

# **CHARACTERISTICS ON FRACTURES OF TIBIA AND FIBULA IN CAR IMPACTS TO PEDESTRIANS AND BICYCLISTS – INFLUENCES OF CAR BUMPER HEIGHT AND SHAPE**

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## **ABSTRACT**

This study deals with the analysis of lower leg fractures in pedestrians and bicyclists after collisions with passenger cars and examines to what extent the shape and location of the fractures in the lower leg changed, following alterations in the shape of bumpers. It can be assumed that the bumpers changed in shape and effective impact height, not least due to the realization of the developments of vehicle safety tests as in the context of the European Union Directive 2003/102/EC on pedestrian protection. In addition, consumer protection tests, EuroNCAP, accomplished a change of the injury situation. All of these are mainly focused on pedestrian protection measurements but adopt the bicyclists also in their goal.

For the study, traffic accidents from GIDAS (German in-Depth-Accident Study) were selected, which had been documented in the years 1995 to 2004 by scientific teams in Hannover and Dresden (Germany) and for which there is detailed information regarding injury patterns and collision speeds. The accident documentations can be regarded as representative and constitute a random sample with statistic weighing of the data. Altogether 143 cases of lower leg fractures (Tibia/ Fibula) with x-rays of pedestrians and 79 cases of bicyclists were differentiated according to new and old vehicles (year of manufacture before/after 1995). The bumper shapes were divided into classical types (protruding pronouncedly/ protruding integrated /integrated rounded). Besides the injuries to the lower leg, those to thighs and feet were also regarded, and the injury conditions involving the head and trunk were included in the kinematic analytics.

**PEDESTRIAN AND BICYCLIST SAFETY** has significantly improved over the past 30 years. While in 1975 in a country like the Federal Republic of Germany (StBA, 2006), n=3973 fatal pedestrians and n=1387 fatal bicyclists and additionally n=60033 casualties amongst pedestrians as well as n=45317 casualties amongst bicyclists were recorded, the number of n=686 fatalities and n=33803 casualties on pedestrians and n=475 fatalities and n=73162 casualties on bicyclists in

the year 2005 seems to good in comparison. Nevertheless it should not be overlooked that in today's Europe of 27 different countries there are still far more than approximately 8,000 pedestrians and cyclists, also categorized as Vulnerable Road Users (VRU), killed and a further 300,000 are injured each year in road accidents in Europe. This requires manifold efforts of scientific research, which can no longer be limited exclusively to passive security like injury reduction, but must also aim at measures of active security for the avoidance of accidents.

This study is concerned with the question to what extent changes to the front design of vehicles - particularly the bumper - caused by test activities and by the test conditions for new vehicles, change the resulting injury pattern on the lower legs of pedestrians and bicyclists. To this end, fractures of the lower legs of pedestrians and bicyclists have been examined after collisions with passenger cars, in order to determine impact height of the bumpers and changes to the fractures of the lower legs, regarding characteristic and location. It can be assumed that that the bumpers changed in shape and effective impact height, not least due to the realization of the developments of vehicle safety tests as specified in the context of the European Union Directive 2003/102/EC (2003). In addition, consumer protection tests, EuroNCAP, accomplished a change of the injury situation. All of these are mainly focused on pedestrian protection measurements but adopt the bicyclists also in their goal. What differences are there between pedestrians and bicyclists concerning their injury pattern?

The test according to the European Union directive as well as that according to EuroNCAP stipulate that with the so-called "Lower leg form impactor" at an impact speed of 40 km/h no accelerations of more than 150 to 200g may occur and that the dynamic lateral shift amounts to less than 6 mm and that the maximum knee bending angle is not to exceed 21 degrees. It is to be expected that this will result in larger force transfer areas of the bumper bodies and to a higher location of the force transfer area in the lower leg especially of the pedestrians compared to the situation of a pedestrian the seat position of a bicyclist is approximately 10 cm higher and the inclined position of the leg depends from the pedal's downward or upward position.

It is the goal of this study to examine the traffic accidents documented in collections of GIDAS at accident sites in Hannover and Dresden for accidents involving pedestrians and bicyclists with passenger cars and for this purpose to analyse the characteristics of the fractures and measure the heights of fractures of the lower legs from x-rays and to assign them to the geometrical shapes and heights of the bumpers. In order to recognize possible shifts of the injury spectrum and the injury mechanisms responsible for the occurrence of the fracture, all accompanying fractures occurring along the entire leg have to be regarded. In order to be able to recognize the influence of newer vehicle models, the vehicles involved should be differentiated according to the

year of their manufacture. As the authors were unable to determine exactly when innovations at the vehicles were incorporated in the bumpers, passenger cars built after 1995 are classified as new.

## **CASE BASE AND METHODOLOGY**

Investigations at the site of accidents, GIDAS (German-In-Depth-Accident-Study financed by the German Federal Highway Research Institute BAST in cooperation with the German Car Industry Research Association FAT), are prospectively accomplished accident documentations, where a scientific team drives to the accident scene immediately after the accident has occurred, alarmed by the police, and conducts the data documentation there, independently of the police (Brühning, 2005). To this end, accident traces and vehicle deformations are recorded and the course of the accident, including the collision speeds, is reconstructed. A comprehensive documentation of the vehicle damages is executed using detailed measurements (Otte, 2005). Thus bumper heights and shapes for the respective vehicle model are ascertainable. The injuries are usually recorded photographically, among other things, by a colleague in the hospital, even before the medical treatment has taken place. Here there is usually also access to the x-rays, which are stored digitally, and from which the type of fracture can be gleaned. For this purpose, in the context of this study the classification according to AO (Arbeitsgruppe für Osteosynthesefragen) (Müller, 1992) was used. All injuries are documented in detail and classified according to AIS (American Association for Automotive Medicine, 1998). The bumper heights and profiles were derived from technical data sheets referring to the vehicles investigated by the team, by means of VIN identification. It was possible to assess the fracture heights from a scaled projection from the radiographs as percentages of the basis of the Malleolaris and transform them to the metric system of persons injured with the help of basic anthropologic data of the lower leg lengths (Flügel, 1986).

It was possible to select altogether 143 cases from all pedestrian-passenger car accidents and 79 cases from bicycle - passenger car accident recorded in the years from 1996 to 2004 based on the applied criteria (collision with the front of the vehicle, fracture of the lower leg, no light trucks N1 vehicles were included, but vans or SUVs are included), for which all relevant information concerning injuries and the technical characteristic data of speed and impact deformations was present. These could be used to make general statistically descriptive frequency representations of the injury situation and the vehicle details. X-rays were required for a detailed look at the fractures, but they were only available in 48 cases of pedestrians and 31 cases of bicyclists. Thus the evaluations of the heights of the fractures related to other parameter

could be carried out on this number of cases, therefore frequency presentations may be based on different n-numbers.

Even if only accidents having occurred after 1995 are included, still a percentage of older cars is involved, i.e. passenger cars manufactured before 1985 were involved in 6.6% of the accidents, 19.9% were manufactured between 1985 and 1989, 36.5% between 1990 and 1994 and only 37.0 % were built after 1995 – thus approximately one-third of the population regarded (figure 1).

## SHAPES OF BUMPERS IN ACCIDENTS INVOLVING PEDESTRIANS AND EFFECTIVE HEIGHTS OF IMPACT

For classification purposes the frontal shapes of passenger cars were sub-divided into 4 different types A, B, C, D (figure 1) regarding the shape of the bumpers.

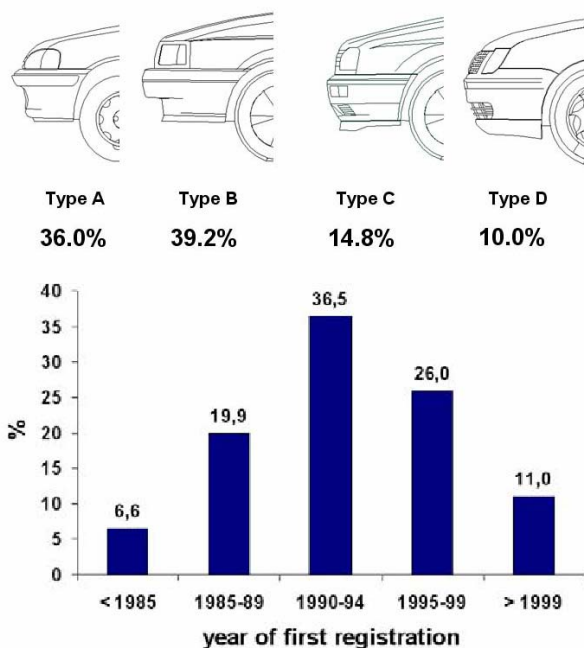


Figure 1: Classified frontal shapes of bumpers and the incidence of involvement in accidents with pedestrians and bicyclists (n= 181, all vehicles = 100 %)

Corresponding to the relatively old population of vehicles in the current accident situation, two thirds of the bumpers were protruding and rather rectangular (Type A at 36.0% and Type B at 39.2%). Newer, significantly rounded bumper structures, which have also been integrated into the front of the vehicle (Type C and D), are represented in accidents in only 14.8% (Type C) and 10.0 % (Type D) of the cases.

The effective height of impact was derived from the sideways profile of the vehicle and the part protruding most was chosen as impact transfer point, the height of which was measured from the road level. If this was not a well-defined point, but rather an area, as can be seen for the shown picture of type B in figure 1, this was taken into account by entering two values for the "lower and upper edge of the bumper". Eighty percent of the bumpers had an effective static impact height of at least 40 cm and at most 52 cm with a maximum at 70 cm for Sport Utility Vehicles SUV (figure 2). The so-called nose-dive of the front occurring during the application of the brakes due to the distribution of the braking power was provided for with a reduction of 8 cm for establishing the effective dynamic bumper height and resulted in the fact that 80 % of the effective dynamic impact power is transferred between heights of 32 cm at least and 44 cm at most.

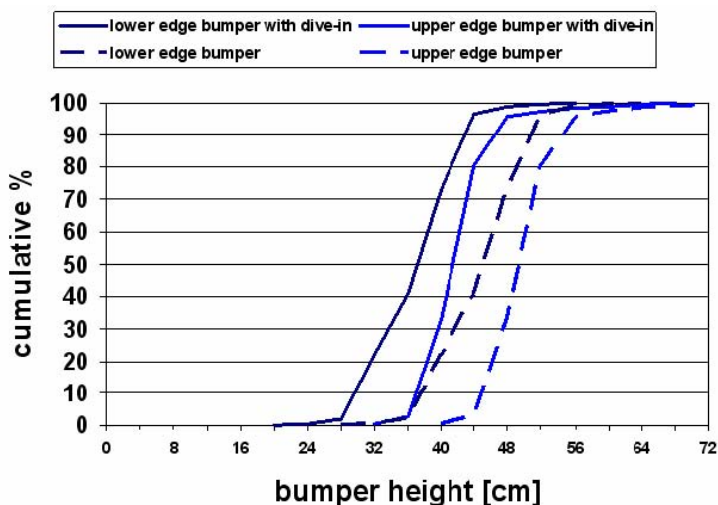


Figure 2: Cumulative frequency of the bumper heights, a measured static height and a derived dynamic height including an 8-cm nose dive (n= 181, 100 %)

# TYPES OF FRACTURES ON TIBIA AND FIBULA AND CORRELATION TO THE BUMPER HEIGHTS

In more than half of the cases (53.8%) both bones of the lower leg, tibia and fibula, of the pedestrians, were fractured; in 23.8% only the tibia and in 22.4% only the fibula. In 36.7% of the cases of bicyclists both bones of the lower leg, tibia and fibula, were fractured; in 21.5% the tibia only and in 41.5% the fibula only. Each long bone was subdivided into intervals as percentages of 10% each. If several fractures had occurred on one bone, these were separately included in the evaluation as lower and upper fractures. Clusters of fractures were found for pedestrians at 31 to 40 % (18.6%), at 51 to 60 % (15.2%) and at 81 to 90 % (22.0%).

This corresponds to the three most frequently occurring fracture heights at the lower leg of pedestrians at bumper heights of 20 to 25 cm (18.6%), of 30 to 35 cm (15.2%) and of 40 to 45 cm (22%). Eighty percent of all fractures of pedestrians occurred at effective dynamic bumper impact heights of at least 32 cm up to 44 cm above road level (Figure 3). Eighty percent of all fractures of pedestrians occurred at a height of 19 cm to 45 cm above road level. This demonstrates that the location of the fracture at the lower leg of pedestrians is frequently situated below the point of force transmission during the bumper impact to the leg that has been determined.

In comparison to pedestrians the bicyclists suffered fractures much more frequently in the lower distal region of tibia/fibula, 26.5% in the area of 20 to 30% height from the ankle joint and 14.7% up to 10% near the joint area. Two-third of the fractures of bicyclists suffered from heights on the leg up to 28 cm compared to 36 cm for pedestrians (figure 3b).

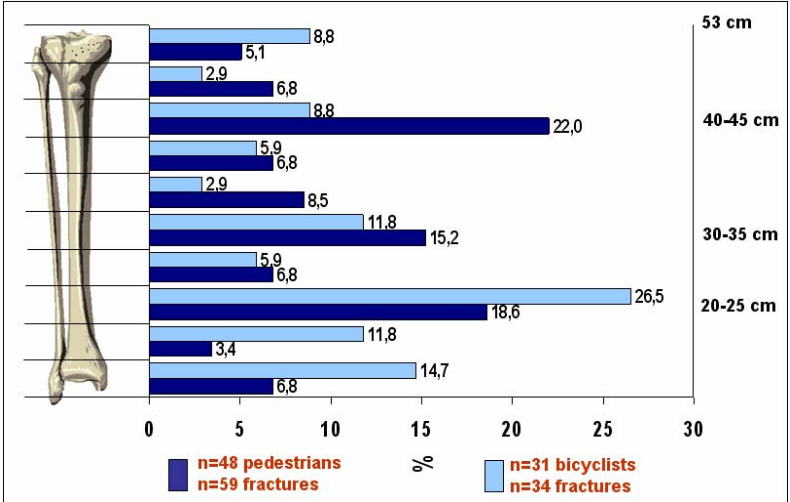
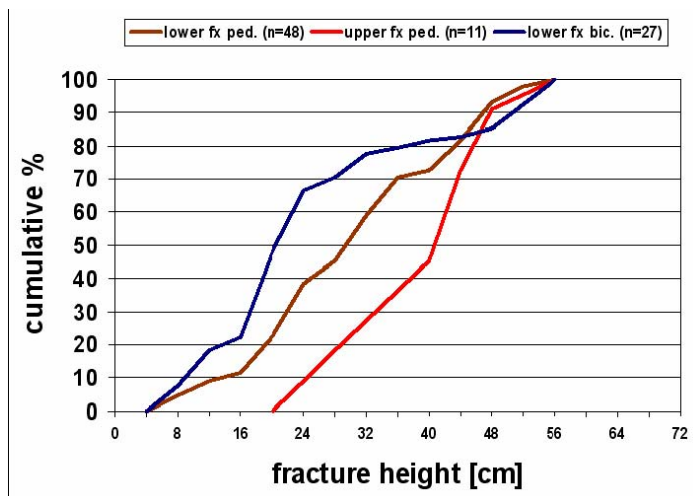


Figure 3a: Incidence of fractures of the lower leg (Tibia and/or Fibula - total length of the lower leg =100 %) and cumulative incidence of the fracture heights from the level of the road in cm Figure 3b: Incidence of fractures of the lower leg (Tibia and/or Fibula - total length of the lower leg =100 %) and cumulative incidence of the fracture heights from the level of the road in cm



If the heights of the fractures are correlated to the effective, dynamic heights of the bumpers, it turns out that 80% of all fractures of pedestrians are located between 19 and 46 cm, whereas 80% of the impact forces are transferred at heights of 32 to 44 cm of the lower leg. Thus the cause of the fractures is frequently located above the fracture itself (Figure 4). Fracture height and bumper height were for pedestrians only identical in 1.5% of the cases, in 47.5% they were lower and in 35% higher.

For bicyclists it can be seen that the height of the fracture is mostly located much lower on tibia/fibula mostly near the ankle joint area. 80% of the fracture heights were found between 9 to 48 cm, while 80% of the bumper heights could be established between 32 and 46 cm above ground level.

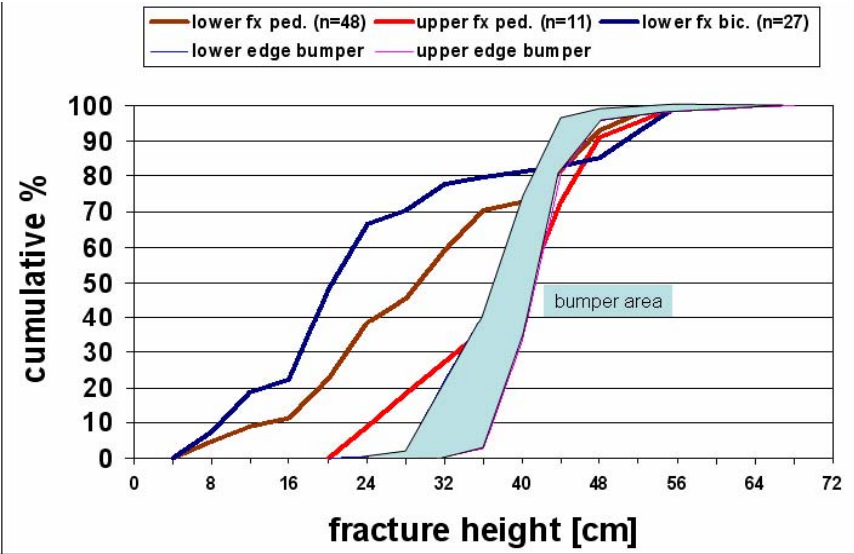
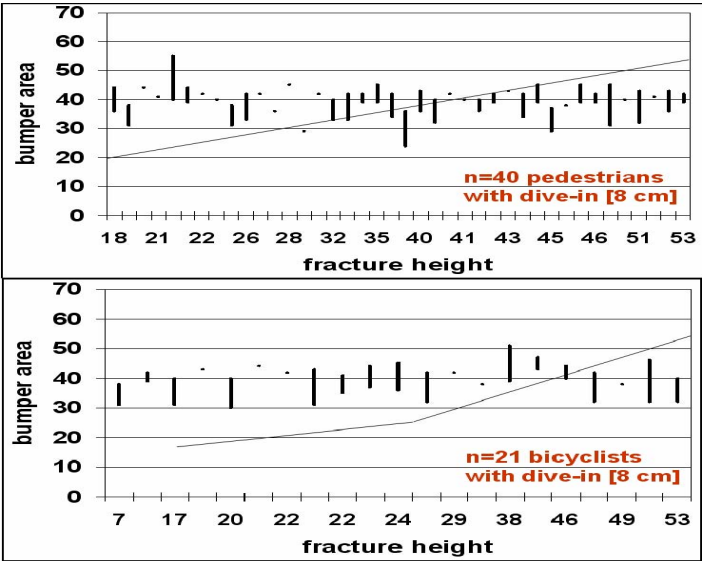


Figure 4a: Measured fracture heights and effective dynamic bumper heights in cm (the line indicates identical heights). The x-axis is non-linear; representation of individual data only  
 Figure 4b: Measured fracture heights and effective dynamic bumper heights in cm (the line indicates identical heights). The x-axis is non-linear; representation of individual data only





# **TYPES OF FRACTURES AND INFLUENCING PARAMETERS**

The AO classification consists primarily of 4 numbers or letters for describing a fracture. The AO as the world's leading organization in the area of osteosynthesis was founded in Switzerland in 1958. Its members are surgeons from all over the globe, who have joined forces to establish uniform standards and operating practices. By establishing individual codes, the associated skin, soft tissue and vascular-nervous injuries were classified. The assessment of the soft-tissue damages was not taken into account for this study, as the hospital documentation did not always contain exact references to the details of soft-tissue defects. For this study we exclusively used the evaluation of fractures according to their degrees of complexity as in: Shaft fractures according to A=simple fracture, B= wedge fractures, C=complex fracture. For broken joints A= extra-articular, B=partially broken joint and C= completely broken joint. In addition, a grading according to the location on the bone is conducted into the proximal, middle and distal thirds.

Especially frequently fractures occurred in the shaft region as shown in Figure 5 (location 42). For pedestrians and bicyclists a nearly same distribution of frequencies can be established. But pedestrians seems to suffer more complex fracture types as multiple fractures (Type C2 n=8), as well as the wedge fracture named after Messerer (Type B2 n=7) and the Oblique fracture Type A2 (n=9) also frequently occurred for bicyclists. Remarkable is for bicyclists that multiple fractures types C occurred very few and B1/B2 types are relatively more frequent.

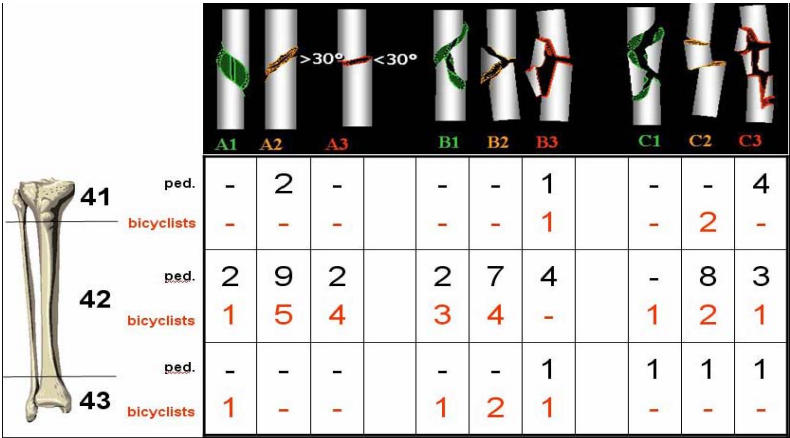


Figure 5: Incidence of fractures according to the AO classification, comparing overall situation and impact velocities <40 km/h

The analysis of different bumper shapes shows that for pedestrians as well as for bicyclists the bending wedged fractures (Type B2) occurred with all bumper shapes, multiple fractures (Types C2 and C3), however, only occurred in collision with cars having A and B bumpers labeled as "old" (figure 6). In contrast, the bumper shapes of the newer cars with integrated and rounded bumper shapes (groups C and D) showed fewer fractures altogether on the one hand, and on the other hand only oblique fractures of the types A1, A2, B2 and no C fractures occurred. Generally, these constitute easily treatable fractures, as a rule without treatments possibly leading to complications.

The origins of fractures are also influenced by the impact power, i.e. impact velocity, besides the design and height of the impact area of the passenger car. In this case the skid marks and the final positions of the vehicles as well as those of the pedestrians and the cyclists were used to determine the impact velocity. For bicycle accidents there could be used the scratch marks on the road of the throw distance of the bike for determination of impact speed as well.

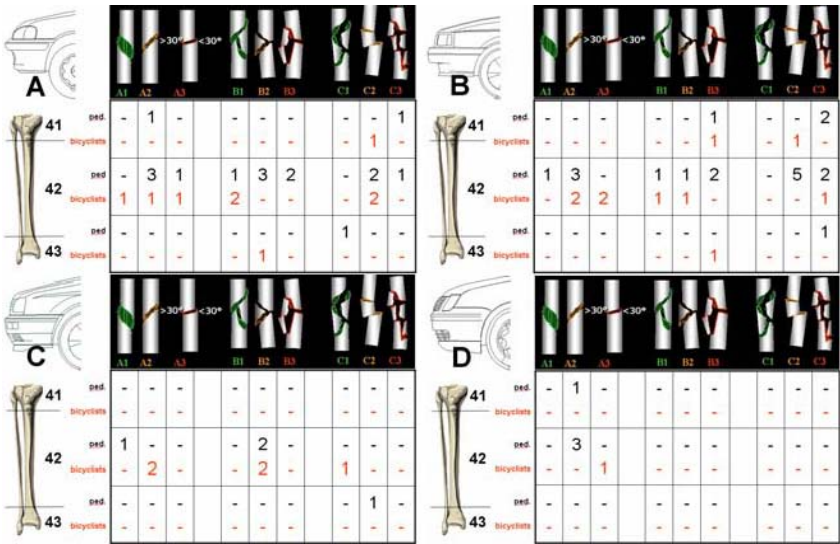


Figure 6: Incidence of fractures according to the AO classification for different bumper types A, B, C, D; comparing the total population and impact velocities <40 km/h

80 % of the documented fractures occurred at collision speeds of up to 55 km/h (Figure 7). Eighty percent of the pedestrians were hit between 20 and 70 km/h of car velocity. The impact speed of bicyclists was mostly lower than for pedestrians (up to 30 km/h: 50% of bicyclists compared to 30% of pedestrians). A correlation between origin of the fracture and the kind of fracture based on the impact velocity was not established. For pedestrians the types of fractures close to the knee (area 41 proximal lower leg) obviously all occur in the lower speed ranges, whereas the shaft fractures in the middle third occurred more frequently at velocities > 40 km/h. Fractures in the area of the ankle (distal lower leg) nearly all occurred at higher impact velocities while these occurred often for bicyclists in lower speed ranges too.

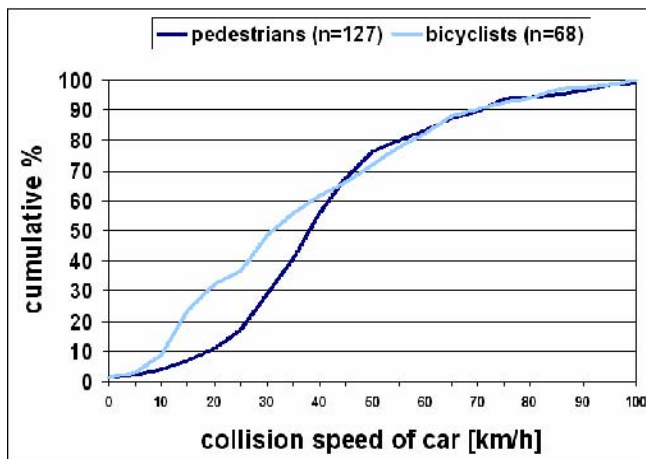


Figure 7: Cumulative incidence of collision speeds of passenger of accidents involving cars and pedestrians compared to bicyclists resulting in fractures

No statistic tests could be carried out for the fracture situation of bicyclists, the numbers were too low for that and the position of the leg relatively to the bumper height spreads too much.

In the statistic tests of pedestrian fracture and bumper height a low negative correlation between collision speed and the height of the fracture ( $r=-0.321$ ,  $p=0.053$ ) resulted; no correlation to the mean bumper height was found (figure 8). If the simultaneous effects of collision speed and the height of the bumper on the height of the fracture are investigated based on a regression analysis, it turns out that only the collision speed has an influence of the origin of the fracture (high-lighted yellow) and at  $p=0.058$  a statistically low one. This interrelation can be expressed in a three-dimensional diagram (figure 9). Using a square fit of the regression analysis it was proved, that the height of the fracture is reduced significantly with the increase in impact velocity on the one hand and

only increases with very high speeds of approximately 60 km/h, and that on the other hand, the height of the bumper seems to have very little influence on the height of the fracture. Still, for very low and very high bumpers a lower height of the fractures occurred more frequently and only for bumper heights between 33 and 43 cm a constant correlation was found.

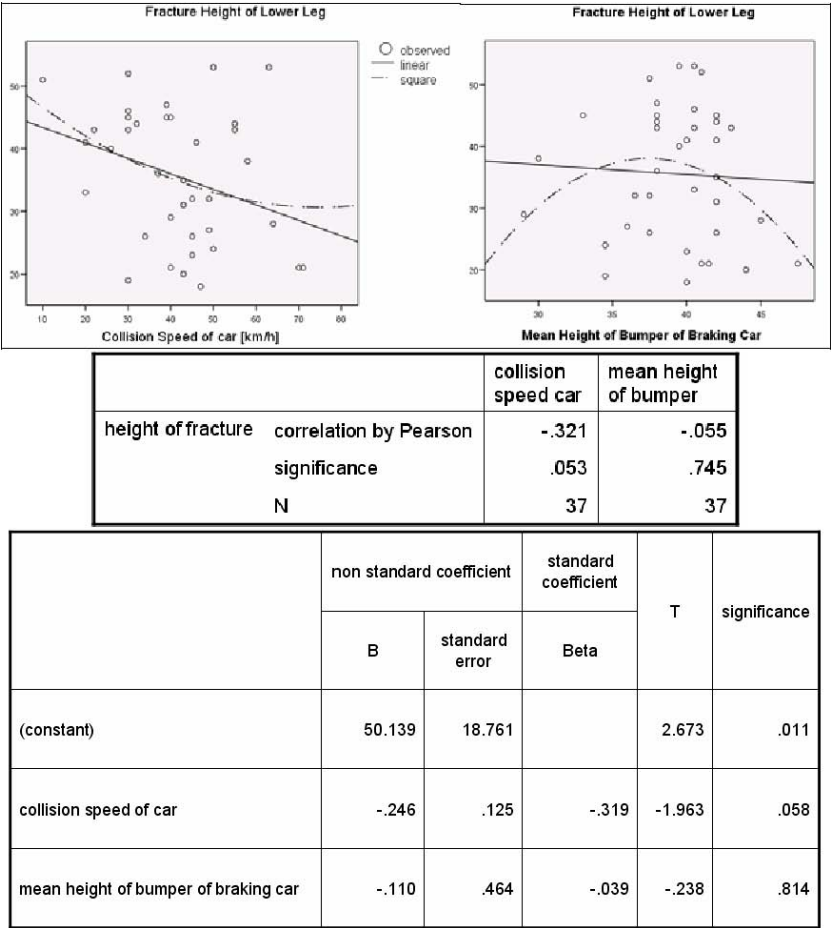


Figure 8: Regression analysis for pedestrian-car-accidents of the correlation between collision speed, the height of the fracture and the height of the bumper

## the height of the bumper

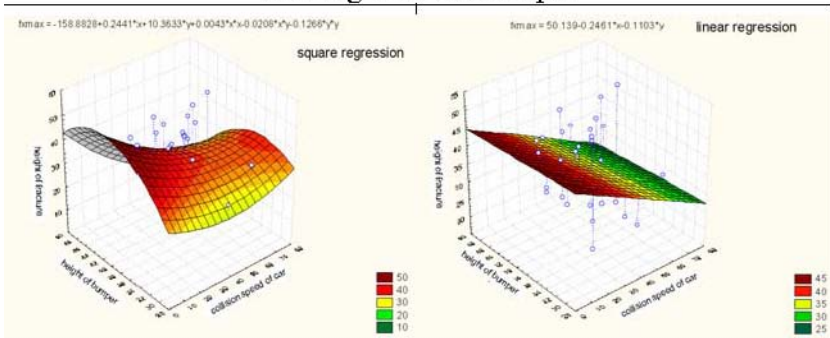


Figure 9: Linear and quadratic adaptation of the regression areas of collision speed vs. height of the fracture of pedestrians vs. height of the bumper in a 3-D-diagram

## CONCLUSIONS

This study dealt with the analysis of fractures of the lower leg in collisions of passenger cars with pedestrians and bicyclist and investigated the change in the type of fractures and their location on the lower leg with modifications of the bumper design. For this purpose 143 accidents involving pedestrian-car impacts and 79 accidents involving bicyclist-car impacts having occurred in the years 1996 to 2004 investigated by GIDAS were selected; the fractures discernible in the x-rays ( $n=48$  pedestrians,  $n= 31$  bicyclists) were documented and measured and compared to the height of the effective impact load of the bumper.

The study showed that the height of the bumper usually does not correlate to the location of the fracture of the legs of pedestrians. 80 % of all fractures occurred in bumper impact to the leg at a height of the bumper at least 32 cm up to 44 cm above road level (effective bumper "height"). 80 % on the pedestrian legs of all fractures were located from 19 cm up to 45 cm above road level. Frequently, the fracture was located below the point of impact effective on the lower leg. Only in 1.5% of the cases did fracture and bumper impact height overlap, in 47.5 % of the cases it was lower and in 35% higher. In comparison to pedestrians the bicyclists suffered fractures much more frequently in the lower distal region of tibia/fibula, 26.5% in the area of 20 to 30% height from the ankle joint and 14.7% up to 10% near the joint area. It can be assumed that the impact load of the bumper is transmitted more direct on the location of the fracture. That could be explained from the different types of fractures registered on the legs of bicyclists followed in more A- and

B-type fractures of the AO classification. Two-third of bicyclists suffered fractures on the lower leg from heights up to 28 cm compared to 36 cm for pedestrians.

It turned out that the design of the front part of the vehicle significantly influences the kind of fractures, which occurred and that bicyclists suffered fractures not so often than pedestrians regarding their impact kinematics and angled impact configuration. It could be seen for pedestrians as well as for bicyclists that usually, the older, protruding bumper shapes or those with a distinct pointed shape of the bumper resulted more frequently in complex fractures as compared to the newer, as a rule integrated and rounded shapes, having a more extensive impact transfer area. For pedestrians could be seen that multiple fractures occurred especially frequently in the shaft region of the lower leg (Type 42C2 n=8), while multiple fractures are rare for bicyclists. The wedge fracture named after Messerer type B2 of the AO-classification (n=7) and the oblique fracture Type A2 (n=9) also frequently occurred on the pedestrian as well as the bicyclist situation. A fracture with bending wedge (Type B2) occurred with all bumper shapes; multiple comminuted fractures (Types C2 and C3), however, only occurred in collision with cars having A-shaped or B-shaped bumpers labeled as "old". In contrast, the bumper shapes of the newer cars with integrated and rounded bumper shapes (groups C and D) showed fewer fractures altogether on the one hand, and on the other hand only oblique fractures and no C fractures, which frequently result in complications. It can thus be postulated that for pedestrians – taking into account the small case base of vehicles built in later years - the fracture incidence was lowered by the altered design of the bumper and the emergence of complicated fractures involving complex long-term consequences has been prevented. A definite statement concerning that fact should only be made, however, after more cases have been collected. The influence of the impact velocity also seems significant for the occurrence of pedestrian fractures. On the one hand it was shown that 65% of all collisions with pedestrians and bicyclists resulting in fractures occurred at velocities of up to 45 km/h. On the other hand it was also shown that for impact velocities up to 40 km/h no complex fractures result. These are only to be expected for pedestrians and there at higher speeds. Thus the majority of all type B and C fractures of the AO classification were documented in a speed range above 40 km/h. A correlation between origin of the fracture and the kind of fracture based on the impact velocity was not established. The types of fractures close to the knee (proximal lower leg) obviously all occur in the lower speed ranges, whereas the shaft fractures in the middle third occurred more frequently at velocities > 40 km/h. Fractures in the area of the ankle (distal lower leg) nearly all occurred at higher impact velocities expect for bicyclists where this area is more frequently involved.

It could be found by statistical correlation analysis of the

pedestrian bumper and fracture heights using a square fit of the regression analysis, that the height of the fracture is reduced significantly with an increase in impact velocity on the one hand and increases only with very high speeds of approximately 60 km/h on the one hand, and that on the other hand, the height of the bumper seems to have very little influence on the height of the fracture. Still, for very low and very high bumpers a lower height of the fractures occurred more frequently and only for bumper heights between 33 and 43 cm a constant correlation was found. The numbers of bicyclists was too low for statistical analysis. But it can be assumed that the lower leg of the bicyclists is positioned on the pedals mostly near the dynamic load transmission zone of the bumper and is therefore more direct loaded, pushed away and fractured more on the lower part of the tibia near the joint region. That can explain that fractures caused by bending moment are much less than on the pedestrian situation.

From our point of view the presented results proves that obviously mass inertia forces act on the lower leg of a pedestrian and especially that the kinematics of the lower leg that has been hit, effectively influence the position of the fracture of Tibia and Fibula. For pedestrians the kinematics of the impact sequence result for lower impact velocities in a classical pushing-away motion of the leg of the pedestrian, with the consequence of a direct momentum resulting in a relatively high position of the fracture. For greater impact velocities, however, the lower leg is as a rule pulled under the bumper, which shifts the position of the fracture downwards. The height of the fracture rises again only for increasing velocities. An analogy of this mechanical correlation was also found in the course of an earlier study (Otte/Haasper) on knee injuries, where injuries of the ligaments of the knee occurred more frequently for higher velocities, whereas fractures occurred already at lower impact velocities. The level of the point of load incidence from the bumper to the knee joint then is also of importance for the occurrence of a fracture, as the ligament structures of the knee result in elastic bending between upper and lower leg. The anatomy of the Tibia bone with a narrowing at the transition from the center to the distal tercile constitutes a kind of predetermined breaking point. 77 % of all fractures of the pedestrians occurred in the middle tercile (Type 42 AO classification). Compared to the situation of pedestrians bicyclists suffered from more fractures in the lower region of the tibia and fibula bone and the ankle joint is often involved. Complex fractures types 43 and C1 to C3 of the AO-classification are occurred in lower frequency. That is the result of lower bending load transmitted to the leg of bicyclists during the collision phase.

The fractures of the tibial and fibular shafts represent a considerable problem for orthopedic trauma surgeons. Those fractures are the most common long-bone fractures. Fractures of the lower leg prevent weight bearing and ambulation and cause pain and instability. If

the fracture is open, serious infection may threaten life and limb. The tibia has poor soft tissue cover which means that all these fractures are often compound. As the blood supply to the bone is poor, the time to union is relatively long, resulting in infection, non- and mal-union. These fractures may be associated with immediate or delayed neurovascular deficits that also threaten survival and function of the limb. Although the average tibial fracture heals approximately in 17 weeks, with more time required for complete rehabilitation, some patients are disabled for a year or more. These substantial socioeconomic facts on these fractures are known for long (Ellis, 1958). Therefore it is important under the point of view of long term consequences respectively long term treatment to distinguish between the different kind of fractures. Indirect fractures, produced by torsional force acting at a distance have typical spiral patterns and usually cause little soft tissue injury. Direct injuries include a bending mechanism combined with direct force transmission area. Naturally such direct impacts result in greater amount of direct local soft tissue injury. Not surprisingly it is long known that the prognosis for such injuries is worse (Burgess, 1987). One danger exists for direct load in the knee area by impacting the head of the tibia. It could be seen that pedestrians as well as bicyclists suffered tibia head fracture with the same percentage (5% of all leg fractures) and the dynamic impact height was always located in the height of the tibia head. Direct force application is often evident by history or appearance of the limb and is also suggested by a fracture pattern that is transverse or has a transverse component on the tension side, with a wedge-shaped butterfly fragment on the side that is compressed during injury. The most severe fractures are those caused by crushing injuries. These have complex highly comminuted segmental patterns with extensive damage to the surrounding soft tissues. It is important not to underestimate the severity and consequences of these fractures by a crushing mechanism in the critical course. The treatment is nowadays still challenging despite advances in this field promoted by the AO.

The conclusion concerning the safety development of today's vehicles has to be derived from the goal of avoiding high fractures close to the knee joint. The study showed generally high heights of bumpers for patients with fractures of the Tibia head, frequently even identical heights. For pedestrians a draw-under mechanism of the lower leg within certain limits seems to have a positive effect, as this lowers the position of the fracture. For bicyclists it seems better to have a higher impact load transmission avoiding ankle joint injuries. Comparing to the situation of pedestrians it is much safer for bicyclists; they suffer fractures on the lower leg in much less frequency and much lower complexity. The design of the bumper will have to ensure that. Edge structures of the bumper, which limit the bending motion, should be avoided especially for pedestrian safety or used for limiting the bending motion in a controlled manner. A coordination on minimizing the knee bending



moment for reducing knee ligament injuries and the height of the fracture to be as close as possible to the shaft at the lower leg based on the design of the bumper is to be aimed for optimized pedestrian safety. This postulation is also supported by the findings based on the population of the distinctly rounded bumper shapes investigated (Type D in this study): few fractures and low-complexity fractures at that were found.

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