Int J Legal Med (2000) 113 : 84–88

ORIGINAL ARTICLE

B. Karger · K. Teige · W. Bühren
A. DuChesne

Relationship between impact velocity and injuries in fatal pedestrian-car collisions

Received: 17 December 1998 / Received in revised form: 2 June 1999

Abstract The most common type of fatal pedestrian-car collision, i.e. a passenger car with a wedge or pontoon shaped front striking an erect adult with this front, was investigated. A reliable calculation of the impact velocity range by a technical expert and a comprehensive autopsy suitable for traffic accidents were performed in every case. A total of 47 fatalities form the material of this study and the impact velocities varied between 18 and 142 km/h. Primary and secondary injuries did not show a relationship to impact velocity. The occurrence of four types of indirect injuries revealed a clear relationship to impact velocity, i.e. spinal fractures, ruptures of the thoracic aorta, inguinal skin ruptures and dismemberment of the body. Important parameters such as the type of car, impact velocity range and indirect injuries are listed for each individual case. Because of the limited number of cases, the impact velocity ranges (3–30 km/h) instead of mean values were considered. A cautious interpretation of the data can be summarised in the following conclusions: If there is no spinal fracture, the velocity was below 70 km/h and probably below 50 km/h. Aortic and inguinal skin ruptures are always present if the velocity was above 100 km/h but never occurred below 50–60 km/h. If dismemberment occurs, the velocity was above 90 km/h. Consequently, an estimation of the impact velocity from the presence or absence of indirect injuries is possible in pedestrian-car collisions of the type examined. However, the selection criteria applied in this study and additional parameters influencing the collision dynamics have to be considered carefully.

Key words Pedestrian traffic accidents · Frontal collision · Impact velocity · Injury pattern · Reconstruction

B. Karger (✉) · K. Teige · A. DuChesne
Institute of Legal Medicine, University of Münster,
Von-Esmarch-Strasse 62, D-48149 Münster, Germany
Fax +49 251 8355158

W. Bühren
DEKRA AG, Otto-Brenner-Strasse 168,
D-33604 Bielefeld, Germany

Introduction

Pedestrians constitute a substantial portion of the overall traffic mortality (Ashton and Mackay 1978; Atkins et al. 1988; Hill et al. 1996). From a forensic point of view, the most frequent questions raised address the primary impact site, the walking direction of the pedestrian, the type of vehicle (in cases of hit-and-run) and the impact velocity. The technical expert can reliably calculate the impact velocity if certain parameters can be determined. However, these parameters are known in only approximately 50% of cases (Kamiyama and Schmidt 1970; Metter 1984a). Knight (1991) believed that it is virtually impossible to estimate the speed of impact from the nature of the injuries. This would require verified relationships between impact velocity and the resulting injury pattern established on the basis of autopsy findings. It was the intention of this study to determine if such relationships could be established in the most common type of pedestrian/vehicle accident, i.e. a passenger car hitting the pedestrian with the frontal surface (Ashton and Mackay 1978; Metter 1984a; Lane et al. 1994). Several additional parameters influencing the collision dynamics of the pedestrian had to be standardised for this purpose.

Materials and methods

From 1983–1996, the technical experts from the DEKRA (Deutscher Kraftfahrzeugüberwachungsverein) office in Bielefeld investigated approximately 1000 pedestrian traffic accidents including more than 100 fatalities. This investigation is based on cases which fulfil the following selection criteria:

- The pedestrians were older than 14 years of age because pedestrian fatalities involving young children constitute a different entity (Brison et al. 1988).
- The pedestrians were hit by the car while standing or walking in an erect position. In particular, fatalities involving a sitting or crouching position were excluded.
- The vehicle was a passenger car with a wedge-shaped or pontoon-shaped front design including a conventional hood. The box-shaped front designs predominating in vans or trucks were excluded because the design of the vehicle front has been shown to influence

Table 1 Summary of important parameters in the 47 individual cases. The injury occurring at the lowest velocity is marked in bold letters. Similarly, when the injury occurred constantly, the case involving the lowest velocity is marked

No.	Sex/age (years)	Height (cm)	Weight (kg)	Car	Impact velocity (km/h)	Spinal fracture	Aortic rupture	Inguinal rupture	Dismemberment
1	m/15	191	80	Renault R5 GT	18.5 (15– 22)	/	/	/	/
2	f/72	162	65	Opel Kadett E	27.5 (20– 35)	**C6**	/	/	/
3	f/79	155	70	Nissan Micro	31.5 (30– 33)	/	/	/	/
4	m/85	168	65	Opel Kadett E	33.5 (32– 35)	C6	/	/	/
5	f/75	162	75	Renault 19	37.5 (35– 40)	/	/	/	/
6	f/82	155	80	Nissan Micra	39 (38– 40)	/	/	/	/
7	m/30	178	80	VW Golf	40 (30– 50)	/	/	/	/
8	m/36	180	80	VW Golf I	42.5 (35– 50)	/	/	/	/
9	f/86	147	45	VW Golf I	43 (40– 46)	/	/	/	/
10	f/82	152	55	Mercedes 200D	45 (40– 50)	T6	/	/	/
11	f/76	166	70	Opel Kadett	45 (40– 50)	C7	/	/	/
12	f/47	164	60	VW Golf	45 (40– 50)	T7	/	/	/
13	f/79	160	62	VW Derby	50 (40– 60)	T8	/	/	/
14	f/82	174	95	VW Passat	50.5 (43– 58)	T5	/	/	/
15	f/76	162	75	Opel Ascona	54 (52– 57)	C7, T4	/	/	/
16	m/75	170	82	Ford Taunus	60 (57– 63)	C6	/	/	/
17	f/62	149	43	VW Polo L	61.5 (57– 66)	C1, C7	/	/	/
18	m/35	169	75	Ford Fiesta	63 (60– 66)	/	/	/	/
19	f/71	170	75	VW Golf	63 (59– 67)	C1, C4, T5	**yes**	/	/
20	m/59	179	65	VW Polo	65 (60– 70)	C1, T1, T11	/	/	/
21	f/86	156	65	Volvo 740	65 (60– 70)	T11	yes	/	/
22	m/80	169	70	Opel Rekord E	65 (60– 70)	C1, C5, T7	yes	/	/
23	m/82	170	75	Audi 90	66 (58– 74)	C1, C7, T4, L2	yes	**yes**	/
24	f/73	163	75	Peugeot 205 GTI	67 (63– 71)	C6	/	yes	/
25	m/58	172	72	VW Beetle	67.5 (65– 70)	/	/	/	/
26	m/54	174	75	Opel Kadett D	67.5 (65– 70)	**C6, T3**	yes	yes	/
27	f/82	156	65	Honda E64	69 (63– 74)	C1, T2	yes	/	/
28	m/86	168	68	BMW 316	70 (60– 80)	C6, T1, T2, T11	yes	/	/
29	m/57	160	55	Ford Fiesta	70 (60– 80)	C1	yes	/	/
30	m/43	182	95	Toyota Corolla	70.5 (67– 74)	T7	/	/	/
31	m/64	169	75	VW Golf	75 (70– 80)	C6, T6, L1	yes	/	/
32	m/86	174	78	Fiat 127 A	75 (70– 80)	C5	/	/	/
33	m/51	172	90	Chrysler Vision	75 (70– 80)	T10	/	yes	/
34	f/74	162	75	Mazda 626	80 (75– 85)	C7, T7	/	yes	/
35	m/60	173	82	BMW 525	85 (80– 90)	T11	/	yes	/
36	m/51	171	70	Opel Kadett D	85 (70–100)	C5, T4	**yes**	yes	/
37	f/20	159	61	VW Passat	86.5 (78– 95)	C3	yes	/	/
38	m/86	168	63	BMW 316	92 (86– 98)	C6, T1, T12	yes	/	/
39	m/45	184	87	Opel Kadett	95 (90–100)	C5	yes	/	/
40	m/83	171	62	Mitsubishi Galant	98.5 (92–105)	T1, T12	yes	**yes**	T12/L1
41	m/51	186	95	BMW 320	100 (95–105)	T7, T12	yes	yes	/
42	m/44	175	70	Volvo 760	100 (90–110)	C1, T3	yes	yes	T3/T4
43	m/38	165	73	VW Golf I	105 (100–110)	L3	yes	yes	/
44	m/81	168	66	Ford Granada	110 (100–120)	C6	yes	yes	/
45	m/17	190	85	Mazda 323	110 (100–120)	C6, T11	yes	yes	T11
46	f/79	170	75	Audi 100	113 (108–118)	C7	yes	yes	left leg
47	m/23	175	80	Mercedes 250	142 (130–154)	C7, T9	yes	yes	pelvis

the collision dynamics of the pedestrian and the resulting injury pattern and severity (McLean 1972; Beier 1973; Ashton 1982; Robertson 1990; Ishikawa et al. 1994).

These first three selection criteria filtered out an impact geometry where the centre of gravity of the pedestrian was always located above the point of primary contact.

- The pedestrians were not involved in a second collision and they were not run over by the car or a subsequent vehicle.
- The point of collision was strictly located at the front of the car, thus excluding combined frontal and tangential collisions.
- The impact velocities were reliably calculated from the site of primary collision and the final site of the injured pedestrian and/or the skid marks and the damage to the car. The technical experts calculated impact velocity ranges of 3–30 km/h (Table 1). The

mean value of this interval was calculated and is called the presumptive impact velocity.
- Autopsies were carried out. The autopsies were complete, i.e. the dorsal aspect of the body and the extremities, especially the legs, were dissected so that the soft tissues as well as the bones could be examined. Special care was taken in dissecting the spine.

Results

The age of the 47 pedestrians was 15–86 years and the mean value was 62.9 years (Table 1). The presumptive impact velocities showed a wide range from 18.5–142 km/h with a peak at 60–70 km/h (Table 1). A detailed analysis of the injuries and of the corresponding impact velocities showed that fractures of the lower extremities resulting from the primary impact were present in every case except for four. The presumptive impact velocities in these four cases were 27.5 km/h (case 2), 40 km/h (case 7), 50.5 km/h (case 14) and 67 km/h (case 24) and the latter two cases involved comminuted fractures of the pelvis. Possibly, the position of the two pedestrians was such that the point of primary impact was located higher than in the rest of the fatalities. Lacerations and pocket-like underminings/decollements of the soft tissues at the point of primary impact were sometimes present in low velocity accidents and were absent in several cases of high velocity impact, which prevented the establishment of a relationship to impact velocity. The occurrence of brain damage and other injuries due to secondary impact with the car or road surface did not depend on impact velocity. In contrast, secondary head injuries were the most common causes of death in the low velocity impact range. If the impact velocity was higher, several body regions were affected and the cause of death was always polytrauma/exsanguination and/or brain injury.

However, the occurrence of four different types of injury showed a correlation to impact velocity. These injuries were fractures of the spinal column, ruptures of the thoracic aorta, inguinal skin ruptures and dismemberment of the bodies (Table 1). Almost half of the vertebral fractures were located in the cervical spine (Table 2). Fractures of the spine first appeared at a presumptive impact velocity of 27.5 km/h, they were common above 45 km/h (36/38 cases) and were present in every case above 67.5 km/h (Table 1). In 12 out of these 22 cases, 2–4 fractures were present in combination (Table 1). The two pedestrians who suffered spinal fractures below 45 km/h impact velocity showed severe signs of degeneration in this segment of the spine (cases 2 and 4). The fractures varied from relatively stable to dislocated to gaping and involved the vertebral bodies and/or the intervertebral discs. Ruptures or tears of the thoracic aorta (Fig. 1) first appeared at 63 km/h and were always present above 85 km/h (Table 1). Injury to the thoracic aorta was commonly combined with a corresponding fracture of the thoracic spine. In no case did a rupture of the aorta occur in the absence of a spinal fracture (Table 1). Ruptures of the inguinal skin (Fig. 2) first occurred at 66 km/h and were always present above 95 km/h (Table 1). Dismemberment of the body was defined as

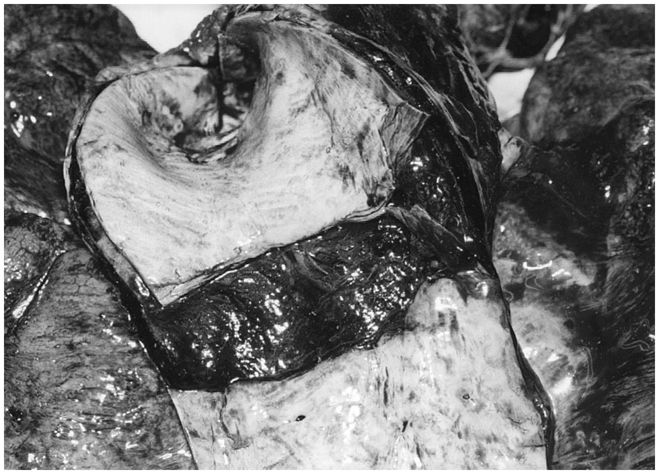

Fig. 1 Complete transversal rupture of the thoracic aorta below the aortic arch in a 64-year-old man struck by a VW Golf at approximately 75 km/h (case 31)

Fig. 2 Rupture (left) and distension mark (right) of the inguinal skin in a 38-year-old pedestrian struck by a VW Golf at approximately 105 km/h (case 43)

Table 2 The topographic distribution of the 64 spinal fractures in the 38 fatalities involving fractures of the spinal column

Vertrebral body	Number of fractures	Vertebral body	Number of fractures
C1	8	T6	3
C2	0	T7	5
C3	1	T8	1
C3	1	T9	1
C5	4	T10	1
C6	10	T11	5
C7	7	T12	3
T1	4	L1	1
T2	2	L2	1
T3	1	L3	1
T4	3	L4	0
T5	2	L5	0

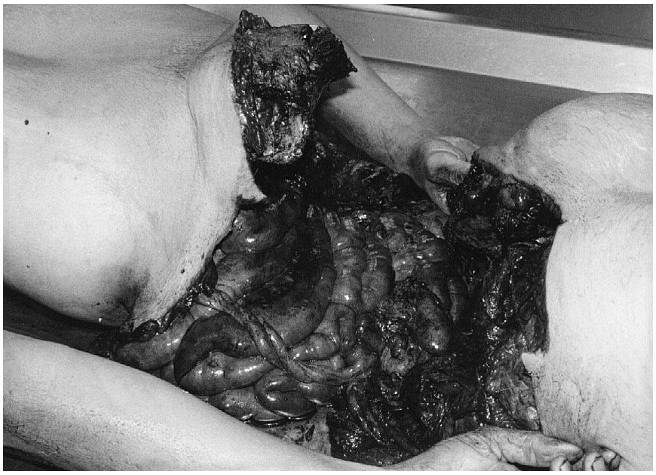

Fig. 3 Complete dismemberment of the body in a 23-year-old man after frontal collision with a Mercedes Benz 250 at approximately 142 km/h. In addition to two gaping fractures of the vertebral bodies, the sacral bone was isolated from the pelvis (case 47)

complete or incomplete ("internal") severance of the trunk (Fig. 3) or the neck or complete amputation of a leg. These gross injuries first occurred at 98 km/h (Table 1).

Discussion

Relationships between impact velocity and the presence or absence of primary or secondary injuries could not be established, which is corroborated by a recent analysis of 217 pedestrian traffic fatalities (Harruff et al. 1998). Secondary head injuries also appeared to be coincidental. For example, death in case 2 involving the lowest impact velocity was due to craniocerebral injury from secondary impact on the kerb. However, when the erect body is impacted below the centre of gravity by the front of a car, the legs are "knocked away" in the driving direction, i.e. a rapid rotational acceleration is imparted to the legs and thus to the long axis of the body. Depending on the precise impact geometry (Beier 1973; Beier and Pfriem 1974), the subsequent forces acting on the body can result in extreme motions of distension/overextension, rotation and translation. This indirect type of trauma can cause fractures of the spine (axis organ), ruptures of the thoracic aorta (susceptible to distension due to fixing points), inguinal skin ruptures or distension marks (overextension in the hip joint from the violent acceleration of the legs due to the primary impact) and dismemberment of the bodies. Body severance can also be caused by contact with the front edge of the hood (Rupp 1992) or by secondary impact against the front edge of the roof (Metter 1984b), which also necessitate high impact velocities.

A comparison of our results with other reports from the literature is difficult for two reasons. Firstly, reliable impact velocities derived from a technical investigation are not readily accessible and secondly, a great variety of parameters interfere with the effects of impact velocity. This probably caused Knight (1991) to consider this type of study impossible. In tangential and lateral impacts Kamiyama and Schmidt (1970) found 14% spinal fractures below and 38% spinal fractures above an impact velocity of 50 km/h. Pollak and Thorwartl (1988) remarked that they never observed inguinal skin ruptures in cases below 50 km/h. Beier and Spann (1975) found aortic ruptures above 50 km/h if the location of the primary impact was close to the centre of gravity of the pedestrian. This impact geometry promotes the occurrence of aortic ruptures because the resulting rapid rotational acceleration of the trunk results in a considerable distension of the vessel wall. In our series, ruptures of the thoracic aorta first occurred at 63 km/h and were also present in cases where the primary impact was located well below the centre of gravity of the pedestrian.

In an effort to overcome the heterogeneity of the pedestrian-car accidents, detailed selection criteria as to the car, pedestrian and point of primary contact were established, which reduced the number of cases included in this series. Therefore, a more detailed analysis as to the influence of additional important parameters such as age, weight and pre-existing diseases (e.g. osteoporosis, degeneration of the spine, arteriosclerosis), the side where the pedestrian was struck by the car, the precise impact geometry or the braking behaviour of the car were not appropriate. The limited number of cases also requires a cautious interpretation of the results. An additional safety margin is introduced if the calculated impact velocity intervals instead of the mean values (Table 1) are considered. Therefore, the following conclusions appear to be reliable for application in casework:

- If there is no spinal fracture, the velocity was below 70 km/h and probably below 50 km/h. The presence of spinal fractures gives no clear indication because low velocity impacts can also cause fractures, especially if the spine shows degeneration or osteoporosis.
- Aortic and inguinal skin ruptures are always present if the impact velocity was above 100 km/h and they never occur below 50–60 km/h.
- If a dismemberment of the body occurs, the impact velocity was above 90 km/h.

In concusion, these "threshold velocities" are derived from a small but well defined group of cases and a considerable safety margin is included by using the velocity intervals. Therefore, an estimation of the impact velocity from these four types of injury in frontal collisions involving adults in an erect position is possible in that certain velocity ranges can be ruled out. A prerequisite is the inspection of the car by the medical examiner. The effects of additional important parameters which have not been standardised in this study such as the exact impact geometry, pre-existing diseases or the build of the pedestrian should also be considered.

Acknowledgements The helpful comments by G. Beier and D. Otte are gratefully acknowledged.

References

Ashton SJ (1982) Vehicle design and pedestrian injuries. In: Chapman AJ, Wide FM, Foot HC (eds) Pedestrian accidents. Wiley & Sons, New York, pp 169–202

Ashton SJ, Mackay GM (1978) Pedestrian injuries and death. In: Mason JK (ed) The pathology of violent injury. Edward Arnold, London, pp 38–55

Atkins RM, Turner WH, Duthie RB, Wilde BR (1988) Injuries to pedestrians in road traffic accidents. BMJ 297:1431–1434

Beier G (1973) Anstossgeometrie und Verletzungsbild beim tödlichen Fußgänger-PKW-Unfall. Beitr Gerichtl Med 31:65–72

Beier G, Pfriem D (1974) Durch die Anstossgeometrie bedingte Besonderheiten im Verletzungsbild tödlich verunglückter Fußgänger. Beitr Gerichtl Med 32:73–77

Beier G, Spann W (1975) Zur Aortenruptur beim Fußgängerunfall. Hefte Unfallheilkd 121:231–234

Brison RJ, Wicklund K, Mueller BA (1988) Fatal pedestrian injuries to young children: a different pattern of injury. Am J Public Health 78:793–795

Harruff RC, Avery A, Alter-Pandya AS (1998) Analysis of circumstances and injuries in 217 pedestrian traffic fatalities. Accid Anal Prev 30:11–20

Hill DA, Delaney LM, Duflou J (1996) A population-based study of outcome after injury to car occupants and pedestrians. J Trauma 40:351–355

Ishikawa H, Kajzer J, Ono K, Sakurai M (1994) Simulation of car impact to pedestrian lower extremity: influence of different car-front shapes and dummy parameters on test results. Accid Anal Prev 26:231–242

Kamiyama S, Schmidt G (1970) Beziehungen zwischen Aufprallgeschwindigkeit, Fahrzeugbeschädigungen, Frakturen und "Wurfweite" bei 50 tödlichen Fußgänger-PKW-Unfällen. Z Rechtsmed 67:282–292

Knight B (1991) Forensic pathology. Edward Arnold, London, p 265

Lane PL, McClafferty KJ, Nowak ES (1994) Pedestrians in real world collisions. J Trauma 36:231–236

McLean AJ (1972) Car shape and pedestrian injury. Proc Symp Road Safety, Canberra, Dept Transport

Metter D (1984a) Rechtsmedizinische Unfallrekonstruktion von tödlichen Fußgänger-PKW-Unfällen. Zentralbl Rechtsmed 26:735–747

Metter D (1984b) Fußgänger-PKW-Unfälle bei Kollisionsgeschwindigkeiten über 70 km/h. Beitr Gerichtl Med 42:319–327

Pollak S, Thorwartl G (1988) Inguinale Dehnungsrisse als indirekte Anfahrverletzungen bei Fussgänger-Pkw-Kollisionen. In: Bauer G (ed) Gerichtsmedizin, Festschrift für Wilhelm Holczabek. Deuticke, Wien, pp 557–564

Robertson LS (1990) Car design and risk of pedestrian deaths. Am J Public Health 80:609–610

Rupp WR (1992) Vollständige Rumpfdurchtrennung bei Fußgänger-PKW-Kollision. Beitr Gerichtl Med 50:357–362