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#### Abstract

The single-case analysis of well documented pedestrian accidents involving impact speeds above 50 kph has yielded findings on the kinematics of accidents on the basis of damage and injuries sustained. In particular, it has been possible to assign the type and location of head injuries to the specific stages of an accident.

Since, at high collision speeds and particularly in the case of unbraked impacts, there are seldom any marks on the road surface and marks on the vehicle are difficult to assign, experimental accident simulations have been performed with the frontal impact of passenger cars against stationary pedestrian dummies.

The test results provide information on the motion of the dumny during and after collision, the impact events, the head- and body-contact zones, the potential injury possibilities as well as the time and velocity curves of vehicle and dummy during an accident.


## INTRODUCTION

Accidents between motor vehicles and pedestrians have so far usually been experimentally investigated only up to collision speeds of approx. 50 kph . At such speeds, it is possible with relative ease to reconstruct an accident, especially as the impacts are in most cases braked.

However, both forensic scientists and technical experts often have to investigate accidents involving higher impact speeds. In accidents in darkness on country
roads, in particular, there is the problem that, owing to the visibility and the speed maintained, the motorist is no longer able to effectively decelerate his vehicle prior to collision. In such cases, interdisciplinary cooperation between medical and technical experts is indispensable in order to reconstruct the accident from motion sequence and injury pattern.

## REAL ACCIDENTS

General statistics
In 1984, 2,266 pedestrians were killed and 47,579 pedestrians injured in road-traffic accidents in the Federal Republic of Germany. Most accidents happened in towns, where over $93 \%$ of accidents involving injured pedestrians were recorded.

As regards deaths, the proportion of in-town accidents is approx. 75\%. If one considers that approx. 7\% of accidents involving personal injury took place outside towns, it can be seen that the risk to a pedestrian of being killed is over three times greater outside than inside built-up areas. This is, without doubt, primarily attributable to the speed level.

In assessing the injury severity, however, it is necessary, in addition to the impact velocity, also to take account of age and constitution.

Accidents inside towns particularly frequently involve children less than six years of age (more than 10\%), whereas their share of out-of-town accidents is just less than $5 \%$. If one considers the numbers of children killed in accidents, children less than six years of age account for $5 \%$ and $3 \%$ of accidents that take place in town and out of town, respectively.

The picture is reversed among older pedestrians that are involved in accidents. The over-65s have a $20 \%$ share of in-town accidents involving personal injury; however, their share of deaths is almost $60 \%$.

## Single-case analysis

In the reconstruction of accidents, well documented accidents are often used for purposes of comparison. In the case of pedestrian accidents, there are various parameters that point to the speed of collision.

The most important requirement is knowledge of the collision location, without which it is not possible to make statements on distances thrown, speed or avoidability. Particularly suitable for evaluation are accidents in which the vehicle has undergone panic deceleration at
the moment of collision, resulting in skid marks.
By means of stopping tests at the location of the accident, which, in the case of passenger-car/pedestrian accidents, can usually still be performed with the accident vehicle, it is possible to determine the speed in a reliable manner subject to small tolerances.

In evaluating the "secondary speed features", position and depth of indentations, it must be taken into account that these depend also on the height and weight of the pedestrian.

## Kinematics from damage and injury patterns

Both at impact speeds of 50 kph and above, a striking factor is that, irrespective of the height of the pedestrian, there are cases in which the windscreen of the vehicle is not destroyed. Furthermore, real accidents exhibit different degrees of damage, particularly in the area of the front edge of the engine hood.

The reconstructible motion sequences are to be indicated with reference to four real accidents.

Case A:
Collision speed:
Vehicle type and model:
Height/weight of pedestrian: $1.75 \mathrm{~m} / 83 \mathrm{~kg}$
As a result of the collision, the front skirt and the bumper were pushed back in the area of the left-hand front section of the vehicle, Fig. 1. This damage corresponds with injuries of the pedestrian in the area of the knees (particularly on the left-hand side). These injuries are abrasions and haematomas.

No deformations are detectable at the front edge of the hood; merely on the hood are slight indentations, which, however, were produced primarily by a vertical application of force. Correspondingly, there are merely abrasions in the areas of thigh and pelvis. The impact of the left shoulder, resulting


Fig. 1: Opel Ascona, collision speed approx. 55 kph, braked impact
in fractures in the sternum and in the area of the ribs, took place in the transition area between hood and cowl panel, i.e. in the area of great rigidity.

The head of the pedestrian impacted against the windscreen, which, as a result, was destroyed. This led to a breaking of the neck with death ensuing immediately.

Further damage is present on the roof of the vehicle; these indentations on the non-rigid roof skin are of a less serious nature.

Taking into account the injuries to the pedestrian and the damage to the vehicle, it can be deduced that the main impact was first of all against the lower legs and the knees. Since virtually no damage was found in the area of the front edge of the hood, it can be assumed that the impact against the bumper and the front skirt initiated a substantial angular acceleration about the transverse axis of the pedestrian, so that there was no heavy impact in the areas of the thighs or pelvis. If one compares the unwound length up to the impact of the shoulder of about 1.90 m with the height of the pedestrian, it can be seen that, at this point in time, the vehicle had already to a considerable extent penetrated under the pedestrian. This also explains the impact of the head against the windscreen. Since, on the other hand, the greatly eccentric impact caused substantial rotation of the pedestrian, the further course of the accident also involved contact with the roof, it not being possible to say which parts of the body caused this damage.

Case B:
Collision speed:
Vehicle type and model: Passenger car, Opel Rekord C 1700 Height/weight of pedestrian: Approx. $1.80 \mathrm{~m} / \mathrm{approx} .75 \mathrm{~kg}$

In this case, too, the front apron panel was pushed back slightly by the collision. In contrast to case A, however, this accident shows a severe indentation of the front edge of the engine hood with the direction of force application being longitudinal with respect to the vehicle. Also worthy of note is the fact there was no contact at the windscreen, Fig. 2. Nor was it possible to detect any damage in the area of the roof.

The initial impact took place by means of the bumper in the area of the knees of the pedestrian. The right leg was pulled partially under the passenger car, and the hip impacted against the front edge of the engine hood. As a result of these impacts in the area of the lower extremities, the pedestrian was set in rotation about his transverse axis and struck the rear region of the engine hood with his shoulder, Fig. 3. The


Fig. 2: Opel Rekord C, collision speed approx. 50 kph , braked impact
head-impact location can be found as a round indentation in the cowl panel at the transition to the fender. If one compares the hip-impact location with the head-impact location, this shows the direction of motion of the pedestrian; the head struck further to the right, as viewed in the forward direction of travel of the vehicle. This is attributable to the time offset between hip impact and head impact in conjunction with the walking speed. The distance the pedestrian was thrown due to the impact is also of importance with regard to the reconstruction of the accident. In this case, the pedestrian was thrown approx. 19 m , which agrees with values obtained from tests with dummies. Fig. 4 shows a sketch of the accident.

If, once again, one compares the unwound length with the headimpact location, it can be seen that, in this case, the penetration of the vehicle under the pedestrian was virtually nil; on the contrary, the pedestrian underwent positive no-slip acceleration and the individual parts of the body contacted the passenger car merely one after the other.


Fig. 3:

Damage to Opel Rekord in respect of case $B$


Fig. 4: Sketch of accident
in respect of case $B$

Case C:

Collision speed:
Vehicle type and model:
Height/weight of pedestrian:

Approx. 70 kph, unbraked Passenger car, BMW 323 i

The bumper was bent back by the impact against the pedestrian who was walking in the forward direction of travel of the passenger car. The pedestrian sustained a fracture of the lower leg from this; in addition, there were numerous superficial skin abrasions. A striking fact is that the area of the front edge of the hood shows no damage stemming from an application of force opposite to the direction of motion of the passenger car.

On the engine hood there are large-area indentations stemming from the impact of the back of the pedestrian. In this area, the pedestrian exhibits numerous injuries, including a fracture of the sternum as well as serial rib fractures. There was also lung-tissue rupturing, rupturing of the pericardium as well as lacerations in the area of liver and spleen.

In the further course of motion, the pedestrian impacted against the windscreen with his head and shoulder, Fig. 5. This resulted in severe injuries, rupturing of the atlantooccipital with tearing of the medulla oblongata from the Lissauer's tract and tearing of the spinal marrow from the medulla oblongata, which led to cerebral paralysis and to the death of the pedestrian. In addition, a fracture of the bony roof of the skull as well as extensive scalp bleeding were found.


Fig. 5: BMW 323 i, collision speed approx. 70 kph , unbraked impact

With the exception of a small indentation on the upper frame of the windscreen, which was apparently caused by the hand of the pedestrian, there was no further damage in the area of the roof.

There is an unwound length of approx. 2.3 m to the impact of the head. If one compares this with the height of the pedestrian, it can be seen that, after the initial impact, in addition to the rotation of the pecestrian there was also a
higher velocity of the passenger car, allowing a relative motion between vehicle and pedestrian.

Case D:

Collision speed:
Vehicle type and model:
Height/weight of pedestrian: Approx. $1.65 \mathrm{~m} / 64 \mathrm{~kg}$

Apart from the contour of the vehicle, particular importance is attached also to the height and weight of the pedestrian when assessing the sequence of motions. In this case, the initial impact took place both in the area of the bumper and front skirt and at the front edge of the upper cowl panel. This damage to the hard front structure shows that relatively large forces were opposed to the forward direction of travel of the passenger car, Fig. 6. Accordingly, in the collision, the pedestrian sustained both a comminuted fracture of the right thigh and a fragmentary fracture of the left thigh-bone. Conversely, the lower legs showed no bone injuries. As a result of the relatively high point of impact on the upper cowl panel, the pedestrian was not only set in rotation about his transverse axis but was also heavily accelerated in the forward direction of travel of the passenger car. There was a large-area indentation on the engine hood as a result of the impact of the shoulder and the chest. The head-impact location is at the level of the air-inlet slits on the engine hood. As a corresponding injury, a serial rib fracture was found on the right-hand side of the chest, covering the 2 nd to the 12 th ribs in the midaxillary line. On the left-hand side of the chest., too, there was a serial rib fracture from the lst to the 9 th rib. In the roof of the skull, a fracture centre was found in the left-hand and right-hand crown areas. Furthermore, the base of the skull could be moved against the cervical vertebral column, there having been in this connection a breaking of the medulla oblongata. This is also to be viewed as the cause of death of the pedestrian.


Fig. 6: Opel Rekord D, collision speed approx. 70 kph , braked impact

The unwound length to the head-impact location is approx. 1.75 m . A comparison with the height of the pedestrian of 1.65 m shows that, in this case too, the vehicle had to a
certain extent penetrated under the pedestrian. This, however, is weakly pronounced, apparently because of the central impact against the pedestrian at the upper cowl panel, since this caused a substantial translational acceleration of the pedestrian.

## Conclusions from the single-case analysis

A study of real accidents shows that there are different damage features and injuries, in part irrespective of the collision speed and the application of the brakes. Apart from the main impact centre in the area of the bumper, some cases involve also the front edge of the hood and the upper cowl panel as impact centres. This leads, in some cases, to major bone injuries in the area of the lower legs and, in other cases, in the area of the thighs and pelvis. Depending on type of impact and body height, the head of the pedestrian contacts the engine hood or the windscreen in the further course of the accident. It was not, however, possible to detect significant differences as far as the injury patterns in the two cases are concerned. Apart from fractures in the area of the bony skull, breaking of the neck is a further principal cause of death.

## EXPERIMENTAL ACCIDENT SIMULATIONS

## Test programme and setup

The accident simulations involving impact of the passenger car against the stationary pedestrian dummy cover the collisionspeed range between 55 and 83 kph . The collisions took place with braked and unbraked passenger cars in the form of centric and eccentric full collisions in the front area of the vehicle.

Owing to the high collision speeds and the associated heavy loading of the dummy with the danger of destruction, this series of tests employed a special design of dummy which corresponds to the $50 \%$ hybrid II pedestrian dummy in terms of dimensions, weight and weight distribution.

The passenger cars with ponton shape were accelerated to collision speed by means of pulling cable and guide cable and were released immediately before the collision, so that, freely travelling, they impacted against the pedestrian dummy both unbraked and braked by means of an automatic braking device.

Kinematics and impact results
The tests were evaluated with regard to the collision speed, the post-impact velocity curves of passenger car and pedestrian, the motion of the pedestrian in the course of the impact and post-impact phases and with regard to the time sequence of the impact events.

Fig. 7 shows test results by way of example. The Ford Taunus passenger car impacts the pedestrian dummy, with brakes applied, at an initial-impact speed of 66 kph . The passengercar deceleration is approximately $8 \mathrm{~m} / \mathrm{s}^{2}$. The head impacts 0.08 s after initial impact in the lower area of the windscreen, the body of the dummy having been accelerated to approx. 35 kph and the vehicle having covered a distance of 1.4 m . In the further course of the collision, the dummy is accelerated to approximately $90 \%$ of the speed of the passenger car, which, at this point in time, is 2.5 m away from the place of collision and has been decelerated to a speed of around 55 kph owing to the application of the brakes and the superimposed, impact-induced reduction in speed.

In the further sequence of motions, the dummy, which was set in rotation upon initial impact, penetrates the windscreen with its head, enters the passenger compartment as far as the shoulder, strikes the roof edge of the windscreen with the back of the head when leaving the windscreen area and finally impacts the roof of the passenger car with its legs. Since, despite being braked, the passenger car is in this phase always faster than the dummy, the dummy performs a rearward motion in relation to the passenger car, so that there is roof damage as far as the rear area of the passenger-car roof. Approximately 0.7 s or 10 m passenger-car distance after the start of contact, dummy and passenger car are moving at the same speed. As a result of the constantly decelerated motion of the passenger car, the passenger car now becomes slower than the dummy, so that the latter performs a forward motion in relation to the passenger car, slides down over the roof and the engine hood, finally reaching the end position on the road in front of the passenger car.

By comparison, Fig. 8 shows a braked passenger-car/pedestrian collision at 54 kph collision speed. It can clearly be seen that, despite the lower impact speed, the phase sequences are in virtual agreement as regards time with corresponding body positions. A comparison of the positions of the dummy in relation to the passenger car starting at approximately 0.4 s after the initial impact shows that, at the lower impact speed, the center of mass of the dummy is above the top edge of the windscreen, while at the higher collision speed, it is above the B-pillar. In both cases, however, after reaching the speed of the passenger car, the dummy slides across the engine hood into a final position in front of the fully stopped passenger car.

Fig. 9 shows the head-impact situation and the speed curve for an unbraked impact at a collision speed of 54 kph , i.e. directly comparable with the braked impact in Fig. 8. The slightly higher position of the front section of the unbraked same-model passenger car - owing to the absence of pitching on


Fig. 7: Impact events and speed curves, Ford Taunus, collision speed 66 kph , braked impact


Fig. 8: Impact events and speed curves, Ford Taunus, collision speed 54 kph , braked impact
braking - means that the thigh/hip area of the dummy is impacted such that the upper part of the body is loaded less far onto the engine hood. Consequently, at the same collision speed, the head impacts before the bottom edge of the windscreen. Another noteworthy aspect in this connection is the non-stretched leg posture of the dummy in the head-impact phase in comparison with the two previously described tests.

The dummy reaches approximately $95 \%$ of the speed of the (this time unbraked) passenger car approximately 2.5 m after the point of collision, but thereafter always remains slower than the passenger car. The absolute speed of the dummy in the case of an unbraked collision is, therefore, higher than in a braked collision.

Finally, Fig. 10 shows the sequence of motions at an impact speed of $\overline{83 \mathrm{kph}}$, the passenger car being a VW Passat which was unbraked at the moment of impact. The impact of the head takes place approx. 0.06 s after the start of impact in the upper area of the windscreen. In the course of further rotation, there is a violent impact in the rear pelvic region of the dummy against the roof edge of the passenger car above the windscreen. As a result of extensive entangling with the passenger car, the body of the dummy is destroyed, with parts of the dummy remaining in the passenger compartment of the vehicle. In this case, the dummy of necessity reaches the speed of the passenger car after approx. 4.5 m .


Fig. 9: Head-impact situation and speed curves, Ford Taunus, collision speed 54 kph , unbraked impact


Fig. 10: Head-impact situation and speed curves, VW Passat, collision speed 83 kph , unbraked impact

## Vehicle damage

Analogously to the real accidents, the passenger cars strikingly showed two typical types of damage.

For the previously described test as in Fig. 7, Fig. 11 shows the damage that was produced. Typical are the comparatively small indentations in the front-impact area and on the engine hood as indications of low collision-contact forces. The dummy contacted the windscreen with its head and destroyed the latter. Even at the considerably higher impact speed in the test as in Fig. 10, one sees this likewise comparatively minor damage in the initial-impact area of the front section of the passenger car, Fig. 12. In contrast, Fig. 13 shows consider-ably greater damage to the front of the passenger car at an impact speed of 68 kph , with the head not impacting in the windscreen but before it on the hood. The characteristic phase of the motion of the dummy at the instant of head impact after


Fig. 11: Damage in respect of test shown in Fig. 7


Fig. 12: Damage in respect of test shown in Fig. 10


Fig. 13: Damage at a collision speed of 68 kph , Opel Rekord, unbraked impact
0.08 s is shown in Fig. 14. The top edge of the front of the passenger car as well as the engine hood undergo severe deformation as a result of the effect of intense initial-impact forces. A high degree of positive no-slip contact with the upper body of the dummy impedes the further motion of the dummy relative to the passenger car in the direction of the windscreen. Already 1.5 m after the initial impact, the dummy reaches the speed of the passenger car, almost simultaneously with the impacting of the head.


Fig. 14: Head-impact situation in respect of test shown in Fig. 13

## Conclusions from experimental accident simulations

Initial conclusions from the tests show that, at impact speeds above 50 kph , an impact of the head against the windscreen is not necessarily to be expected. The tests confirm the known, in some cases additive influences on the sequence of motions particularly between initial impact and head impact in the case of a pedestrian collision - also for high collision speeds. However, the head-impact location, in particular, depends not only on the height of the top edge of the engine hood, but also on the influence of the vehicle pitching as a result of braking and on the collision speed. Also of importance is the magnitude of the contact forces upon initial impact. In the range of higher collision speeds, therefore, the head-impact location cannot be used exclusively as a measure of the collision speed; on the contrary, the type and extent of the damage in conjunction with the injuries are of major importance with regard to the reconstruction of the accident.

## APPENDIX

## Fatal injuries in general

If cases with collision speeds of 50 kph and above are considered, survial of the pedestrian struck is unusual. However, we found fatalities at impact speeds of 5 kph and Kamiyama (197l) reported a lower limit of 12 kph . In a sample of 51 killed pedestrians the collisions speed was "mostly" between 30 and 50 kph (Metter 1984). Three other studies show that 50 of all fatalities occur at speeds up to 50 kph (Hutchinson 1975 , Appel 1975 , Ashton l979). In the following some details on injuries to killed pedestrians are given.

Not only the severity but also the frequences of injuries with fatalities are different to those seen in a larger casualty sample. Leg injuries still are absolutely dominant. Cranio-cerebral traumata, however, become far more important. We also found more injuries of pelvis, thorax and abdomen, as well as of the cervical spine (Interdiscipl. Workgroup Accid. Mech. Zürich, l986). Metter (1984) found the following severe injuries in l69 killed pedestrians (excluding overruns): 122 leg fractures, lll craniocerebral traumata, 92 rib fractures, 75 detachments (decollements), 61 pelvic fractures, 53 bleedings of the renal bed, 52 ruptures of the aorta, 23 liver ruptures.

| 1 Localization of injury | 1 N | 1 | Injury |
| :---: | :---: | :---: | :---: |
| I brain/skull unspecified | 142 | 1 | 22 fractures |
| I brain | 138 | 1 | 38 |
| 1 base | 118 | I | 18 fractures |
| I skull cap | 130 | 1 | 25 fractures |
| I face | \| 11 | I | 6 fractures |
| I cervical spine | 16 | 1 | 5 fractures |
| I dorsal spine | I 13 | 1 | 13 fractures |
| I chest wall | 137 | 1 | 37 fractures |
| I inner thoracic organs | 122 | I | 15 lung, 1 cava |
| 1 | 1 | I | 4 heart, 2 aorta |
| I inner abdominal organs | I 21 | I | 6 liver, 2 bowel |
| 1 | I | I | 2 spleen, 3 kidn. |
| I | I | I | 1 bladder |
| I pelvis / groin | 128 | 1 | 27 fractures |
| I lumbar spine | 14 | 1 | 4 fractures |
| I legs unspecified | I 39 | I | 22 fractures |
| I left upper leg | I 13 | 1 | 6 fractures |
| 1 right upper leg | 1 14 | 1 | 12 fractures |
| 1 right knee | 16 | 1 | 5 fractures |
| 1 left knee | 15 | 1 | 4 fractures |
| I left lower leg | \| 18 | 1 | 13 fractures |
| 1 right lower leg | 120 | I | 18 fractures |
| I clavicle | 17 | 1 | 7 fractures |
| I left hand | 14 | 1 | 4 fractures |
| I right hand | 14 | 1 | 4 fractures |
| I shoulder | 14 | 1 | 3 fractures |
| I right amm | 18 | 1 | 7 fractures |
| I left arm | 15 | I | 4 fractures |
| I others | 19 | 1 | 8 fractures |

Fig. 15: AIS $>=2$ injuries in fatalities $(N=61)$

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