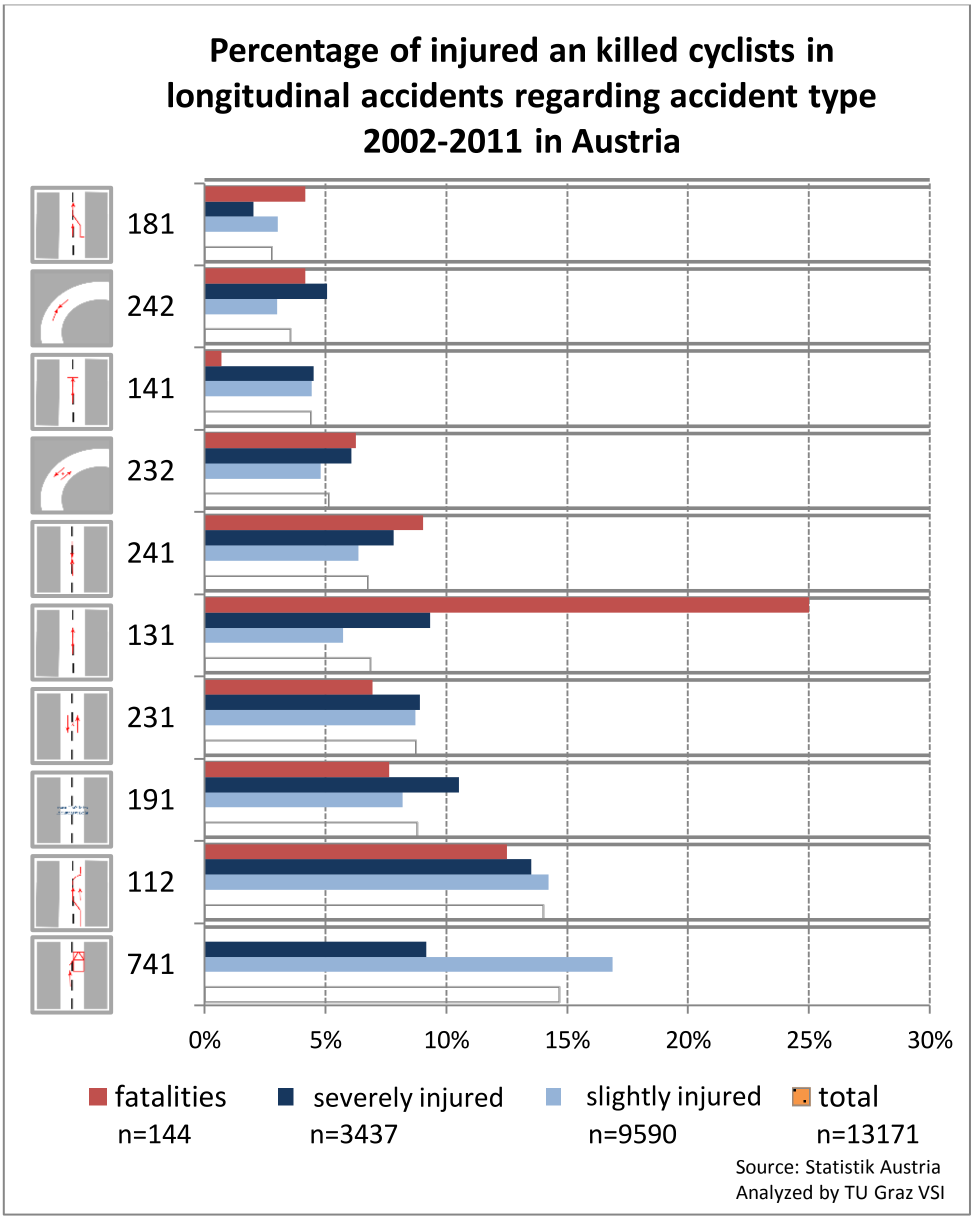


Figure 6-20: Percentage of injured and killed cyclists in longitudinal accidents

6.3.4 Discussion

The most common accident types are accidents where the bicycle or the car is crossing the road. In more detail, the scenario where most cyclists were injured and killed is a collision at a junction with two vehicles proceeding at right angles to each other (511). This reflects also findings from literature, where it has been said that in 76% of all car to bicycle accidents, the bicycle approaches from the right or left side of the car [21].

It can be recognized that if there is one vehicle (bicycle or car) in stationary position, the outcome of the accident tends to be less fatal. Examples would be accident type 144 (rear-end collision on a stationary vehicle) with one fatality and 741 (bicycle collides with open door of a car) with zero fatalities over 10 years. Contrary to this, rear-end collisions where both vehicles are moving have a higher fatality rate than most other accident types. Possible reasons could be higher impact velocities of the car (no need to brake for turning), different impact kinematics and the point that only one participant has the chance to recognize the conflict early enough (only the car is able to notice the bicycle, but not the other way around). In fact, only one participant has the chance to prevent the accident or minimize the outcome of slight, severe and fatal injuries by steering or braking. It has been shown previously in chapter 6.2.2 that, from the perspective of the car driver, the most causative risk factor of fatal injuries in fatal bicycle accidents is inattentiveness. This inattentiveness may cause many of the aforementioned rear-end collisions, as it was also the main causative factor for all reconstructed accidents with the same scenario. After inattentiveness, ignoring priority is the most frequently met risk factor for fatal accidents. It seems that accident type 511, a right angle junction collision, presupposes a violation of priority rules in most cases.

6.4 Impact directions and damaged car parts

This chapter deals with the impact direction of the bicycle and the resulting damage distribution on the car. Afterwards relations to accident scenarios should be discussed and a more detailed further analysis of car frontal impacts should be justified.

6.4.1 Car damage distribution

When reconstructing accidents, damaged car regions provide the basis for the assumption of the impact direction and the scenario of the accident.

Figure 6-21 displays the direction of the car damage causative impact force with the support of the PDoF (Principal direction of force, see chapter 4.2.1). From 90 CEDATU accidents, 85 could be taken into consideration; for the rest there was no identifiable visible damage. Damage in the rear part of the car occurred in only 7% of all these cases. Front collisions are much more frequent: Almost half of all damages occur at the front of the car (PDoF 11 to 1). This increases to 80% when expanding to PDoF 10-2. Of front damages, the most frequently observed are damages in the middle front of the car (PDoF 12) with 28%. The amount of damages caused from the right side of the car is about 21% higher than from the left side of the car. However, damages to the left have a higher percentage than damages in the right (only one case) when confining to rear damages.

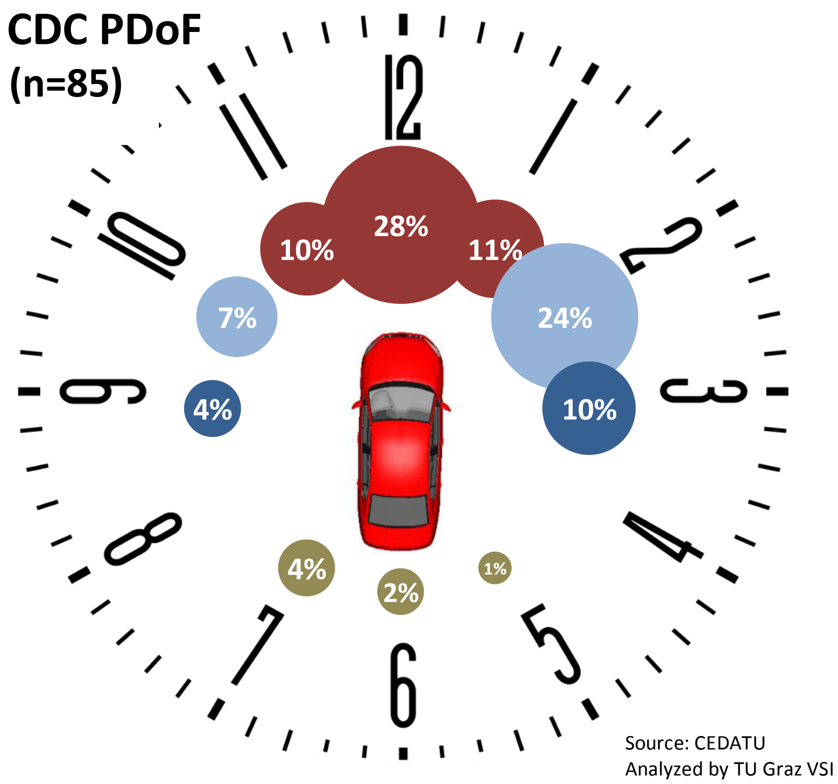


Figure 6-21: Collision Damage Classification PDoF

For 47 reconstructed cases, car impact parts have been recorded (2 without visible damages) and the eight most frequently damaged car parts are described in Figure 6-22. In more than half of all fatal accidents, an impact with the windshield has been observed. Damages on the hood were frequently noticed (in 51% of all cases) as well. Damage on the fender and bumper can be found in 40% of all cases. Interestingly, a high percentage of 17% can be noticed for exterior mirrors that have been either ripped off or retracted.

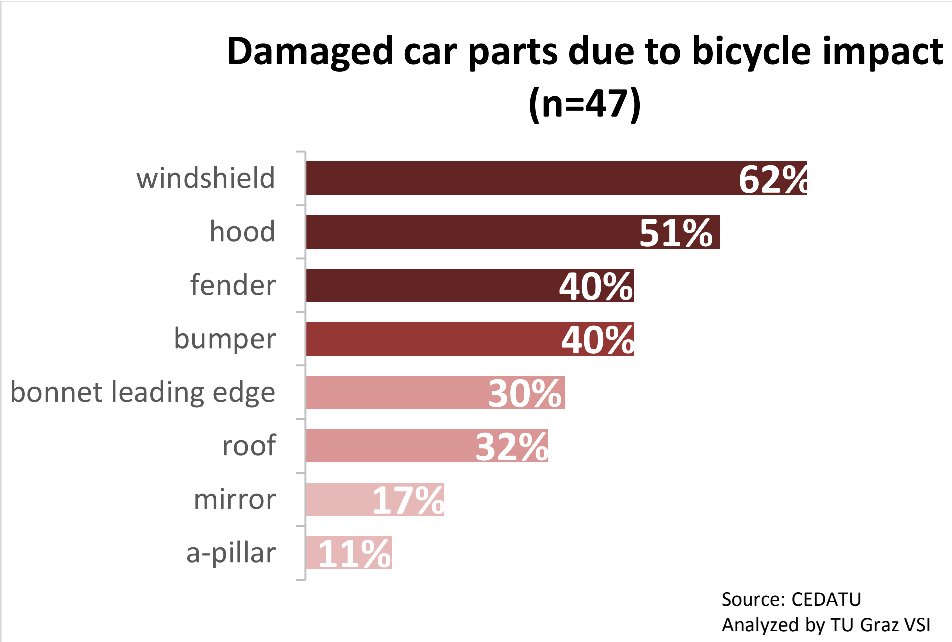


Figure 6-22: Damaged car parts due to bicycle impact

6.4.2 Frontal impact

As already discovered and illustrated in Figure 3-2 and Figure 6-21 most bicycles collided with the front of the car. Figure 6-23 focuses on impact angles of bicycles on the car front, as recorded from reconstructed accidents (n=43), and additionally states the car velocity at the moment of the impact for each case. Furthermore, the car front has been divided into thirds, which are displayed in different colors. The scope of the impact angle ranges from 0 to 360 degrees, which enables a description of side, front and rear impacts of the bicycle.

When considering all frontal impacts, 49% of cases showed that the first contact between the car and the bicycle happened at the right third of the car (light blue). Every third collision showed a first impact point at the left side of the front and every fifth showed a first impact point in the middle of the car. A high distribution of accidents can be noticed in the angle range of 90 to 180° (46% of all accidents), with car velocities ranging from 20 to 105kph. 84% of those are bicycle impacts with the right side of the car. In other words 46% of all bicycles approached from the right side or where following the same direction as the car. About 17% were bicycle rear end collisions with 180°±10° and about 12% were front to front collisions with 0/360°

In two cases the car was already in stationary position when the bicycle collided with it (bicycle into front and into side of the car). 47% of all accidents occurred at a car impact velocity above 50kph. The average impact velocity of the car was 51kph.

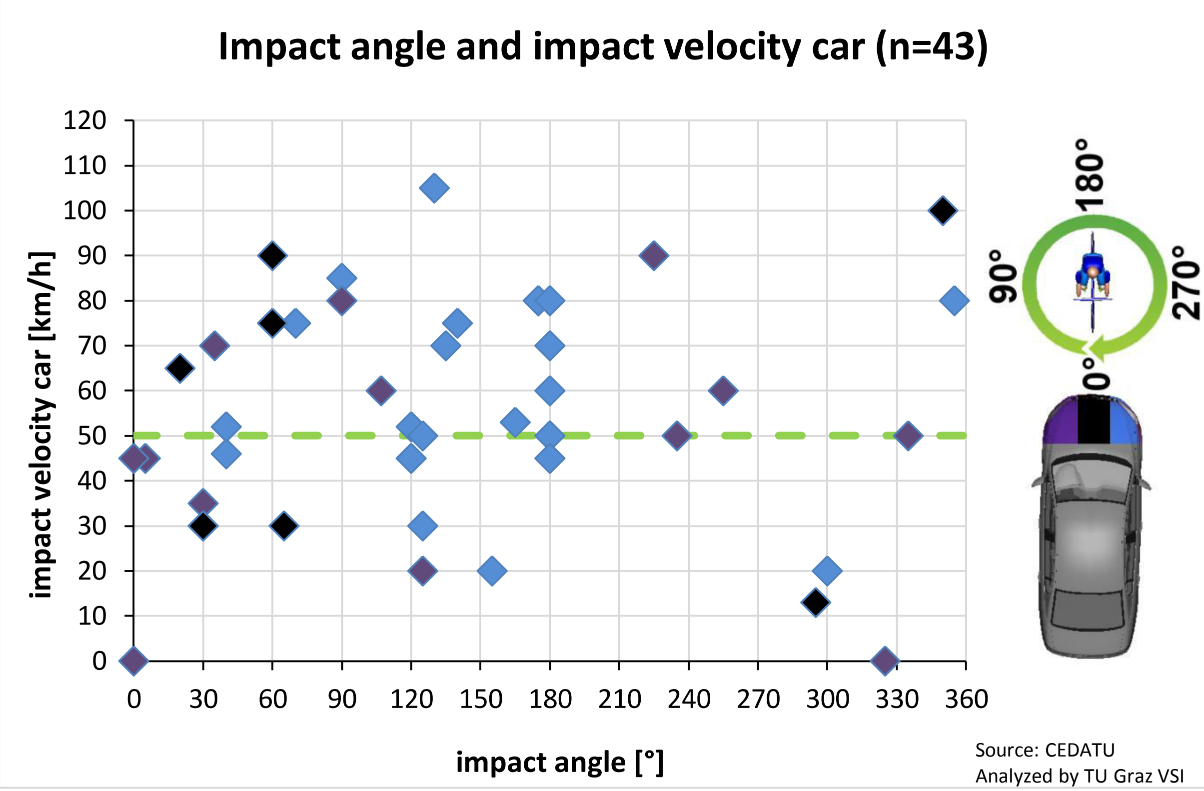


Figure 6-23: Impact angle and impact velocity car

6.4.3 Discussion

With the support of the PDoF distribution it can be detected that there are more damages on the right side of the car than on the left side of the car. This goes hand in hand with the fact that most bicycle approaching from the right side (see Figure 6-23 and Figure 3-3) and, when only focusing on frontal collision, have their first impact point on the right side. The fender, which is located on the front side of the car and established therefore often the first contact with the bicycle, got deformed in about 40% of all reconstructed cases. Crossing accidents, as they happen at junctions (about every third accident occurs there – see previously), are excellent examples for such scenarios.

Another constellation where the fender was damaged frequently shows a high proportion in the diagram of impact angle and impact velocity: Rear-end constellations with first contact zones on the right front of the car. Scenario examples would be overtaking accidents with neglected distance between bicycle and car or rear-end collision where the driver of the car didn't recognize a bicycle in front. This goes hand in hand with the previous finding about the high fatality rate of bicycle rear collisions, as the data from the impact angle diagram only considers fatal bicycle accidents.

About 50% of all fatal bicycle accidents occur on rural roads. This percentage can be also reflected by the percentage of car impact velocities above 50kph (maximum speed for urban roads in Austria), which is 47%. Literature speaks about 46% of fatalities above the speed limit of 48kph [28]. This minor difference could be balanced with the argument that many drivers don't stay within this speed limit and the actual velocity at the time of the crash might be higher.

Even though the damaged car parts reflect impact regions of the cyclist on the surface of the car, it has to be clear that it doesn't mean that on not damaged car parts, no impact has occurred. Damage interpretation draws only conclusion about definitively happened impacts. Due their differences in stiffness, car parts permit individual visible damages for the same impact forces. The percentage of a-pillar damages seems to be low, however the percentage of injury effective impacts can be higher (fewer deformations due to higher stiffness).

6.5 Injury distribution and sources

The aim of this chapter is to present typical injuries caused by car to bicycle accidents. A distribution of injuries on the human body and their severity will be covered, as well as the source of these injuries. Therefore the three most critical body parts will be undertaken closer inspection, regarding impact zones on the car.

6.5.1 Injury severity and distribution

Figure 6-24 provides a general overview of all injured body regions, generated by analyzing 26 fatal bicycle accidents from the CEDATU. This graphic confines to AIS injuries of 2 or higher. The mentioned percentage stands for the injury frequency of occurrence. In 21 fatal accidents the head was at least moderately injured (81%), which presents therefore the highest frequency of all body regions. Examples for head injuries AIS 2+ are multiple skull fractures, traumatic brain injuries (e.g. subdural hematoma AIS 4) and compound fracture of nose. Through the information (medical reports) of the causative injury for the death of the cyclists it was found out that in about 58% of all cases injuries of the head were causative for the death of the cyclist. The second highest AIS 2+ injury frequency showed the thorax with 65%, which is also in second position concerning cause of death, with about 19%. Examples for detected thorax injuries are lung contusion (AIS 3) and pneumothorax (AIS 3). The proportion of neck AIS 2+ injuries was lower with 19%. However a cervical dislocation was causative for the death of about 3 cyclists (12%). Injuries of the upper leg and arms occurred in 23% of all cases, which makes them therefore the third most frequently injured body parts. Nevertheless the average AIS for upper leg injuries is higher than the average AIS for injuries of the upper extremities. One example of an upper leg injury has already been mention in chapter 4.4.4 (tibia shaft fracture AIS 3). In about 34% of all cases, whether the lower leg, upper leg or knee was injured (AIS 2+). Other body regions, which were causative for the death of cyclists, are abdomen (15% frequency) and spine (12% frequency). For pelvis, knee and shoulders the lowest percentage of occurrence, of at least moderate injuries, could be detected.

As the head, the thorax and the upper legs are the most frequently seriously injured parts of the body (arms have an average lower AIS than legs), they will be used for further analysis of the impact region and injury sources.

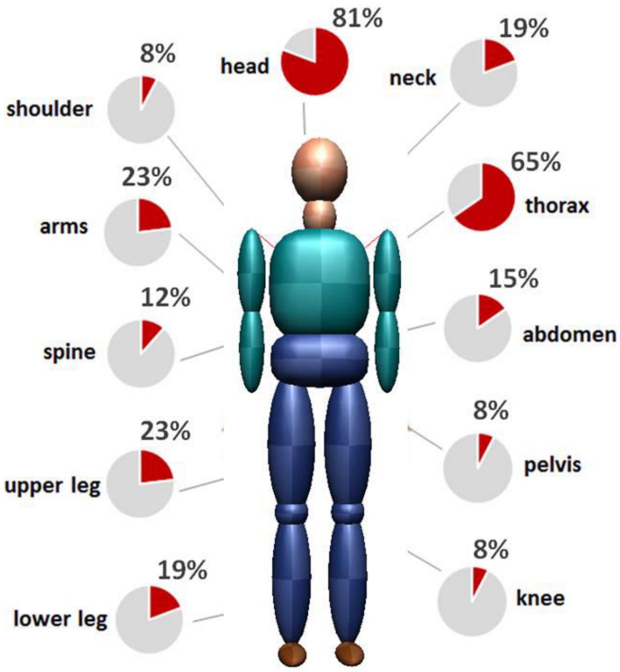


Figure 6-24: Injured body regions AIS 2+ (26 cyclists)

6.5.2 Impact regions and injury source

In this chapter the previously found statistics are used for concretization of the impact regions and injuries sources of cyclists on the surface of the car. Figure 6-25, Figure 6-26 and Figure 6-27 illustrate the impact distribution of the cyclists head, thorax and femur on the front of the car, based on data of 49 reconstructed accidents from the CEDATU. Several car types were investigated separately into the car front geometries: Family Cars, Superminis and MPV/1-Box, which presented together 82% of all accidents.

For each car geometry and part of the body, impact proportions are provided. Impact combinations with zero percent occurrence are not illustrated (e.g. head on hood of Family Car). Out of all accidents that have been taken into account, only two cyclists were younger than 18 years. Both of them collided with the fender of the car and subsequent impact with the head on the windshield/a-pillar.

Family Car:

The impact region of the cyclist's femur ranged from the bumper to the upper half of the hood (including impacts with the fender). The highest amount of impacts occurred on the lower half of the hood (58%), followed by the very front region of the car, including bumper and bonnet leading edge (34%). From another perspective in about 67% of all cases the first impact region of the car was the right side and for much lower proportion the middle and the left side of the car were affected. Thorax impacts on the car front had a lower range, concentrating on the upper half of the hood and lower half of the windshield with 50% proportion each. Like the femur, the thorax has its impact region mainly on the right side of the car as well (60%), with decreasing proportion to the left. Head impacts reached from the lower windshield up to the roof, where the latter presents only 7% of all head impacts. The rest is divided equally on the windshield. When looking at impact points at the left, middle and right part of the car front, a more balanced distribution than for femur and thorax can be recognized.

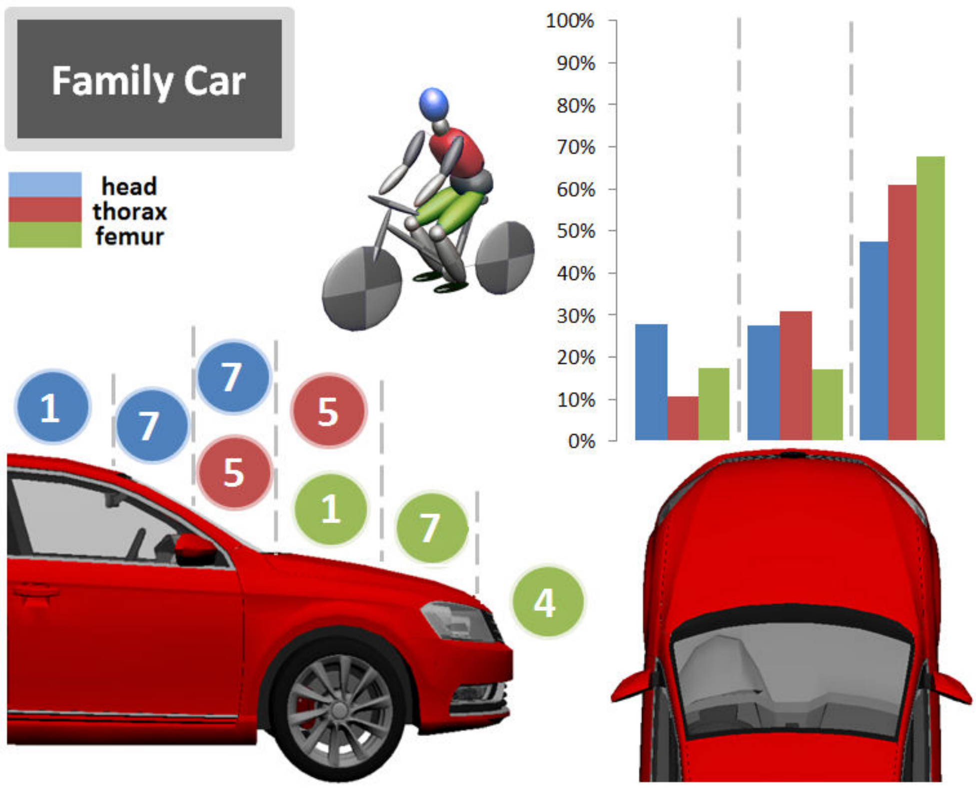


Figure 6-25: Cyclist impact regions Family Car

Supermini:

The impact region of the cyclist's femur ranged from the bumper to the lower half of the hood with a 50-50 distribution. As already found out for Family Cars, the highest amount of impacts for Superminis occurred on the right side of the car as well (50%). The range of the thorax impacts was higher with 38% on the upper half of the hood, 50% on the lower half of the windshield and 11% on the upper half of the windshield. From another perspective, most impacts happened in the middle third of the car front (50%). Similar results delivered records of the head impact with 56% on the middle part of the car surface. For roof impacts a higher proportion could be recorded, compared to Family Cars, with 11%. The rest of head impacts were shared by the lower and upper half of the windshield equally.

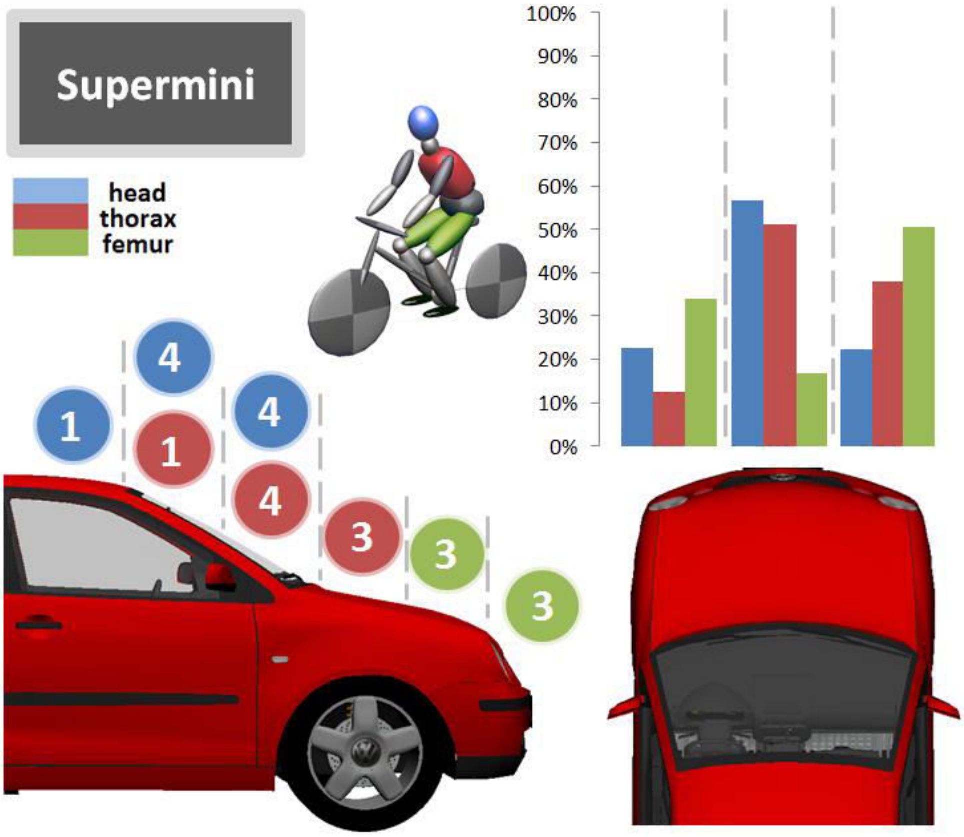


Figure 6-26: Cyclist impact regions Supermini

MPC/1-Box

For MPV/1-Box no roof impacts were recorded. The head impacts were exclusively observed on the windshield, where 40% were on the upper half of the windshield and 60% on the lower half of the windshield. These impacts were quite decentralized with 80% on the sides (left plus right). Most thorax impacts occurred on the lower half of the windshield and upper half of the hood (43% each) and another 14% impact points on the lower part of the hood. Also these impacts are decentralized and balanced on the left and right side of the car front with 43% each. The highest proportion of femur impacts could be noticed on the lower half of the hood with 50% followed by very front car region with 33% and upper half of the hood with 17%.

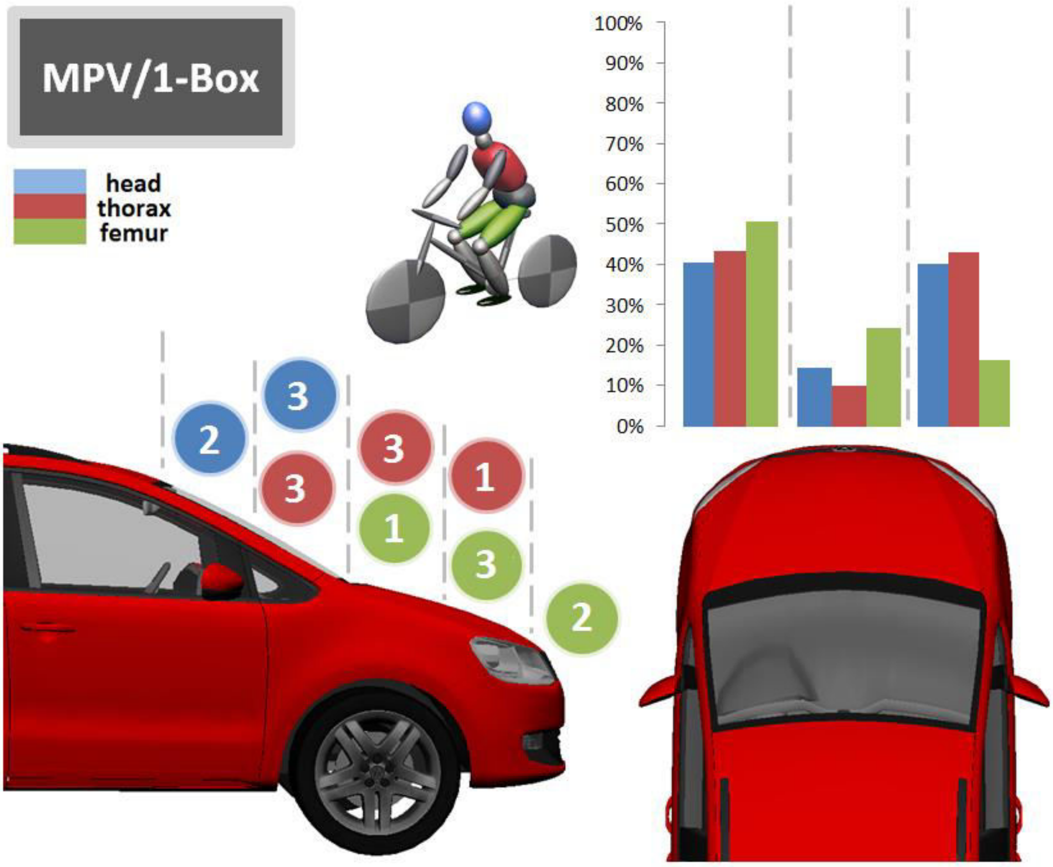


Figure 6-27: Cyclist impact regions MPV/1-Box

Figure 6-28 displays the proportion of causative car parts for fatal head injuries that has been recorded when reconstructing 49 accidents from CEDATU. With 64% the windshield had the largest number of impacts in accidents where the cyclists succumbed to their fatal head injuries. In about every fifth accident an impact with the a-pillar of the car was the reason for the death of the cyclists.

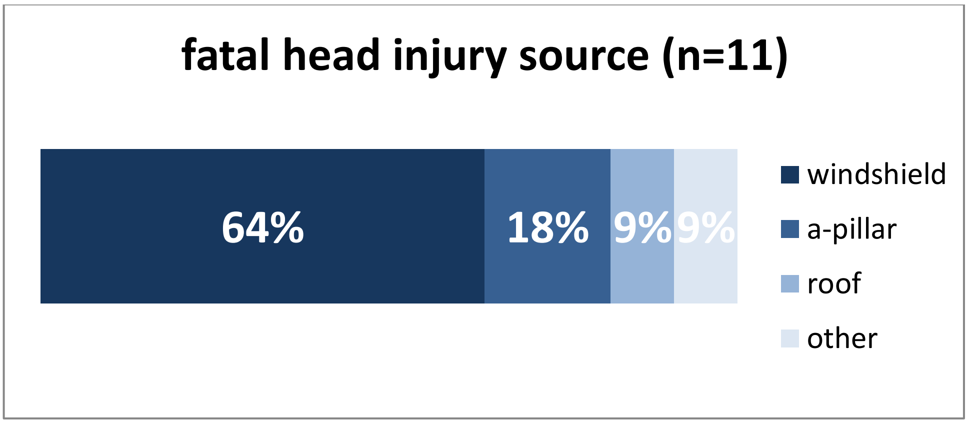


Figure 6-28: Fatal head injury sources

6.5.3 Discussion

Studies, which analyzed mainly non-fatal cyclist injuries, found out that the most relevant body regions for AIS3+ injuries are the lower extremities and the torso, followed by the head [34]. Together these body regions also presented the most frequently injured body regions for all analyzed killed cyclist cases of the CEDATU. Head injuries were here in the most cases the reason for the death of the cyclist and occurred in the observed fatal cases most frequently (AIS2+ 81%). AIS2+ injuries of the torso and lower extremities were observed in 65% (torso) and 34% (lower extremities) of all cases.

The results from the injured body regions might only represent the minimum percentage of occurrence, since it may be possible that injuries, which were not causative for the death of the cyclist (e.g. arm fractures), are not mentioned in the medical report and in fact, not taken into account for further analysis. One point that is indicating that the real percentage of arm injuries AIS2+ is higher than recorded, might be the reviewed injury distribution mentioned in chapter 3.4.3, where injuries of upper extremities occurred in almost 50% of all cases (car velocity below 40kph and also above 40kph) [32].

Impact regions of the femur on all three chosen vehicle front geometries were quite the same: The very front of the car until the upper half of the hood. Only for Superminis no impacts on the upper hood could be recorded. The thorax impact range reached further towards the roof for Superminis and further to the front of the car for MPV/1-Box compared to Family Cars. Similar behavior showed the head impact on all three car geometries: The highest percentage of roof impacts had the Supermini (similar to the small hood, large windshield angle car front geometry mentioned in chapter 3.3.2, which represented also the largest proportion of head to roof impacts [24]), followed by the Family car and no roof impacts at all could be recorded for the MPV/1-Box. Beside of influence factors of the bicycle on the impact high of the head and thorax, the reason for these differences, regarding the car front, may have their origin in geometry parameters, like bonnet leading edge height, the relative length of the bonnet and the windshield, as well as their angles.

When taking a look at Figure 6-25 (Family Car impact regions) and Figure 6-23 (Impact angle of the bicycle), a high amount of impacts on the right side of the car can be recognized. While the femur has its first impact mainly on the right side of the car front, the thorax and especially the head has a much more balanced impact all over the car front. On the one hand a strong dependency of the impact of the thorax and even more the head on the speed and relative angle of the bicycle can be assumed, on the other hand however, to which extend this really influences the impact points should not further be discussed in this thesis.

When extending the impact data, generated from the mentioned front geometries, to impact data from Roadster and SUV impact regions (49 accidents), no single head impact on the hood of the cars can be recorded. Same results show multi body simulations, which were reviewed earlier in chapter 3.3.2, with less than 5% hood impacts [24].

A Finnish study, based on accident reconstruction, revealed that 57% of all fatal injuries are caused by impacts with the windshield (including windshield frame) [37]. For the analyzed accidents in this thesis, the windshield caused most of fatal head injuries (64%) and also numerous fatal thorax injuries. AIS2+ injuries of the femur were mainly caused by the lower part of the hood and the bonnet leading edge. The mentioned injury sources are also represented in the top five damaged car parts, which shows somehow a relation between damage and injury source. Another part which has a high proportion of damages is the bumper. These damages could be caused by the impact with the lower leg, knee, upper leg or bicycle frame as well. Another interesting injury source for lower extremity injuries is the leading bonnet edge, which were causative for some tibia or femur fractures, observed within accident reconstruction (the latter the most frequent low extremity injury [19]).

What seems to require closer inspection is the dependency of kinematics, impact points and in fact injuries on the pedal position of the bicycle at the moment of the collision with the car. During car to bicycle accident reconstructions, it could be discovered, that the position of the pedal has a substantial influence on the kinematic behavior of the motion of the multi body system. Thus, adjusting of pedal positions supported regularly the correct reconstruction of impact points. In fact the variation of injury sources for lower and upper leg seems to be able to lead to ambiguity often and could be therefore an interesting point for further researches.

Impact points of the cyclist's heads were mainly distributed on the windshield of the car for all front geometries. Component tests according to the directive 2009/78/EG consider the windshield as impact region only for monitoring purpose. There are no specific limits for head impacts on the windshield. Furthermore head impacts on the roof are totally neglected. For the reconstructed bicycle accidents however more head impacts on the roof than on the hood could be found. Also the Euro NCAP executes head impact test mainly on the hood and lower half of the windshield and may therefore neglect a large proportion of possible head impacts towards the upper windshield and roof as well.

7 CONCLUSION

This thesis has covered a broad spectrum of car to bicycle accident parameters by analyzing real world accidents, previously reconstructed, as well as national accidents that have been recorded by Statstik Austria. The following conclusion can be drawn:

- For fatalities as well as injured cyclists there is a larger amount of male cyclists than female cyclists (62% of injured cyclists and even 71% of fatalities). In terms of specific age groups, the highest injured cyclist percentage was seen in 10-14 year old cyclists. In contrast fatalities could be recognized for cyclists mainly of older age - between 60 and 80 years.
- While most accidents occurred in urban areas, rural areas are of greater importance when it comes to serious injuries and fatalities (only 14% of slightly injured cyclists, in contrast 50% of fatalities noticed on rural roads).
- Injuries and fatalities had their peak in the afternoon, between 5 and 6, which reflect the pattern of urban bicycle traffic. A much lower amount of injured cyclists and fatal cyclists could be observed in the morning hours between midnight and 5 a.m. (when the bicycle and car traffic were low). Although the number of injured cyclists decreased from 6 p.m. to midnight, there was an increase of fatalities that could be recognized between 9 p.m. and 12 p.m.
- The most frequently occurring accident scenarios were cross-section accidents. Most frequently here were accidents where the vehicles were approaching in right angles to each other. When excluding cross-section accidents, overtaking accidents caused the highest number of slightly and severely injured cyclists. An outstanding percentage of fatalities could be noticed for rear end collision.
- Inattentiveness and very often resulting ignoring of priority are the main causative factors for bicycle to car accidents. In 65% of all reconstructed CEDATU cases, no speed reduction of the car before the impact with the bicycle could be observed. Possibly causative factors were mainly driver conditions, high car speed and lightning conditions (about 30% of the accidents happened in moments of not sufficient light or dazzled sun).
- In regards to car damages after a collision with a bicycle, damages to the car front reflect 80% of all cases. In 49% of all reconstructed front collisions the right third of the car represented the first impact point of the bicycle on the surface of the car. Overall, the windshield was the most frequently damaged car part followed by the hood, fender and bumper.

- In most of the analyzed bicycle fatalities, a head injury (AIS2+) could be found (in 81% of all accidents), which was the causative factor leading to death in most of the cases (58%). Thorax, arm and upper leg injuries contributed with high AIS2+ injury percentages as well (65%, 23%, 23%).
- The car part most responsible for fatal head injuries was, in the most cases, the windshield (64%), followed by the a-pillar and the roof. For the considered car geometries the head impacted exclusively with the windshield and roof of the car (for the MPV/1-Box no roof impact). The area of thorax impact ranges from the upper half of the hood to the lower half of the windshield for the Family Car. This range extended to the upper half of the windshield for Superminis and until the lower half of the hood for MPV/1-Box. Femur impacts are most frequently observed on the lower half of the hood for all considered front geometries.

It cannot be ignored that a large number of fatal car to bicycle accidents are rear end collisions and that inattentiveness of the car driver plays an essential role for the causation of most scenarios. As a result, further research of the use of driving assistance in real world accidents is suggested. The possibility of avoidance or at least reduction of the impact velocities and how this affects the impact speed of each cyclist’s body part remains to be studied.
Another approach that could be an objective for future research could be the analysis of active safety systems that have been implemented for reducing pedestrian injuries, such as hood airbags. A point to ponder is if they would cause positive effects for cyclists as well, as the majority of head impacts happen in conjunction with the windshield and roof. The same concerns may exist for current legislations, where the head impactor test is only applied on the hood of the car.
Furthermore, the influence of varying bicycle speeds (including several impact angles) and pedal position on the impact regions and impact forces could be analyzed by studying generic car-to-bicycle accidents.

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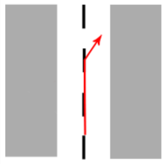
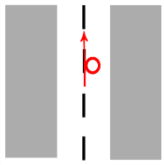
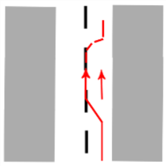
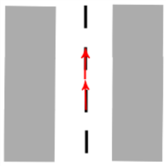
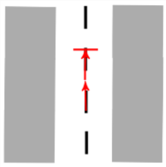
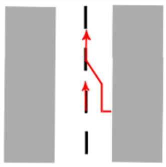
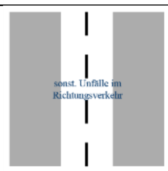
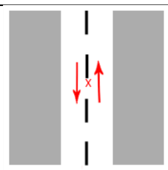
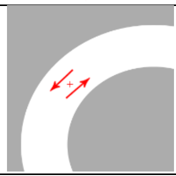
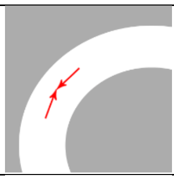
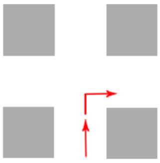
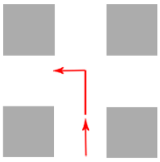
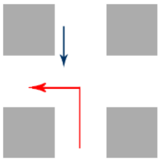
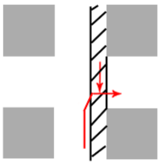
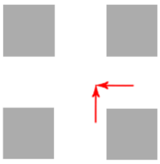
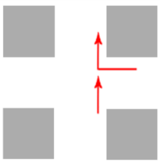
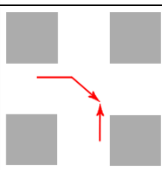
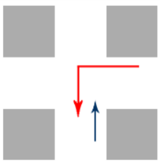
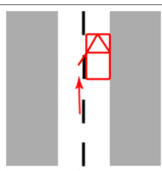
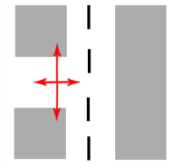
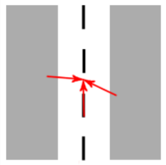
APPENDIX

Table 5: Accident types [4]

Type general	Type specific #		Description
Single vehicle accidents	011		single vehicle accident due to leaving the road on the right side of a straight section
Single vehicle accidents	051		single vehicle accident due to sideway skidding or forward skidding and overturning of the vehicle
Collision between two vehicles driving in the same direction	112		collision between two vehicles driving in the same direction after overtaking on the right side and returning to the original lane
Collision between two vehicles driving in the same direction	131		rear-end collision into moving vehicle on a straight section
Collision between two vehicles driving in the same direction	141		rear-end collision into stationary vehicle on a straight section
Collision between two vehicles driving in the same direction	181		collision of a vehicle which is merging into traffic from the right with a vehicle which is moving in the same direction
Collision between two vehicles driving in the same direction	191		other collisions between two vehicles driving in the same direction
Collision between two vehicles driving in the opposite direction	231		Lateral collision between two vehicles proceeding in opposite direction on a straight section
Collision between two vehicles driving in the opposite direction	232		Lateral collision between two vehicles proceeding in opposite direction in a curve

Collision between two vehicles driving in the opposite direction	242		collision between two vehicles proceeding in opposite directions in a curve
Collision while turning – same direction	312		collision of a vehicle which is turning right from the second lane at a junction with another vehicle which is moving straight ahead
Collision while turning – same direction	322		collision of a vehicle which is turning left from the right lane at a junction with another vehicle which is moving straight ahead
Collision while turning – opposite direction	411		collision of a vehicle which is turning left with an-other vehicle which is proceeding from the opposite direction to the left-turning vehicle at a junction
Collision while turning – opposite direction	451		collision of a vehicle which is turning right with a bicycle which is proceeding in the opposite direction to right-turning vehicle on a special track (e.g. cycle way, right-of-way)
Crossing collisions without turning	511		collision at a junction of two vehicles proceeding at right angles to each other
Crossing collisions with turning	611		collision at a junction of a vehicle which is crossing straight ahead with another vehicle which is turning right
Crossing collisions with turning	621		collision at a junction of a vehicle which is moving straight with a another vehicle which is turning right in the opposite direction to the first vehicle
Crossing collisions with turning	622		collision at a junction of a vehicle which is moving straight with a another vehicle which is turning left in the opposite direction to the first vehicle
Collision with a stopping or parking vehicle	741		collision of a vehicle which is driving past left with an open vehicle door of another vehicle which is parked or stopped on the right side of the road

Other accidents with 2 or more participants	948		collision by the entrance of a building or plot
Other accidents with 2 or more participants	951		collision with a bicyclist coming from the left or right side

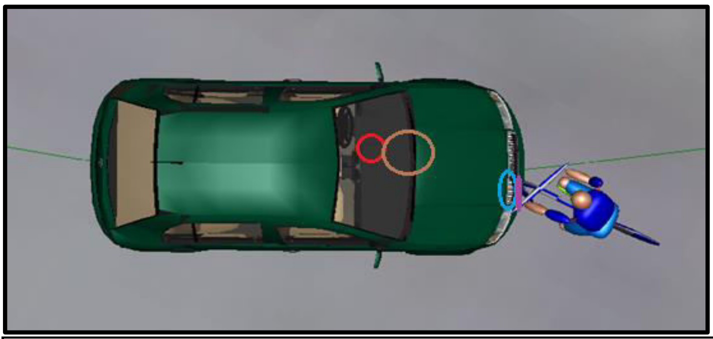
FE-Bicycle accident selection:

TUG-4165062

Car	Model			Skoda Fabia 50kW 2000
	velocity			30 km/h
	pre brake			no
bicycle	velocity			20 km/h
	angle			30°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	swan's neck
			z coordinate seat	775mm
			seat height	40mm
			z coordinate chain wheel	305mm
		human	hight	171cm
			weight	82kg
	Position	pedal		right knee up
		thorax angle		standard
x,y distance	x-Front Wheel-CenterCar			0,776m
	y-Front Wheel-CenterCar			1,715m

cyclist injuries
multiple rib fracture left
basal skull fracture right



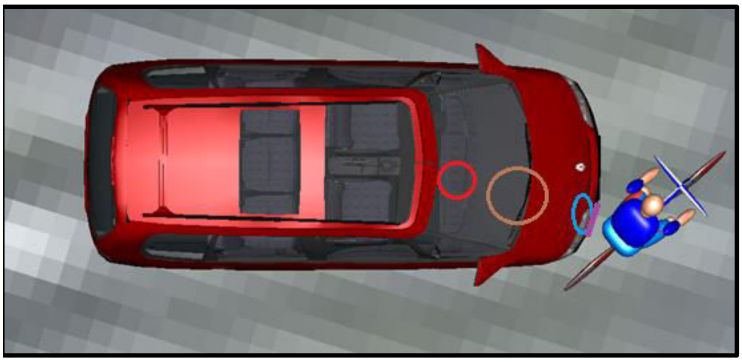


TUG-4454479

Car	Model			Renault Espace 65kW 1993
	velocity			70 km/h
	pre brake			yes
bicycle	velocity			15 km/h
	angle			42°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	trapeze
			z coordinate seat	811mm
			seat height	40mm
			z coordinate chain wheel	307mm
		human	hight	179cm
			weight	86kg
	Position	pedal		standard
		thorax angle		standard
x,y distance	x-Front Wheel-CenterCar			3,13m
	y-Front Wheel-CenterCar			0,08m

cyclist injuries
nasal fracture
dental injury
cervical fracture
rib fracture
rupture aorta





red	head
olive	thorax
blue	upper leg
purple	lower leg

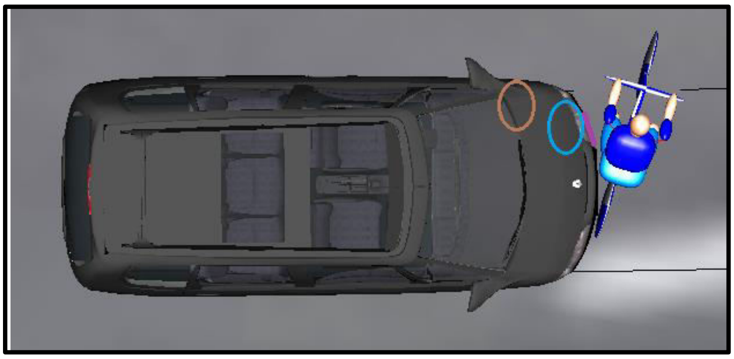
TUG-4171859

Car	**Model**			Renault Megane 72kW 1998
	velocity			60 km/h
	pre brake			yes

bicycle	**velocity**			15 km/h
	angle			107°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	trapeze
			z coordinate seat	559mm
			seat height	40mm
			z coordinate chain wheel	305mm
		human	hight	164cm
			weight	71kg
	Position	pedal		standard
		thorax angle		15° racing

x,y distance	**x-Front Wheel-CenterCar**	1,395m
	y-Front Wheel-CenterCar	2,489m

cyclist injuries
traumatic brain injury (ground impact)
cerebral hemorrhage (ground impact)
multiple skull fracture (ground impact)
multiple rib fracture left
tension pneumothorax left
hemopneumothorax right



TUG-4468113

Car	**Model**			Skoda Octavia 81kW 1998
	velocity			45 km/h
	pre brake			no

bicycle	**velocity**			10 km/h
	angle			116°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	kids bike (mountain)
			z coordinate seat	635mm
			seat height	40mm
			z coordinate chain wheel	203mm
		human	hight	130cm
			weight	29kg
	Position	pedal		left knee up
		thorax angle		standard

x,y distance	**x-Front Wheel-CenterCar**	2,072m
	y-Front Wheel-CenterCar	0,763m

cyclist injuries
multiple skull fracture (rear,left)
lung contusion
serious brain edema

head
thorax
upper leg
lower leg

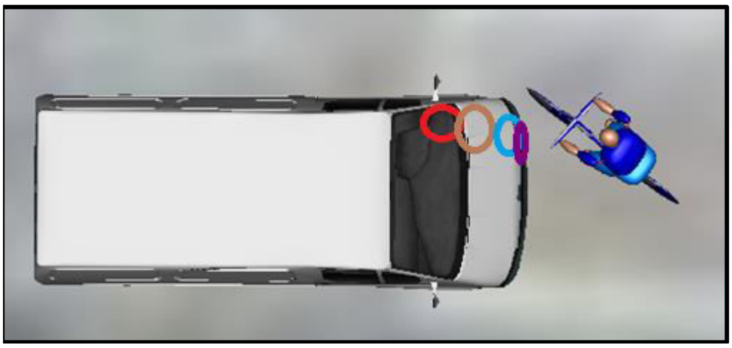
TUG-4161240

Car	**Model**			Ford EDS Transit 63kW 2000
	velocity			70 km/h
	pre brake			no

bicycle	**velocity**			15 km/h
	angle			35°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	Trekking bike
			z coordinate seat	760mm
			seat height	40mm
			z coordinate chain wheel	300mm
		human	hight	164cm
			weight	75kg
	Position	pedal		standard
		thorax angle		standard

x,y distance	**x-Front Wheel-CenterCar**	0,584m
	y-Front Wheel-CenterCar	2,604m

cyclist injuries
facial contused laceration and cutting injuries
injured shoulder and collarbone
fracture lower arm
fracture left upper leg
knee "unhappy triad"
fracture lower leg
serial rip fracutre
rupture heart, aorta, spleen, liver, pancreas
hemopneumothorax



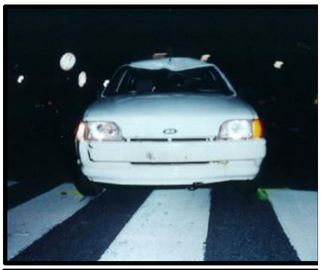
TUG-4461210

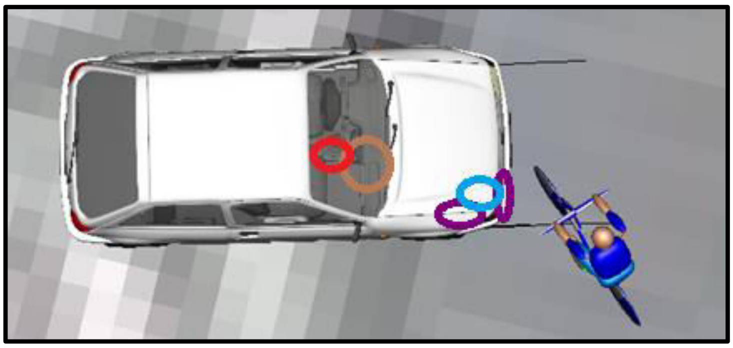
Car	**Model**			Ford Fiesta 37kW 2000
	velocity			30 km/h
	pre brake			yes

bicycle	**velocity**			15 km/h
	angle			65°
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	City Bike
			z coordinate seat	812mm
			seat height	40mm
			z coordinate chain wheel	305mm
		human	hight	168cm
			weight	61kg
	Position	pedal		left knee up
		thorax angle		standard

x,y distance	**x-Front Wheel-CenterCar**	2,239m
	y-Front Wheel-CenterCar	0,136m

cyclist injuries
skull fracture
vertebral fracture
brain contusion
contused laceration knee right





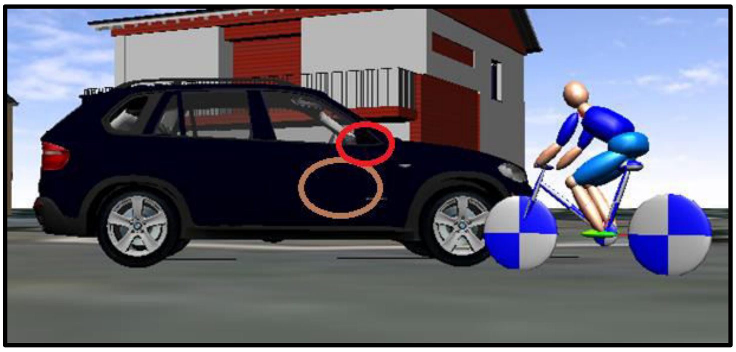
(red)	head
(olive)	thorax
(blue)	upper leg
(purple)	lower leg

TUG-4476000				
Car	Model			BMW X5 160kW 2000
	velocity			16 km/h
	pre brake			no

bicycle	velocity			20 km/h
	angle			-
	friction	bike		0.7 µ
		human		0.2 µ
	Dimension	bike	type	Racing bike
			z coordinate seat	843mm
			seat height	40mm
			z coordinate chain wheel	308mm
		human	hight	177cm
			weight	86kg
	Position	pedal		standard
		thorax angle		20° racing

x,y distance	x-Front Wheel-CenterCar	2,262m
	y-Front Wheel-CenterCar	0,389m

cyclist injuries
traumatic brain injury
pneumothorax
serial rip fracture
fracture upper arm right



red	head
olive	thorax
blue	upper leg
purple	lower leg