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

Otte, D.*; Haasper, C. **
* Accident Research Unit
** Trauma Department
Medical University Hanover, Germany

ABSTRACT

This study deals with the analysis of lower leg fractures in pedestrians after collisions with passenger cars and examines to what extent the shape and location of the factures in the lower leg changed, following alterations in the shape and height of bumpers. It can be assumed that the bumpers changed in form 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. In addition, consumer protection tests, EuroNCAP, accomplished a change of the injury situation.

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 areas 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 pedestrian cases of lower leg fractures (Tibia/ Fibula) with documentation of the fractures by X-rays were differentiated according to new and old vehicles (year of manufacture before/after 1995). The bumper shapes were divided into 3 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.

KEYWORDS: Legs, Tibia, Fibula, Pedestrians, Injuries, Bumpers, Front Shape

PEDESTRIAN 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 fatalities and n=60033 casualties amongst pedestrians were recorded, the number of n=686 fatalities and n=33803 casualties in the year 2005 seems good in comparison. Nevertheless it should not be overlooked that in today's Europe of 27 different countries there are still far more than 40000 pedestrians killed annually. This requires manifold efforts of scientific research, which can no longer be limited exclusively to passive safety like injury reduction, but must also aim at measures of active safety 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. To this end, fractures of the lower legs in pedestrians have been examined after collisions with passenger cars, in order to determine to what extent changed shape and impact height of the bumpers have resulted in changes to the fractures of the lower legs, regarding shape and location. 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 specified in the context of the European Union Directive 2003/102/EC (2003) and in addition by consumer protection tests, EuroNCAP.

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. With these developments kinds and pictures of fractures of tibia and fibula bones will probably change in praxis.

It is the goal of this study to examine the traffic accidents documented in GIDAS collections of accident sites in Hannover and Dresden for accidents involving pedestrians and passenger cars and for this purpose to measure the heights of fractures of the lower legs and their characteristics from x-rays and to assign them to the geometrical shapes of the bumpers. In order to recognize possible distributions 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 and the shapes of bumpers. As the authors were unable to determine exactly when innovations at the vehicles were incorporated on the bumpers, passenger cars built after 1995 are classified as new. Of course it can be expected that the newest generation of car fleets with cars after 2003 are much more developed regarding the test directive 2003/102/EC, but the numbers of accident cases within this sample is too low for comparison.

CASE BASE AND METHODOLOGY

The German In-Depth Accident Study (GIDAS) is a cooperative research activity financed by Federal Highway Research Institute BASt and the association of car manufacturers (FAT). GIDAS investigations at the site of accidents are carried out prospectively, where a scientific team goes to the accident scene immediately after the accident has occurred, notified by the police, and conducts the investigation independent 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, 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 Arbeitsgruppe Osteosynthese (AO Working Group Osteosysthese) (Müller, 1992) was used. All injuries are documented in detail and classified according to AIS (Association for the Advancement of 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 persons injured with the help of basic statistical anthropologic data of the lower leg lengths (Flügel, 1986).

It was possible to select altogether 143 cases from all pedestrian-passenger car accidents recorded in the years from 1995 to 2004 based on the applied criteria (collision with the front of the vehicle, fracture of the lower leg (Tibia/ Fibula), no light trucks N1-vehicles were included, but vans or SUVs or similar vehicles 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; they were only available in 48 cases. Thus the evaluations of the heights of the fractures are limited to this number of cases; other 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 8.3% of the accidents, 22.5% were manufactured between 1985 and 1989, 35.0% between 1990 and 1994 and only 34.2% were built after 1995 – thus approximately one-third of the population regarded.

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 regarding bumper shapes (figure 1).

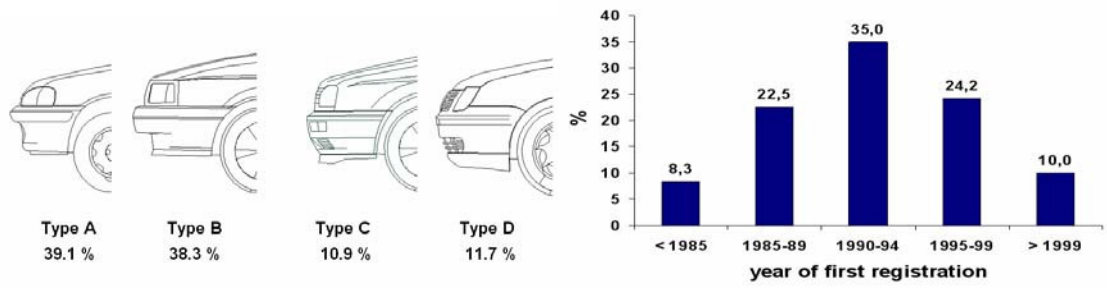


Figure 1: Classified frontal shapes of bumpers and the incidence of involvement in accidents with pedestrians (all vehicles = 100%, n=120, 23 missing)

Corresponding to the relatively old population of vehicles within the current traffic scenery, two thirds of the bumpers were protruding and rather rectangular (Type A at 39.1% and Type B at 38.3%). Newer, significantly rounded bumper structures, which have also been integrated into the front of the vehicle (Type C and D), are represented in only 10.9% (Type C) and 11.7% (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 partly approached on the pictures of Types B and C in figure 1, this was taken into account by entering two values for the "lower and upper edge of the bumper“. Always the most frontal point was chosen as effective impact height. 80% 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 weight change 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.

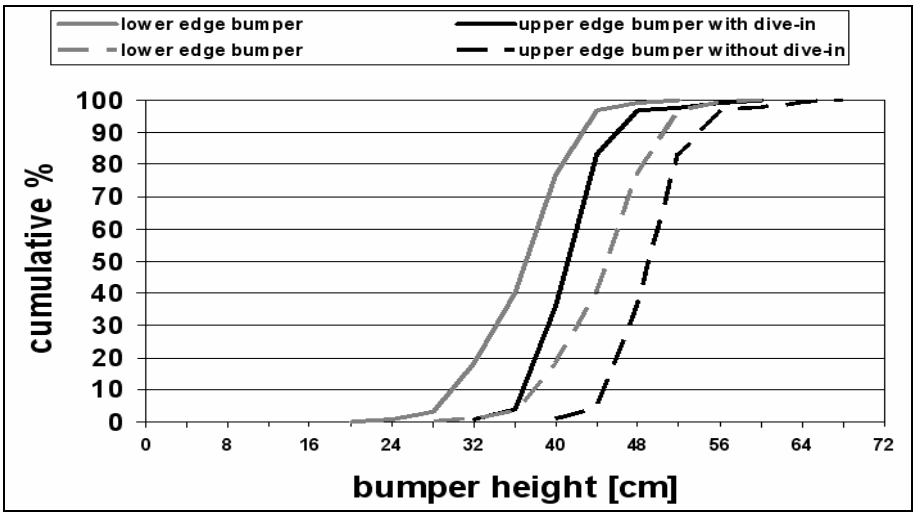


Figure 2: Cumulative frequency of the bumper heights derived dynamic height including an 8-cm nose dive (n= 130, 100%)

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

In more than half of the n=143 cases (53.8%) both bones of the lower leg, Tibia and Fibula, were fractured, in 23.8% only Tibia and in 22.4% only Fibula. The long bone was subdivided into intervals

as percentages of 10% each started the account at ankle joint level (figure 3). If several fractures had occurred on one bone, these were separately included in the evaluation as lower (n=48 with X-rays) and upper fractures (n=11 with X-rays). Clusters of fractures were found 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 20 to 25 cm (18.6%), of 30 to 35 cm (15.2%) and of 40 to 45 cm (22.0%).

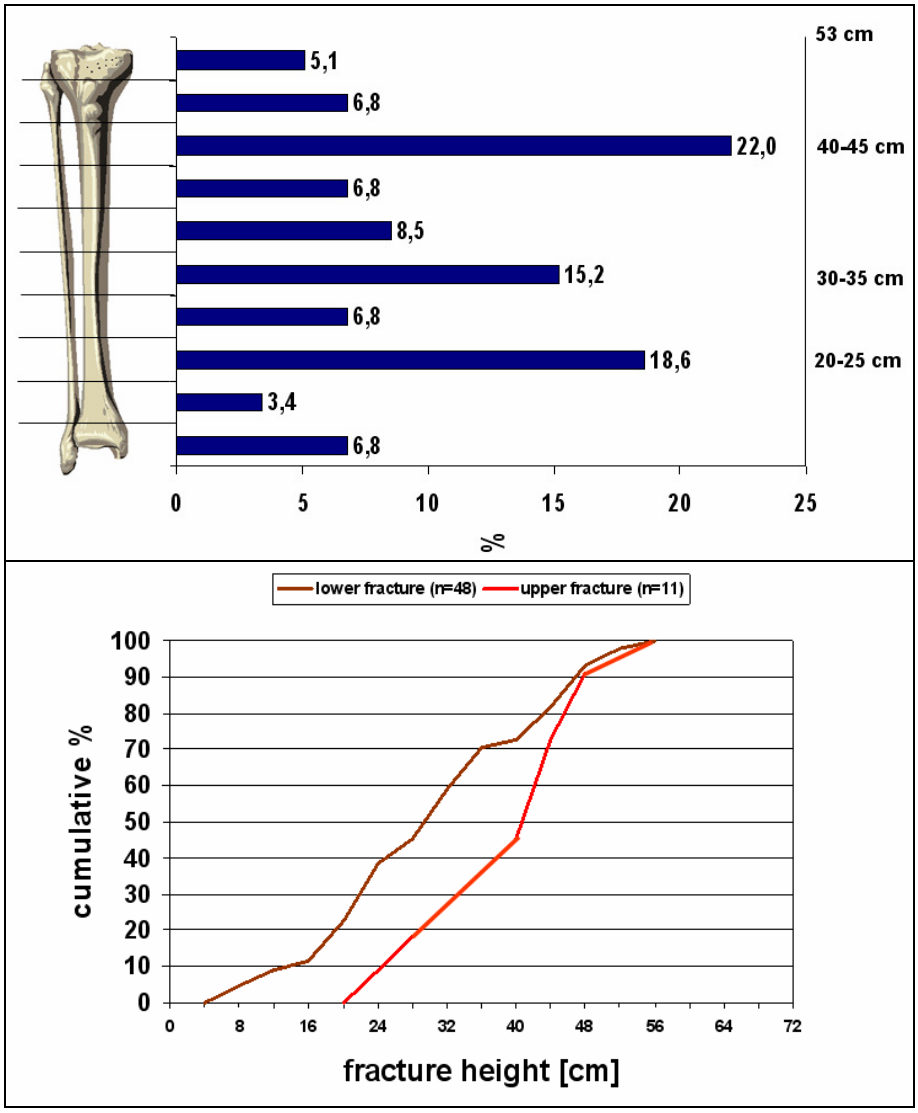


Figure 3: Incidence of fractures of the lower leg (Tibia and/or Fibula - total length of the lower leg =100%) and cumulative incidence of the fracture heights from the level of the road in cm

If the heights of the fractures are correlated to the effective dynamic heights of the bumpers, it turns out that 80% of all fractures 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 (Figure 4). Thus the cause of the fractures is frequently located above the fracture itself. Fracture height and bumper height were only identical in 17.5% of the cases, in 47.5% fracture was above the bumper and 35% fracture below the bumper.

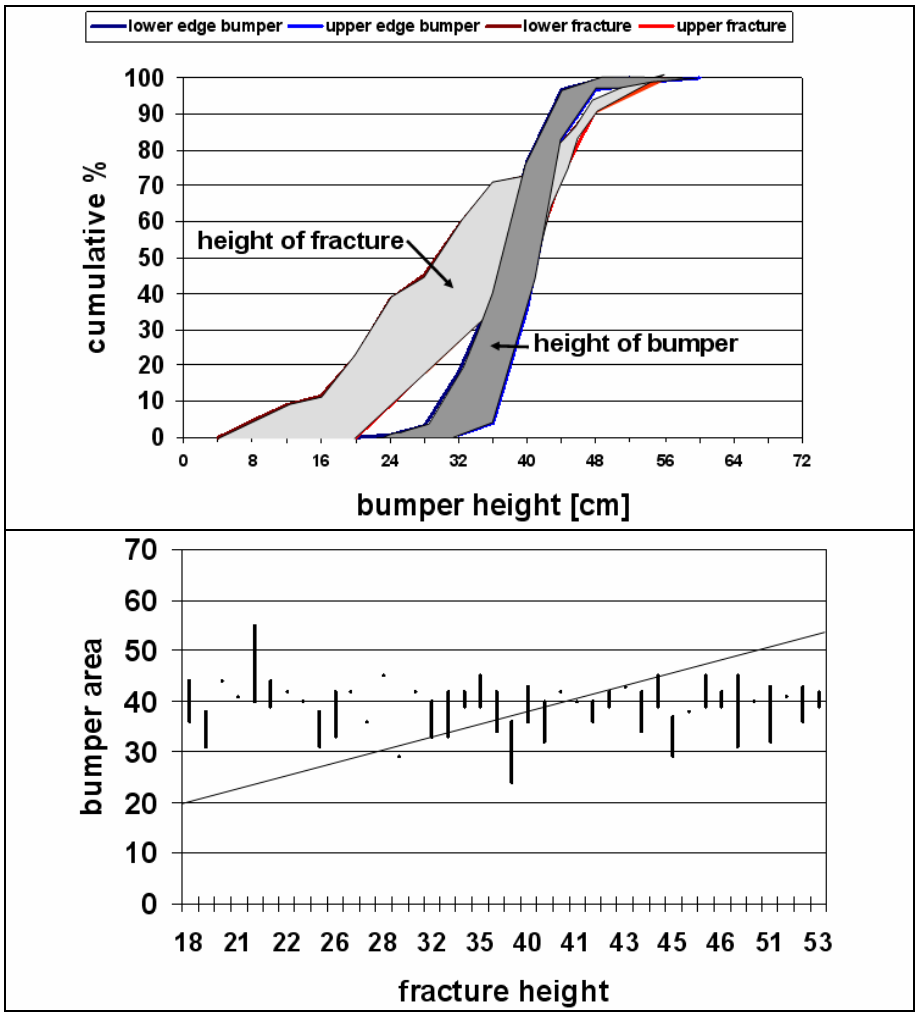


Figure 4: Measured fracture heights and effective dynamic bumper heights in cm (the line indicates identical heights). The x-axis is non-linear; representation of individual data only

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 fractures at the joints A= extra-articular, B= partial articular and C= complete articular. 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 middle third of the bone as shown in Figure 5 (location 42). 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 in the middle third.

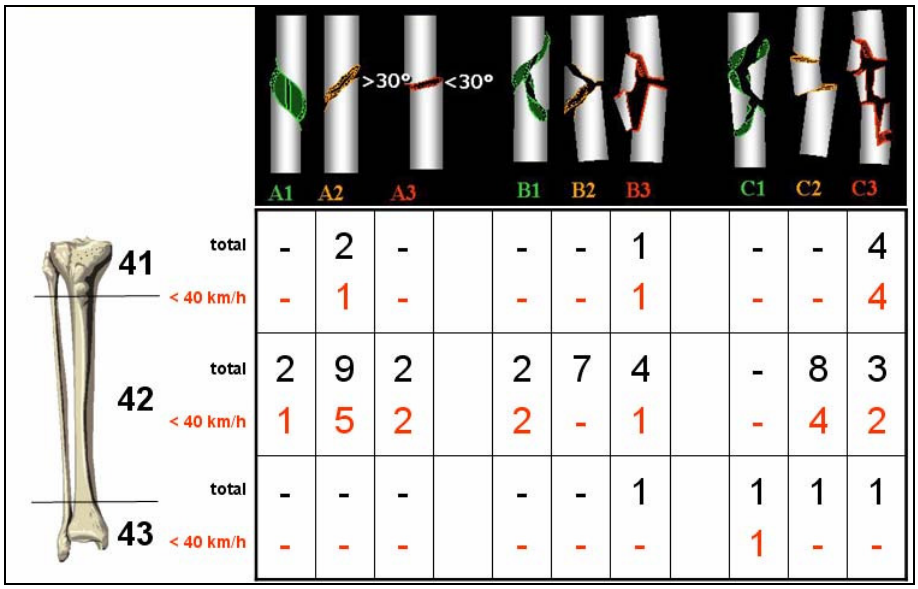


Figure 5: Incidence of fractures according to the AO classification, comparing overall situation and impact velocities <40 km/h

The analysis of different bumper shapes shows that the bending wedge fracture (Type B2) occurred with bumper shapes A, B and C, 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.

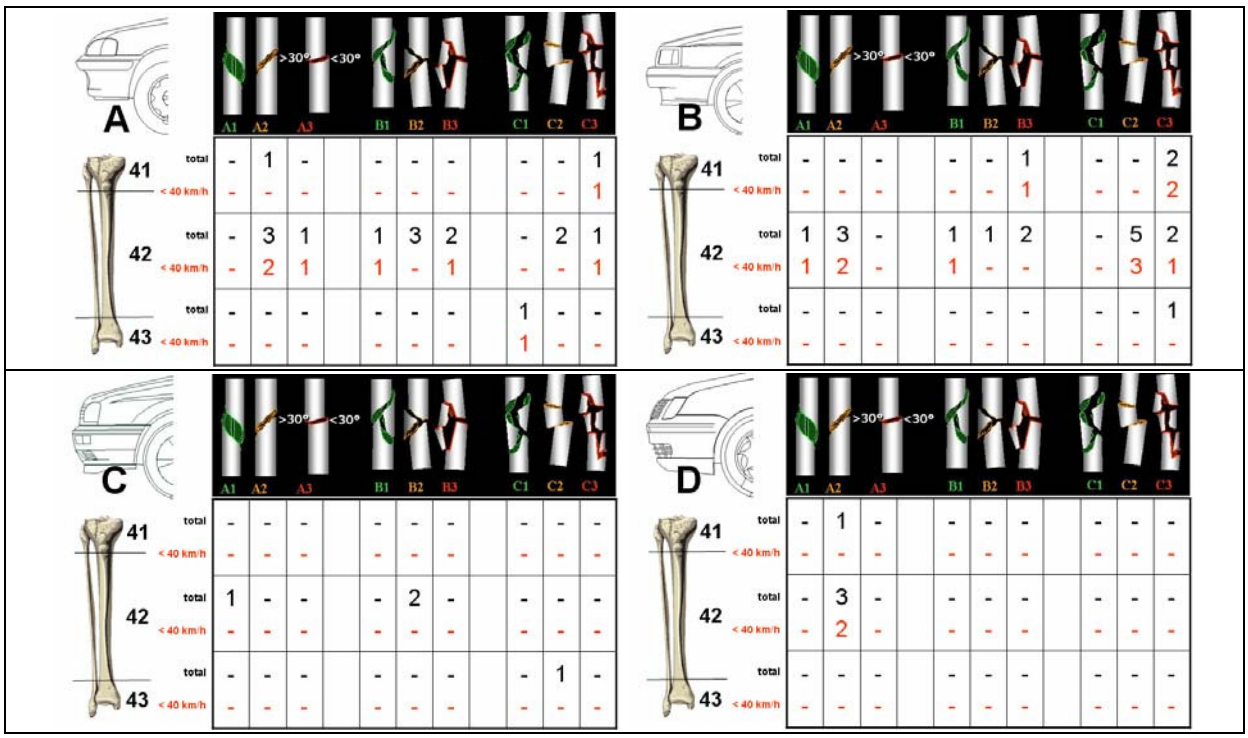


Figure 6: Incidence of fractures according to the AO classification for different bumper types A, B, C, D; comparing the total population and impact velocities <40 km/h

The origins of fractures are also influenced by the impact energy, i.e. impact velocity, besides the design and height of the impact area of the passenger car. In this case the traces with brake marks and the final positions of the vehicles as well as those of the pedestrians (throw distances) were used to determine the impact velocity.

80% of the documented fractures occurred at collision speeds of up to 55 km/h (Figure 7 - 80% between 20 and 70 km/h). A correlation between origin of the fracture and the kind of fracture based on the impact velocity was not established.

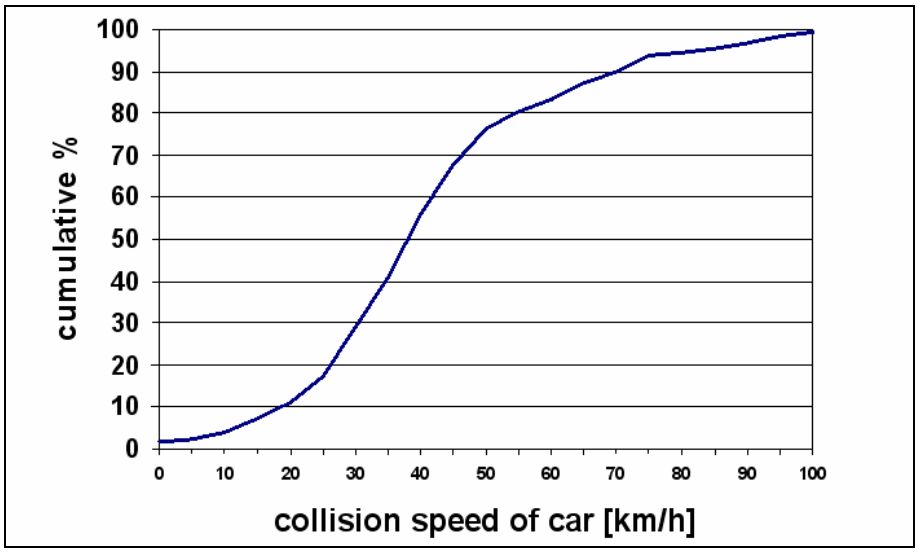


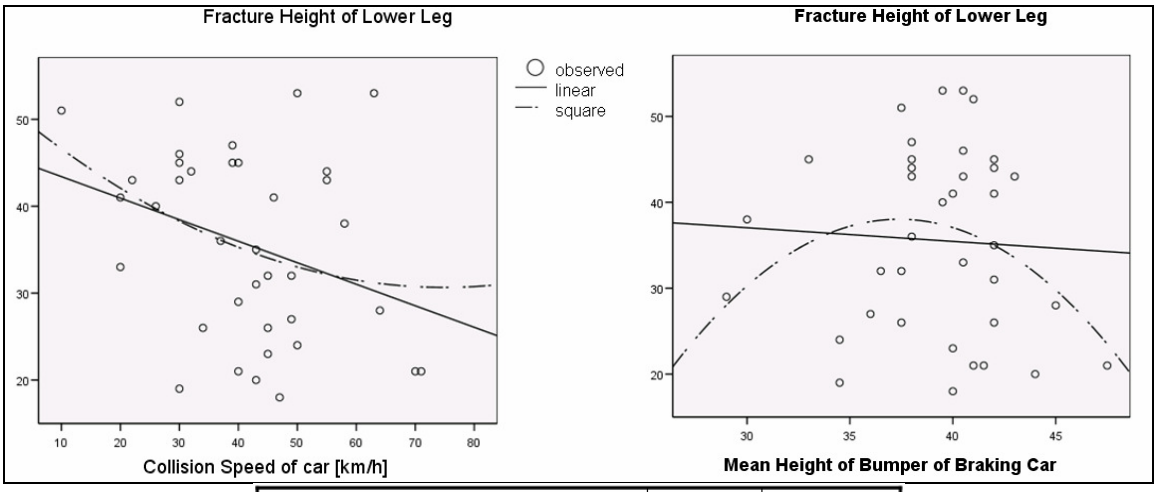
Figure 7: Cumulative incidence of collision speeds of passenger of accidents involving cars and pedestrians and resulting in fractures

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. It can be established that in case of tibia-plateau fractures all impacts were happened in the height of tibia shaft.

ANALYSIS OF RELATION BETWEEN FRACTURE ON LOWER LEG AND BUMPER HEIGHT

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 and at $p= 0.058$ a statistically low one. In the statistic tests 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).

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.



		collision speed car	mean height of bumper
height of fracture	correlation by Pearson	-.321	-.055
	significance	.053	.745
	N	37	37

	non standard coefficient		standard coefficient	T	significance
	B	standard error	Beta		
(constant)	50.139	18.761		2.673	.011
collision speed of car	-.246	.125	-.319	-1.963	.058
mean height of bumper of braking car	-.110	.464	-.039	-.238	.814

Figure 8: Regression analysis of the correlation between collision speed, the height of the fracture and the height of the bumper

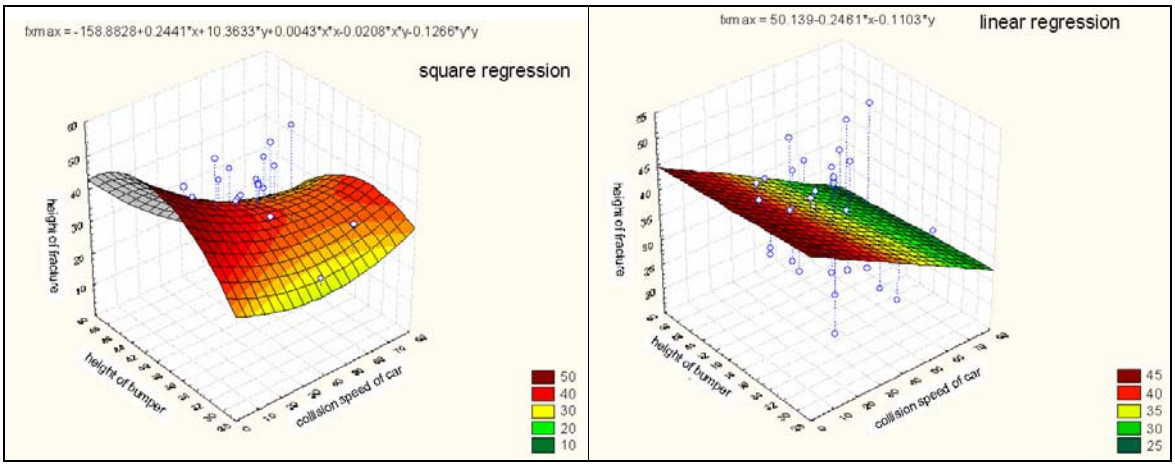


Figure 9: Linear and quadratic adaptation of the regression areas of collision speed vs. height of the fracture vs. height of the bumper in a 3-D-diagram

CONCLUSIONS

This study dealt with the analysis of fractures of the lower leg (Tibia/ Fibula) in collisions of passenger cars with pedestrians 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 having occurred in the years 1995 to 2004 investigated by GIDAS were selected; the fractures discernible in the x-rays were documented and measured for 48 pedestrians and compared to the height measurements 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 at an effective bumper height of at least 32 cm up to 44 cm above road level considered the braking of the car with approx. 8 cm. 80% 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.

It turned out that the design of the front part of the vehicle significantly influences the kind of fractures, which occurred. Thus 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. Multiple fractures occurred especially frequently in the middle third of the lower leg (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 in the middle third. A fracture with bending wedge (Type B2) occurred with bumper shapes A, B and C; 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 – taking into account the small case numbers 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, but with this study a trend can be seen. The influence of the impact velocity also seems significant. On the one hand it was shown that 50% of all collisions resulting in fractures occurred at velocities of up to 40 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 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

Using a square fit of the regression analysis it was proved, 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.

From our point of view this proves that obviously mass inertia forces act on the lower leg and especially that the kinematics of the lower leg that has been hit, effectively influence the position of the fracture of Tibia and Fibula. The kinematics of the impact sequence result for lower impact velocities in a classical pushing-away motion of the leg, 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, 2005) 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 occurred in the middle tercile (Type 42 AO classification).

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 kinds of fractures. Indirect fractures, produced by a torsion 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).

Direct force application is often evident by history or appearance of the limb and is also suggested by a fracture pattern that is transverse and 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 of 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 study in 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. 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. The design of the bumper will have to ensure that. Edge structures of the bumper, which limit the bending motion, should be avoided 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 at in this case. 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.

REFERENCES

Association for the Advancement Automotive Medicine: The Abbreviated Injury Scale - Revision 98, American Ass. f. Automotive Medicine., Morton Grove, Illinois (USA) 1998

Brühning, E., Otte, D., Pastor, C.; 30 Jahre wissenschaftliche Erhebungen am Unfallort für mehr Verkehrssicherheit, Zeitschrift für Verkehrssicherheit 51, 175-181, 2005

Burgess, A.R., Poka, A., Brumback, R.J.: Pedestrian tibial injuries, Journal of Trauma 27, 596-601, 1987

Commission of the European Communities; Proposal for a Directive of the Euopean Parliament and of the Council relating to the protection of pedestrians and other vulnerable road users in the event of a collision with a motor vehicle and amending Directive 70/156/EEC, Brussels, 2003

Ellis, H.: The speed of healing after fractures of the tibial shaft, JBJS 40B, 42-46, 1958

Flügel, B.; Greil, H.; Sommer, K.: Anthropologischer Atlas, Edition Wötzel, Frankfurt/Main, 1986

Müller, M.E., Allgöver, M., Schneider, R., Willenegger, H. Manual der Osteosynthese, AO-Technik der Arbeitsgruppe Osteosynthese, Springer Verlag, Berlin, Heidelberg, New York, 1992

Otte, D.; 3-D Laser systems for scaled accident sketches and documentation of the traces after traffic accidents as basis of biomechanical analysis, Ircobi Conference, 435-438, 2005

Otte, D., Haasper, C.; Technical Parameters and Mechanisms for the Injury Risk of the Knee Joint of Vulnerable Road Users impacted by Cars in Traffic Accidents, International Ircobi Conference, 281-297, 2005

StBA- Statistische Daten der Verkehrsunfälle in Deutschland 2005 Stat. Bundesamt Wiesbaden, Fachserie P, Reihe 7, Verlag Metzler-Poeschel, 2006