



Literature review of pedestrian fatality risk as a function of car impact speed

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ARTICLE INFO

Article history:

Received 8 February 2010

Received in revised form 1 April 2010

Accepted 4 April 2010

Keywords:

Pedestrian

Fatality risk

Impact speed

Real-world data

ABSTRACT

The aim of this review was to evaluate all studies of pedestrian fatality risk as a function of car impact speed. Relevant papers were primarily investigated with respect to data sampling procedures and methods for statistical analysis. It was uniformly reported that fatality risk increased monotonically with car impact speed. However, the absolute risk estimates varied considerably. Without exceptions, papers written before 2000 were based on direct analyses of data that had a large bias towards severe and fatal injuries. The consequence was to overestimate the fatality risks. We also found more recent research based on less biased data or adjusted for bias. While still showing a steep increase of risk with impact speed, these later papers provided substantially lower risk estimates than had been previously reported.

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1. Introduction

The largest group of road user fatalities worldwide are pedestrians struck by motorised vehicles (Naci et al., 2009; WHO, 2004). In order to develop effective countermeasures to save pedestrian lives, a proper understanding of car-to-pedestrian crashes is needed. This includes knowledge of both the exposure to crashes and the incidence of fatal crashes as functions of car impact speed. Furthermore, when estimating the potential benefits of new countermeasures, the pedestrian fatality risk as a function of car impact speed is of particular interest. It also provides important information for the development of future pedestrian safety systems and can be used as a guideline when designing pedestrian friendly cars and infrastructures.

Historically, the incidence of fatal crashes has been far better understood than exposure to crashes. This can be explained by most real-world pedestrian accident investigations being biased towards the severe end of the accident spectrum. By including an out of proportion number of severe and fatal accidents, fatality risks may be overestimated unless appropriate weighting procedures are applied (Amemiya, 1985, pp. 319–338; Hsieh et al., 1985; Manski and Lerman, 1977).

The impact speed of the striking car is widely accepted as a prime factor for the injury risk in car-to-pedestrian collisions. However,

people's opinions differ as to the exact relationship between car impact speed and pedestrian fatality risk. Therefore, the aim of this review was to evaluate all studies of pedestrian fatality risk as a function of car impact speed. Relevant papers were primarily investigated with respect to data sampling procedures and methods for statistical analysis.

2. Methods

A literature search was conducted with the aim to find all relevant papers published up to and including 2009. One study published in 2010 was also found and therefore included. The search terms included only English words, but researchers from China, Germany, and Japan were asked for information about relevant articles written in these languages. Thus, there was no clear restriction to English literature.

2.1. Relevant papers

Papers were gathered according to the following:

1. The following search engines were queried for relevant articles: Google (www.google.com), PubMed (www.ncbi.nlm.nih.gov/pubmed), SAE (www.sae.org), ScienceDirect (www.sciencedirect.com), and Transportation Research Board (trb.metapress.com). Search terms included combinations of the following words: *pedestrian*, *fatality*, *mortality*, *death*, *risk*, and *speed*. Titles and abstracts were briefly considered and relevant articles were then purchased for detailed analysis (see Section 2.2).

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2. Conference proceedings were systematically searched by studying tables of contents from the Association for the Advancement of Automotive Medicine (AAAM) from 1959 to 2009, the International Technical Conference on the Enhanced Safety of Vehicles (ESV) from 1987 to 2009, the International IRCOBI Conference on the Biomechanics of Impact from 1973 to 2009, and the Stapp Car Crash Conference from 1966 to 2009.
3. The reference lists of the relevant papers were screened to identify other potentially relevant studies.
4. Researchers in this field were asked to contribute with suggestions of relevant articles.

2.2. Analysis of papers

All papers including an analysis of the pedestrian fatality risk as a function of impact speed were investigated with respect to how real-world data was collected. In many cases, reading related articles and reports from references provided this information. Special emphasis was made on identifying sources of bias towards either the higher or lower end of the injury severity spectrum, e.g., by comparing the dataset with national statistics. Furthermore, the crash inclusion criteria were investigated. As a second step, statistical methods for data analysis were considered. If data was biased, we checked for attempts to adjust for this in the statistical analyses. As a third step, the methods for assessing car impact speeds were considered.

3. Results

In total, 11 highly relevant studies met the inclusion criteria. These studies are summarised in Table 1. It was uniformly reported that fatality risk increased monotonically with car impact speed. However, the absolute risk estimates varied considerably. Nearly all data sources used in the study of pedestrian fatality risk comprised a higher percentage of fatalities than the corresponding national pedestrian statistics. In the following review, we refer to this phenomenon as sample bias towards fatal accidents. Such a bias can have two causes: (1) the sampling region differed from the nation as a whole with respect to parameters such as impact speed, car fleet, and/or pedestrian characteristics. If such sample bias were only due to differences in impact speed, the risk curve would, however, not have been affected, since impact speed was included in the fatality model as an explanatory variable. (2) The sampling plan was such that it favoured accidents with severe and/or fatal injuries (so called outcome-, response-, or choice-based sampling). In these cases, appropriate weighting procedures must be applied to adjust for the bias, otherwise risk curves will produce excessively high fatality risks. For discussions on probabilistic models and outcome-based sampling, see Amemiya (1985, pp. 319–338), Davis (2001), Hsieh et al. (1985), and Manski and Lerman (1977). Furthermore, Rosén and Sander (2009, p. 537) includes an example illustrating the effect of outcome-based sampling on fatality risks.

The intention of weighting data is to estimate the influence of missing (underreported) cases. Typically, these accidents involve slightly injured pedestrians. The effect of a simple weighting procedure can be described as follows: first, weight factors (w_{slight} , w_{severe} , and w_{fatal}) are derived by comparing the proportions of slightly, severely, and fatally injured pedestrians in the in-depth data (study data) to nationally representative data. Second, the study data is used to derive impact speed distributions for slightly, severely, and fatally injured pedestrians respectively. Third, these distributions are combined into a single impact speed distribution for all casualties (the exposure) by applying the weight factors to adjust the relative proportions of slightly, severely, and fatally injured pedestrians. Finally, the fatality risks are estimated by

dividing the weighted number of fatalities (the incidence) to the weighted number of casualties (the exposure) at each impact speed. In this way, the precise effect of the weighing at a particular impact speed automatically depends on the exact relations of the number of slightly, severely, and fatally injured pedestrians at that impact speed in the study data. Note that this weighting procedure stands independent of any subsequent regression analysis of the data.

Papers including an analysis of pedestrian fatality risk as a function of impact speed are reviewed below according to the following: (Section 3.1) Ashton (1980)¹, Cuerden et al. (2007), Davis (2001), Neal-Sturgess et al. (2002), and Pasanen (1992) (Section 3.2) Anderson et al. (1995, 1997) (Section 3.3) Yaksich (1964) (Section 3.4) Hannawald and Kauer (2004) and Rosén and Sander (2009) (Section 3.5) Oh et al. (2008a,b) (Section 3.6) Kong and Yang (2010). The often cited articles by Teichgräber (1983) and Walz et al. (1983) are also treated in this review (see Sections 3.7 and 3.2 respectively).

3.1. British data 1965–1979 and 2000–2006

In the UK, two large scale pedestrian accident investigations have been conducted. Section 3.1.1 describes investigations during the 1960s and 70s in Birmingham and Worcestershire. Section 3.1.2 describes the accident investigation project On The Spot (OTS) that started in 2000. Fatality risks derived from these two separate data sets are described in the corresponding subsection.

3.1.1. Birmingham/Worcestershire 1965–1979

From 1966 to 1969, on-the-scene traffic accident investigations were carried out in Birmingham and Worcestershire in England (Ashton et al., 1977). This study included both pedestrian and other accidents. A related on-the-scene pedestrian accident study was conducted in Birmingham from 1973 to 1979 (Ashton, 1980). According to Ashton et al. (1977), 208 injured pedestrians struck by the fronts of cars or car derivatives with assessed impact speed were investigated in these two studies until 1976. These 208 pedestrians, with assessed car impact speeds, were part of a larger sample comprising 336 pedestrians. Ashton et al. (1977) compared this total sample to the national population of pedestrian casualties from 1974 and found it was largely biased towards severe injuries and fatalities. The sample included 20% fatalities, while the corresponding national proportion was 3.5%. Ashton et al. (1977) therefore concluded that this sample could not be used directly to study the risk of death or injury as a function of car impact speed.

“Care must be taken in interpreting these results, and in particular the results cannot be used directly to make statements about the general nature of pedestrian accidents as the sample is not a representative sample; it being biased towards the severe end of the accident spectrum. One effect of this is to increase the percentage of the more serious injury cases in each speed band and thus statements that a certain percentage in a specified speed band sustain a given severity of injury only apply to the sample and not to the total population of accidents.” (Ashton et al., 1977, p. 5)

The Birmingham pedestrian accident investigations continued after 1977 and a later article by Ashton (1980) described a sample that included yet another 150 car-to-pedestrian collisions with assessed car impact speeds. This total of 208 + 150 = 358 pedestrian accidents with assessed car impact speeds comprised 81 (23%) fatalities. Once again, it was pointed out that the sample was biased towards the more severe end of the accident spectrum when com-

¹ This study is sometimes referred to as “Ashton (1982)”.

Table 1

Summary of the most relevant articles and their corresponding data sources.

	Data source	Sample size	Fatality rate	National fatality rate	Adjusted for bias	No. of pedestrians in the ages 0–14 years, 15–59 years, 60+ years	Section of this article
Ashton (1980)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	No	155, 121, 82	3.1
Pasanen (1992)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	No	155, 121, 82	3.1
Davis (2001)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	Yes	155, 121, 82	3.1
Cuerden et al. (2007)	OTS, in-depth on-the-scene, 2000–2007, UK.	108	6.5%	2.4%	No	–	3.1
Anderson et al. (1997)	Zürich, Police and medical data, 1978, Switzerland.	56	11%	5% ^a	No	–	3.2
Yaksich (1964)	St. Petersburg, Florida, Police data, 1958–1963, USA.	498	10%	–	No	120, 120, 258 ^b	3.3
Hannawald and Kauer (2004)	MUH/GIDAS, in-depth on-the-scene, 1991–2003, Germany.	712	5%	2.2%	No	–	3.4
Rosén and Sander (2009)	GIDAS, in-depth on-the-scene, 1999–2007, Germany.	490	7%	2.2%	Yes	0, 328, 162	3.4
Oh et al. (2008a)	In-depth on-the-scene, 2003–2005, Korea.	182	30%	5%	No	–	3.5
Oh et al. (2008b)	In-depth on-the-scene, 2004–2005, Korea.	101	~30%	5%	No	–	3.5
Kong and Yang (2010)	In-depth on-the-scene, 2003–2009, China.	104	11%	–	–	–	3.6

Based on the national database STATS19 (Cuerden, private communication 2010).

^a Estimate refers to Zürich 1978 (Walz et al., 1983).^b Estimated from Table 2 of Yaksich (1964).

pared to national statistics for 1976 (Ashton, 1980). We conclude that the accidents included in the final sample of the Birmingham studies ($N=358$) are by now more than 30 years old and that the sample was largely biased towards severely and fatally injured pedestrians. In Fig. 1a, we provide the empirical fatality rates of this sample as presented by Ashton (1980).

The data from the Birmingham studies has been the basis for two separate risk analyses, namely Pasanen (1992) and Davis (2001): a decade after the presentation of the Birmingham data, Pasanen (1992)² set out to derive the risk of pedestrian death as a function of car travel speed. To proceed with the analysis, the risk of death as a function of impact speed was needed. Pasanen then used the data from Ashton (1980) and fitted an analytic function to these by using regression analysis. This function showed a steep increase of fatality risk with impact speed, e.g., reaching 40% at 50 km/h (see Fig. 1a). Pasanen's risk curve was challenged by Davis (2001)³, who pointed out the inappropriateness of directly using the biased data from Ashton (1980) in a risk analysis. Davis instead proceeded by weighting this data so that the proportions of fatal, severe, and slight crashes in the sample were adjusted to the corresponding national proportions in the UK for the year 1976. Furthermore, Davis (2001) applied an ordered logit regression model with “slightly-,” “severely-,” and “fatally injured” as response categories. Finally, the age groups of 0–14 years, 15–59 years, and 60+ years were treated separately. His results for the two former age groups showed substantially lower risks than those of Pasanen (1992); while the risk curve for the latter group was comparable to Pasanen's risk curve for the entire sample (see Fig. 1a

and b). For the group of pedestrians aged 15–59 years, the fatality risk was 7% at an impact speed of 50 km/h. It should be noted that neither Pasanen nor Davis had access to the exact impact speeds from the Birmingham data. Instead, these authors based their analyses on the information given by Ashton (1980), where all impact speeds were given as “0–10 km/h,” “11–20 km/h,” “21–30 km/h” etc. Davis was concerned that this could lead to biased parameter estimates in the regression analysis and therefore assumed that the impact speeds were uniformly distributed within each impact speed group. This procedure may be interpreted as introducing measurement error and implied slightly flattened risk curves. Furthermore, impact speeds presented by Ashton (1980) as “71+ km/h” were particularly difficult to handle. Davis modelled these cases as uniformly distributed from 71 to 100 km/h (Davis, private communication 2008). Pasanen, on the other hand, treated these cases as having an impact speed of 80 km/h (Pasanen, private communication 2008). Needless to say, neither of these approaches was perfect and therefore imposed some limitations on the results.

Ashton and Mackay (1979) presented the incidences of slightly, severely, and fatally injured pedestrians as functions of car impact speed in a figure. These curves were claimed to be based mainly on the Birmingham data weighted to become nationally representative. This information could in principle be used to derive weighted risk estimates from the Birmingham data. However, one would have to rely on taking measurements from the curves. Cuerden et al. (2007) attempted this approach and found the fatality risk was 10% in the speed interval of 40–50 km/h and 40% in the interval of 50–60 km/h. However, it was clearly pointed out that the method was not very accurate. It should be noted that anyone can proceed by starting from the raw Birmingham data given by Ashton (1980) and weight it so that the proportions of slightly, severely, and fatally injured pedestrians agree with the 1976 national statistics presented in the same article. One then finds that the fatality risk becomes approximately 10% in the speed interval of 40 to

² The same risk curve was provided in Pasanen (1991) and Pasanen and Salmivaara (1993).

³ Davis et al. (2002) basically contained the same analysis as provided in Davis (2001).

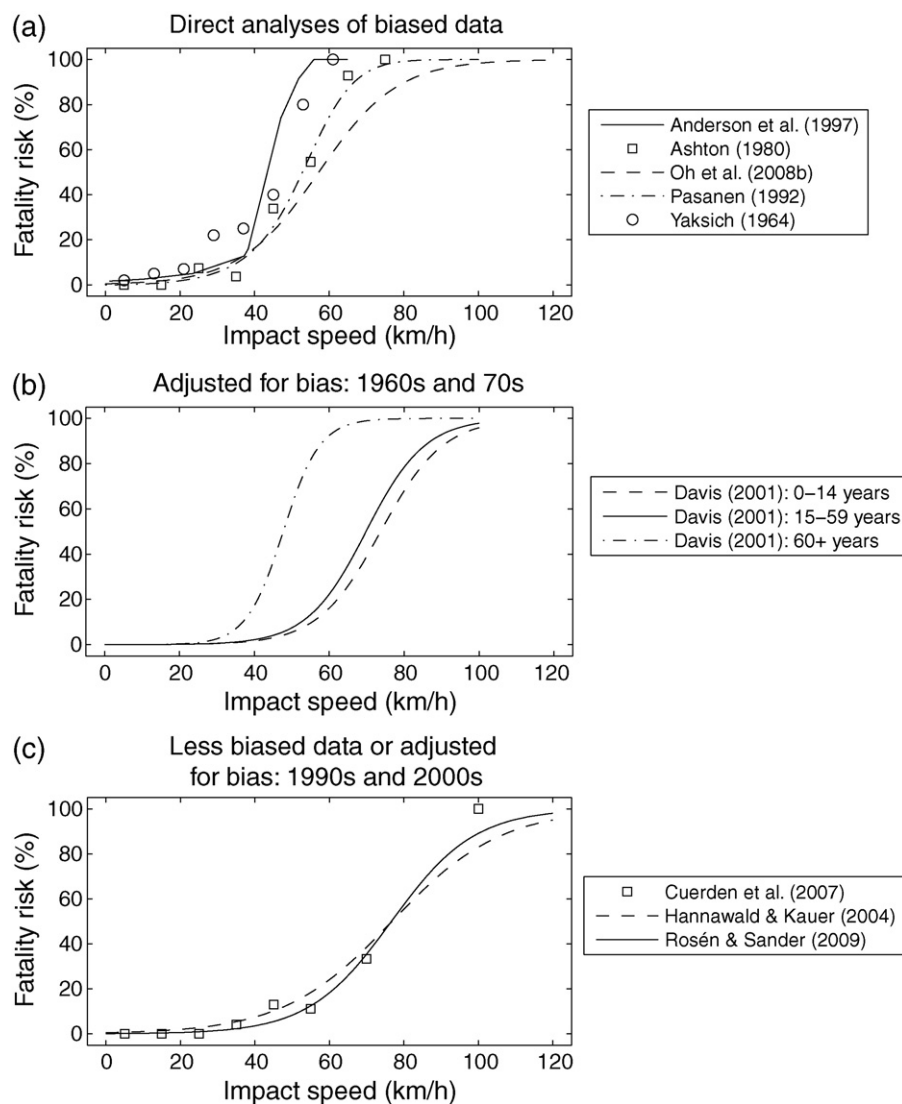


Fig. 1. Fatality risk as a function of impact speed for pedestrians struck by the front of a passenger car. (a) Results based on biased data. (b) Results for crashes in the 1960s and 70s adjusted for bias. (c) Results for crashes in the 1990s and 2000s based on less biased data or adjusted for bias.

50 km/h but only 20% in the interval 50 to 60 km/h. Finally, Neal-Sturgess et al. (2002) fitted quadratic and cubic polynomials to risks claimed to be taken from Ashton and Mackay (1979). Firstly, these risks did not agree with the reference. For example, the risk at 50 km/h was 70% according to Neal-Sturgess. Secondly, the derived risk curves reached 100% probability of death at an impact speed of about 60 km/h. This is quite remarkable considering the fact that there was a survivor in the Birmingham data with an impact speed above 60 km/h. Thirdly, in these kinds of linear regression models the errors are assumed to be homoscedastic, which means that the errors should have a constant variance. However, the variance of a binary variable with mean p is $p(1-p)$. In this case, p is the pedestrian fatality risk, which depends on impact speed and therefore the errors are in fact heteroscedastic.

3.1.2. OTS 2000–2006

The accident investigation project On The Spot (OTS) started in 2000 and has conducted about 500 on-the-scene traffic accident investigations annually from the Thames Valley and Nottinghamshire. Part of the study included vehicle-to-pedestrian accidents, and until July 2006 a total of 175 pedestrians struck by vehicles had been investigated. Of these pedestrians, 108 were injured with known injury severity and struck by the front of a pas-

senger car with an estimated impact speed (Cuerden et al., 2007). This sample only included 7 (6.5%) fatalities, which is much closer to the UK national proportion of fatalities in car-to-pedestrian crashes than the Birmingham sample described above (The national fatality rate for pedestrian casualties was 2.4% in STATS19 for the years 2005–2007, Cuerden, private communication 2010). The data was analysed by Cuerden et al. (2007) who found that all seven fatalities were struck at impact speeds exceeding 30 km/h. From Fig. 7 of that article one can derive that at the speed band 30–40 km/h, 1 of 24 pedestrians was killed, at 40–50 km/h 3 of 23 were killed, at 50–60 km/h 1 of 9 was killed, and at impact speeds above 60 km/h 2 of 4 were killed. The impact speeds for the two survivors over 60 km/h were 69 and 72 km/h, and the impact speeds for the two fatalities were 71 and 97 km/h (Cuerden, private communication 2008). The sample size was too small to draw any definite conclusions on the risk of death as a function of impact speed. However, these initial findings are in sharp contrast with those of the raw Birmingham data described above, but more in line with the results of Davis (2001) that were based on the weighted Birmingham data (see Fig. 1).

The statistical analysis of Cuerden et al. (2007) was clear, simple, and of good quality. However, the reliability of impact speeds in the OTS database might be questioned. Cuerden et al. (2007) stated

that only 41% of the 175 cases in their sample had impact speeds based on robust physical evidence, with the remaining 59% having impact speeds based either on some physical evidence or subjective opinion. We refer to the Limitations (Section 5) for a discussion on the implications of errors in estimated impact speeds.

3.2. Swiss data 1978 and 1981

As described in an article by Walz et al. (1983), pedestrian accidents were investigated in Zürich in 1978 and 1981. Between these years, city speed limits were reduced from 60 to 50 km/h, and the scope of the article was to assess the effect on pedestrian casualties. It was stated that a total of 946 pedestrians were involved in accidents during these 2 years, and that these accidents were investigated retrospectively in co-operation with police and hospitals. From the medical records, Abbreviated Injury Scale (AIS) codes were registered and the Injury Severity Score (ISS) was calculated for each pedestrian. (For information on AIS and ISS, see Baker et al., 1974 and AAAM, 2001.) The article by Walz et al. (1983) has many citations and it is often claimed that the risk of pedestrian fatality as a function of impact speed was derived in that study. However, this is not true, instead Walz et al. found that the chances of pedestrian survival were 99% for ISS 1–10, 87% for ISS 11–20, 27% for ISS 21–30 and 7% for ISS > 30. Compared to findings reported by standard references on ISS (Baker et al., 1974; Baker and O'Neil, 1976; Bull, 1975), the survival chances found by Walz et al. (1983) were very low. Since the chances of survival at any given ISS are strongly dependent on age (Baker et al., 1974; Bull, 1975), this could possibly be explained by the fact that the pedestrians in the Zürich data were relatively old. The age distribution for the Zürich sample of 946 pedestrians was later presented by the Interdisciplinary Working Group for Accident Mechanics (IWGAM, 1986), where it was shown that 39% were 60 years or older. Walz et al. (1983) selected a sub-sample for in-depth study (containing 66 pedestrians from 1978) and impact speeds were estimated in 56 of those cases, including 6 fatalities (11%). This sub-sample was further described by IWGAM (1986), where it was shown that the sub-sample was largely biased towards severe injury accidents compared to the total sample of 946 pedestrians. For example, in the total sample, 14% of the pedestrians had maximum AIS3+ (MAIS3+) injuries, whereas for the sub-sample (with estimated impact speeds) the corresponding proportion was 53%. IWGAM (1986) used this largely biased sub-sample to estimate the mean ISS value as a function of impact speed. It is obvious that this curve was bound to give largely exaggerated ISS values at any given impact speed due to the substantial bias of the sub-sample.

The findings of Walz et al. (1983) and IWGAM (1986) were later used by Anderson et al. (1995, 1997) in two similar articles to derive the risk of pedestrian death as a function of impact speed. The intention of these articles was to demonstrate the benefit to pedestrian safety of reduced travelling speeds of cars. In order to do this, a risk curve was needed. Starting from the curve of average ISS versus impact speed (as derived by IWGAM, 1986) and combining it with the risk of death for different ISS values (as estimated by Walz et al., 1983) the risk of death as a function of impact speed could be estimated. The derived fatality risks increased very rapidly with impact speed, reaching almost 90% at 50 km/h (see Fig. 1a). This approach deserves a number of comments: firstly, none of the pedestrians in the sub-sample were subjected to an impact speed above 55 km/h, hence it is not possible to estimate the risk at higher speeds using these data. Secondly, the sub-sample used to derive the risk curve comprised only 56 pedestrians with assessed impact speeds, including 6 fatalities. This is to be regarded as a very small sample when it comes to deriving risk curves. Thirdly, the obtained risk curve showed a risk ranging from 60% to nearly 100% within the speed interval of 46–55 km/h. However, according to IWGAM

(1986) 5 of the 56 pedestrians in the sub-sample were struck at an impact speed between 46 and 55 km/h, whereas (according to Walz et al., 1983) only 1 of the 6 fatalities belonged to this speed interval. Hence, in the sub-sample used to derive the risk curve, the empirical risk was only 20%, which should be compared to the estimated 60–100% by Anderson et al. (1995, 1997). Finally, as explained above, the sub-sample was largely biased towards severe injuries. In the article by Anderson et al. (1997, p. 669) the following sentence is included: “Although the data have acknowledged limitations in application, little alternative data exist.” Unfortunately, no discussion on these acknowledged limitations was included.

3.3. US data 1958–1963 and 1994–1998

A study by Yaksich (1964) considered police reports from pedestrian accidents in St. Petersburg, Florida, from 1958 to 1963 and provided fatality rates at different impact speeds (see Fig. 1a). The sample included 536 injury producing accidents (some of which involved death or injury of more than one person), but the fatality rates were based on 498 accidents of which 48 (10%) were fatal. It is important to note that the study region was chosen in order to include as many elderly pedestrians as possible (the name of the study being “Pedestrians with mileage: A study of elderly pedestrian accidents in St. Petersburg, Florida”). Pedestrians aged 65 years or older constituted nearly 50% of the injured and 70% of the fatalities, thus partly explaining the high fatality rates. Furthermore, the impact speeds were based on police estimates and most of the striking vehicles are by now more than 50 years old.

The history of US pedestrian crash investigations was described by Henary et al. (2003). We have not been able to find any articles deriving the fatality risk as a function of impact speed from this USA data. However, some USA-based studies have been conducted on the fatality risk as a function of travel speed, or posted maximum travel speed (see Gärder (2004) and references within Leaf and Preusser (1999)). In spite of the lack of fatality risk curves based on impact speed, we would like to mention the Pedestrian Crash Data Study (PCDS), which contains detailed information on more than 500 pedestrian crashes collected in the US during 1994–1998 (Chidester and Isenberg, 2001). The PCDS data constituted a clinical study and the crashes were not selected to be representative of the total US population of pedestrian crashes. Only pedestrians struck by late model cars and light trucks and vans were included. Furthermore, first point of impact between vehicle and pedestrian must have been forward to the top of the A-pillar. Finally, pedestrians lying on the ground or sitting down were excluded. It has been reported that the total PCDS sample contained 12% fatalities, which is to be compared to the national figures of 6% in 1994 and 8% in 1998 (Chidester and Isenberg, 2001). Since the inclusion criteria are not the same for the PCDS data and the national statistics, these figures cannot be directly compared. However, this potential bias should be investigated and possibly adjusted for before using the PCDS data to estimate the risk of death or injury as a function of impact speed.

Henary et al. (2003, 2006) and Roudsari et al. (2004) investigated pedestrian mortality by multiple logistic regression analysis of the PCDS data. The model effects included pedestrian characteristics, such as age, gender, height, weight, and vehicle type influences. Impact speed was recognised as a strong confounder and was therefore included in the models. Both Henary et al. (2003) and Roudsari et al. (2004) reported how the relative odds of dying increased with impact speed. However, no functions or curves were presented showing the dependence of fatality risk on impact speed.

Finally, we need to mention the work of Tharp and Tsongos (1977), often cited in the pedestrian literature. However, that article treated the risk of critical injury rather than death.

3.4. German data 1973–2007

On-the-scene road traffic accidents have been investigated in Hanover and surroundings, since 1973 by the Medical University of Hanover (MUH). In 1999, a similar study was initiated in Dresden and surroundings, and the data from these two sampling regions were combined to form the German In-Depth Accident Study (GIDAS). This database includes only accidents involving at least one injured person (Otte et al., 2003). The GIDAS data has higher proportions of severely and fatally injured pedestrians than the German national population of pedestrian casualties (Rosén and Sander, 2009). In particular, the GIDAS pedestrian data from 1999 to 2007 contains 4.9% fatalities and the corresponding national proportion during 2003–2007 was 2.2%.

Hannawald and Kauer (2004) estimated the potential effectiveness of a brake assist system. The target population of accidents included frontal car-to-pedestrian collisions in which the forces through the car were coded as being more or less parallel to its longitudinal direction. Using data from MUH and GIDAS for the years 1991–2003, a total of 712 pedestrians were gathered, including 35 (5%) fatalities. The risk of sustaining a maximum AIS5+ injury as a function of car impact speed was derived by applying logistic regression to the data. It was then claimed that this risk curve closely resembled the risk curve for pedestrian fatality. No analytical expression was given, but the risk curve was plotted in a figure. From this risk curve it can be seen that the fatality risk (i.e. MAIS5+ risk) was 14% at an impact speed of 50 km/h reaching 50% at 77 km/h (see Fig. 1c).

Rosén and Sander (2009) analysed GIDAS data from 1999 to 2007. The study was limited to injured pedestrians aged 15 years or more, struck by the front of a passenger car (excluding pedestrians lying on the ground prior to impact, as well as sport utility vehicles and other light trucks and vans). The sample contained 490 cases, including 36 (7%) fatalities. In comparison to national statistics, the GIDAS data was weighted to adjust for the sample bias towards severe and fatal accidents. A risk curve was derived by logistic regression analysis and an approximate 95% confidence band was given. As a result of the sparseness of high speed collisions, the confidence band was quite wide for impact speeds exceeding approximately 60 km/h. The fatality risk was estimated at 8% at 50 km/h (95% CI: 5–13%) and reaching 50% at 75 km/h (95% CI: 26–68%). A sensitivity study showed that the risk curve was stable against changes in the weighting factors. However, it was pointed out that unknown errors in the reconstructed impact speeds may have affected the results. The fatality risk curve derived by Rosén and Sander (2009) is reproduced in Fig. 1c.

Fildes et al. (2004) analysed MUH data from 1973 to 2000 and Australian fatal files from 1997 to 1999. The pedestrian fatality risk as a function of impact speed was presented in a figure with their results. However, via private correspondence, the authors of that paper confirmed that the curve was based on the Anderson risk curve, and that their paper inadvertently omitted the citation attributing the work to Anderson et al. (1995, 1997).

3.5. Korean data 2003–2005

In Korea, vehicle-to-pedestrian accidents were investigated from 2003 to 2005 (Oh et al., 2008a). A total of 182 accidents with assessed impact speeds were collected, comprising 55 (30%) fatalities. The striking vehicles included passenger cars, SUVs, vans, trucks, and buses. According to Youn et al. (2005), the pedestrian fatality rate was only 5% for the total population of vehicle-to-pedestrian accidents in Korea 2003. Hence, the sample of the in-depth study had a large bias towards fatal crashes. Since the sampling procedure has not been described in the literature, the reason for bias is not known. However, it is likely that the bias is a

result of outcome-based sampling or, equivalently, underreporting of slight injury accidents, which makes a direct risk analysis of the sample inappropriate.

Nevertheless, Oh et al. (2008a) performed multiple logistic regression analysis on this biased sample, using impact speed, pedestrian age, and vehicle type as explanatory variables in their fatality model. The resulting risk curves showed high fatality risks even at moderate impact speeds. However, their analysis was bound to result in largely exaggerated risk estimates, since no weighting procedures were applied to account for the bias. It is surprising that the authors did not detect this phenomenon, since the previously mentioned article by Davis (2001) (where the problem of using data with an outcome-based bias was pointed out) was referred to. Furthermore, in the statistical model, the various vehicle types were given a number from 1 to 4 (1: passenger car, 2: SUV, 3: van (1box), 4: bus/truck), which means that the logistic regression model would treat this variable as a continuous variable. The correct procedure would have been to include it as a nominal variable.

In a related article, Oh et al. (2008b) analysed pedestrian fatality risk as a function of impact speed as part of assessing the effectiveness of a certain pedestrian protection system. The data used was a sub-sample of the above mentioned 182 pedestrians, including 101 pedestrians struck by vehicles from 2004 to 2005. Both passenger cars, SUVs, vans, buses, and trucks were included as striking vehicles. However, in this article Oh et al. (2008b) did not distinguish between different vehicle types. It was not stated how many fatalities were included in the sub-sample, but it might be assumed that the proportion of fatalities was about 30% for the sub-sample as well. Thus, the bias in the sample is again likely to render the risk estimates exaggerated. From the logistic regression parameters given in the article, it follows that the fatality risk estimate equalled 34% at an impact speed of 50 km/h (see Fig. 1a).

3.6. Chinese data 2003–2009

A Chinese study of pedestrian fatality risk was published during the beginning of 2010 (Kong and Yang, 2010). An in-depth sample of frontal vehicle-to-pedestrian crashes in urban areas was studied. For a case to be selected, the striking vehicle had to be a car, SUV, or MPV, while the pedestrian was at least 14 years old and sustained AIS1+ injuries. The sample included 104 injured pedestrians of which 11 were killed. To account for sampling bias, the data was weighted in two different ways: (1) by comparing to police data for the study region (Changsa) and (2) by comparing to national police data. It should be noted that the in-depth data contained 11% fatalities whereas the Changsa and national data had fatality rates of 19% and 24% respectively. The fatality rates of the two latter data sets are remarkably high. This was likely due to substantial underreporting of slight and severe injury crashes. Furthermore, in the first weighting procedure, Kong and Yang claimed that MAIS3+ injury in the in-depth data was equivalent to severe injury in the Changsa police data. This cannot be true, since it would require the police to collaborate with hospitals familiar with the AIS coding system. From the unweighted in-depth data, the fatality risk was estimated to 13% at an impact speed of 50 km/h. The weighted risk curves yielded corresponding fatality risks of 26–27%. These risk curves are not reproduced in Fig. 1 because of the questionable fatality rates in the Changsa and national police data. The unweighted risk curve is probably more representative to the actual fatality risks in China.

3.7. Teichgräber's article 1983

One of the more frequently cited pedestrian risk curves was presented by Teichgräber (1983). This curve showed a fatality risk of approximately 60% at an impact speed of 50 km/h. It is inter-

esting to note that no fatality risk analysis was presented in the article. Instead, Teichgräber stated that the risk curve was taken from a report with the following reference: “Jahresbericht 1976 der Schweizerischen Beratungsstelle für Schadenverhütung, Bern.” However, to the best of our knowledge, there has never been a “Beratungsstelle für Schadenverhütung” in Switzerland, but a “Beratungsstelle für Unfallverhütung” (BfU) does exist. According to the BfU (private communication), the annual report from 1976 did not include any such risk curve, although the report from 1975 did (BfU, 1975). The risk curve in BfU (1975) was in turn based on the report by Yaksich (1964) (see Section 3.3), whose fatality rates were indeed similar to the risk curve provided by Teichgräber (1983) (this risk curve is not reproduced here).

4. Summary of findings

As described in Section 3.1.1, the articles by Ashton (1980) and Pasanen (1992) treated a biased data set from the Birmingham/Worcestershire investigations in the 1960s and 70s. This bias was pointed out by Ashton et al. (1977) and Ashton (1980), but most subsequent articles referring to that data have overlooked this fact. Davis (2001) pointed out the inappropriateness of Pasanen’s approach and adjusted for the sample bias by weighting the data. However, that data is by now more than 30 years old and thus unlikely to capture the present situation of pedestrian fatality risk, e.g., due to changes in car design, rescue chain, and medical treatment. Furthermore, neither of these researchers had access to the exact impact speed assessments, thus placing some restrictions on the reliability of their results. Nevertheless, the analysis by Davis (2001) provides the most reliable fatality risks available for crashes during the 1960s and 70s.

The empirical risks reported by Cuerden et al. (2007) were based on OTS data from 2000 to 2006 comprising only seven fatalities, thus providing rather crude estimates of the actual risks (see Section 3.1.2).

The risk curve derived by Anderson et al. (1995, 1997) was based only on 56 pedestrian crashes (including 6 fatalities) with assessed impact speeds (see Section 3.2). This sample, first described by Walz et al. (1983), was largely biased towards severe injury accidents. Nevertheless, it was used by IWGAM (1986) to calculate the mean ISS value at different ranges of impact speed, and then related to fatality risk via the ISS values by Anderson et al. (1995, 1997). This derivation was bound to yield largely exaggerated and crude risk estimates. Furthermore, the data was collected in 1978 and is by now more than 30 years old.

As described in Section 3.4, the analysis of Hannawald and Kauer (2004) involved frontal car-to-pedestrian collisions. The analysis was based on a large, but unweighted, data sample (712 cases) from MUH and GIDAS from the years 1991–2003. Their report did not describe in detail how the statistical analysis was conducted. In particular, no discussions on the model fit and/or highly influential observations were included. Furthermore, pedestrian fatality risk was approximated by the risk of sustaining MAIS+ injury.

The paper by Rosén and Sander (2009) analysed the fatality risk for pedestrians aged 15 years or more struck by the front of a passenger car (see Section 3.4). The analysis was based on weighted GIDAS data from 1999 to 2007 comprising 490 cases, of which 36 were fatal. The statistical analysis included logistic regression, model fit investigations, and the derivation of an approximate 95% confidence band for the risk curve. As a result of the sparseness of high speed collisions, the confidence band was quite wide for impact speeds exceeding approximately 60 km/h.

The analyses of Oh et al. (2008a, b) were based on substantially biased pedestrian data from Korea collected between 2003 and 2005 (see Section 3.5). The bias of the sample is likely to have rendered the risk estimates too high.

As described in Section 3.6, Kong and Yang (2010) analysed 104 adult pedestrians that were struck by the front of a car, SUV, or MPV in Changsa, China. Weight factors were derived by comparing the in-depth data to Changsa and national police data. However, the fatality rates of the two latter data sets were remarkably high, which likely implied exaggerated risk estimates. The unweighted risk curve is probably more representative to the actual fatality risks in China.

Finally, as described in Section 3.5, the risk curve reported by Teichgräber (1983) was traced back to a study by Yaksich (1964), which was based on police reported pedestrian accidents in St. Petersburg, Florida from 1958 to 1963. The sample included a high proportion of elderly pedestrians and the striking vehicles are by now more than 50 years old (see Section 3.3).

5. Limitations

Most studies of pedestrian fatality risk as a function of car impact speed were based on European data, the exceptions being the analyses of Oh et al. (2008a,b), which used Korean data, Kong and Yang (2010), which used Chinese data, and Yaksich (1964), that used American data. When deriving fatality risks, it is important to acknowledge the role of medical treatment. Furthermore, it is well known that pedestrian age is an important predictor of fatality risk (see Henary et al., 2006 and references therein, as well as Rosén and Sander, 2009). Hence, the fatality risk as a function of impact speed derived from e.g. German data necessarily reflects the age distribution of the German population of pedestrian victims as well as the medical treatment offered in Germany. The fatality risks may differ substantially in developing countries where the majority of fatal pedestrian crashes occur.

Assessing impact speeds in car-to-pedestrian crashes is difficult and requires presence at the accident scene in order to collect relevant evidence and information. Furthermore, the derivation of risk curves is sensitive to errors in the impact speed estimations. A systematic error towards higher or lower impact speeds would obviously shift the derived risk curve to the right or left respectively. Furthermore, as pointed out by Davis (2001), random errors can produce inconsistent parameter estimates in the regression analysis. Generally, random errors lead to a flattening of injury risk curves. A recent textbook on this problem is provided by Carroll et al. (2006). See also Funk et al. (2008) for an example related to road traffic crashes.

The data sources used in the risk analyses reviewed in this paper only included pedestrians that were injured in the crash. Hence, all fatality risks that have been derived to date are the probabilities of death given that pedestrians had at least one injury. It might be speculated that an overwhelming majority of pedestrians would be injured in crashes even at very low impact speeds.

6. Suggestions for deriving injury risk curves

When using real-life accident data to establish a statistical relationship between injury risk and impact speed, it is of utmost importance to consider the sampling procedures for the accident data collection. In particular, sources of systematic bias towards either the higher or lower end of the injury spectrum need to be identified. In the context of pedestrian casualties, it is typical that some kind of outcome-based sampling is operating. If this bias is substantial, it is advisable to derive appropriate weight factors by comparing the sample to a larger and more representative database, e.g., national statistics of accident data. Good working examples of how this can be done include Davis (2001) and Rosén and Sander (2009). It is important that the study data and national data use the same definitions of injury severity and that the acci-

dent inclusion criteria are comparable. Preferably, the study data should contain the same injury severity code as used in the national statistics, which is possible when the study data is a subset of the national data. If the study data were collected from a region that differed from the nation as a whole with respect to, e.g., pedestrian ages or other important characteristics, more advanced weighting procedures are required that take these characteristics into account. Furthermore, it should be noted that the quality of national data differ between countries. In particular, the reported number of non-fatal accidents is usually lower than the actual number due to underreporting by the police. The effect of underreporting in the national statistics can be investigated by a sensitivity analysis (see e.g. Rosén and Sander, 2009).

Having established a statistical relationship between pedestrian injury risk and impact speed, it is desirable that confidence intervals are derived. Confidence intervals are a good tool for assessing the degree of certainty of the results. If empirical risks are derived at different impact speed intervals, exact binomial confidence intervals should be derived at each interval. Asymptotic confidence intervals can be used if the number of cases in each interval is large enough (guidelines are readily available in most introductory textbooks on applied statistics). If an analytical risk curve is derived using logistic regression, approximate confidence intervals may be derived following Kutner et al. (2004) (see Rosén and Sander (2009) for an example). Furthermore, model fit investigations and sensitivity analyses should be conducted.

Finally, it is important that the accident investigations and impact speed estimations are of high quality to assure that systematic errors in impact speeds are minimised and that the random errors are under control. Large random errors tend to flatten injury risk curves, whereas systematic errors shift the risk curves horizontally.

7. Conclusions

Data from real-world, car-to-pedestrian crashes can provide important knowledge on the fatality risks of pedestrian casualties. However, it is important that high quality accident investigations are conducted and that the data is treated with care in the statistical analysis. In the studies considered in this review, the proportions of fatally and severely injured pedestrians were generally higher than corresponding national statistics. Weighting methods adjusting for this bias should then be considered. All this taken into account, few papers in the literature provided reliable information on the pedestrian fatality risk as a function of car impact speed. Nevertheless, it was uniformly reported that pedestrian fatality risk increased monotonically with car impact speed.

Studies based on direct analysis of data biased towards severe and fatal accidents include Anderson et al. (1995, 1997), Ashton (1980)⁴, Oh et al. (2008a,b), and Pasanen (1992). (We note that the study of Anderson et al. is often erroneously cited as Walz et al. (1983).) These studies provided risk estimates of 35–90% at an impact speed of 50 km/h (see Fig. 1a). The data bias inevitably rendered these risk estimates too high.

The Chinese study of Kong and Yang (2010) used weight factors that were derived from Changsa police data and national statistics. The remarkably high fatality rates of these two data sets most likely implied exaggerated fatality risks.

The study of Yaksich (1964) was based on a sample largely dominated by elderly pedestrians. We note that this study is often erroneously cited as Teichgräber (1983).

Studies that were based on data with only a small bias towards severe and fatal accidents, or accounting for bias, include Cuerden et al. (2007), Davis (2001), Hannawald and Kauer (2004), and Rosén and Sander (2009). These studies provided risk estimates of approximately 10% at an impact speed of 50 km/h (see Figs. 1b and c). In particular, the analysis by Davis (2001) is likely to provide fairly reliable fatality risks for crashes in the 1960s and 70s. For accidents occurring in the 2000s, the analysis by Rosén and Sander (2009) provides high-quality risk estimates at impact speeds below approximately 60 km/h. However, due to the sparseness of high speed car-to-pedestrian collisions, the fatality risks reported at higher impact speeds are associated with large confidence intervals.

Acknowledgements

The authors have been in contact with many researchers around the world, most of which were very helpful and encouraging. We would like to especially mention Anders Kullgren, Eero Pasanen, Gary Davis, Rikard Fredriksson, Claes Tingvall, Anders Lie, Rainer Wiebush-Wothge, Murray Mackay, Lars Hannawald, Richard Cuerden, David Richards, Clay Gabler, Brian Fildes, Dietmar Otte, Koshiro Ono, Uwe Ewert, Hugo Mellander, Douglas Stein, Benny Nilsson, and Torbjörn Andersson.

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⁴ It should be noted that Ashton pointed out that his results did not give representative fatality rates because of the data bias (see Section 3.1).

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