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The relationship between impact speed and the probability of pedestrian fatality during a vehicle-pedestrian crash: a systematic review and meta-analysis

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ABSTRACT

Background: Pedestrians struck in motorised vehicle crashes constitute the largest group of traffic fatalities worldwide. Excessive speed is the primary contributory factor in such crashes. The relationship between estimated impact speed and the risk of a pedestrian fatality has generated much debate concerning what should be a safe maximum speed limit for vehicles in high pedestrian active areas.

Methods: Four electronic databases (MEDLINE, EMBASE, COMPENDEX, and SCOPUS) were searched to identify relevant studies. Records were assessed, and data retrieved independently by two authors in adherence with the PRISMA statement. The included studies reported data on pedestrian fatalities from motorised vehicle crashes with known estimated impact speed. Summary odds ratios (OR) were obtained using meta-regression models. Time trends and publication bias were assessed.

Results: Fifty-five studies were identified for a full-text assessment, 27 met inclusion criteria, and 20 were included in a meta-analysis. The analyses found that when the estimated impact speed increases by 1km/h, the odds of a pedestrian fatality increases on average by 11% (OR=1.11, 95% CI: 1.10-1.12). The risk of a fatality reaches 5% at an estimated impact speed of 30km/h, 10% at 37km/h, 50% at 59km/h, 75% at 69km/h and 90% at 80km/h. Evidence of publication bias and time trend bias among included studies were found.

Conclusions: The results of the meta-analysis support setting speed limits of 30 to 40 km/h for high pedestrian active areas. These speed limits are commonly used by best practice countries that have the lowest road fatality rates and that practice a Safe System Approach to road safety.

KEY WORDS: Pedestrian; fatality; impact speed; meta-analysis; systematic review

1. INTRODUCTION

Injuries and fatalities from road traffic crashes are a major public health problem. They account for the majority of deaths and disabilities due to all forms of injury worldwide [1]. Pedestrians in motorized vehicle crashes constitute the largest group of traffic fatalities, which accounts for approximately 400,00 each year worldwide [2], and the number is predicted to increase [1, 3, 4]. Speed has been identified as a key risk factor in such crashes: it influences both the probability of a crash and its severity [5-9].

Although drivers do not often travel at the speed limit, posted speed limits are strongly correlated with average travel speed [10]. The higher the travel speed of a vehicle, the higher the impact speed will be, assuming other physical parameters are constant such as deceleration, perception reaction time, and braking effectiveness. The impact speed during a crash with a pedestrian is strongly related to the risk of a pedestrian fatality [11, 12] and, hence, to the speed limit. Therefore, the relationship between impact speed and risk of fatality can be considered to be a critical factor in making decisions regarding the setting of speed limits.

Many studies have been conducted to date to estimate the relationship between estimated impact speed and the risk of a pedestrian fatality from pedestrian collision data [10]. The data is often collected either from an in-depth on-scene investigation or from police and/or medical reports. Logistic regression analysis is often used to determine the associated risk curves relating the probability of a fatality as a function of estimated impact speed. Although there is agreement that the risk of a fatality or injury increases with increased estimated impact speed, the odds ratios for any given particular estimated impact speed vary extensively between studies. This is particularly important when comparing earlier and later studies. This discrepancy has generated further scientific discussions concerning what is a safe speed limit and survivable impact speed for pedestrians on roads where their activity is high. Three previous reviews of estimated impact speed and pedestrian fatality or injury risk have been published to date [11-13].

Rosen et al. [11] conducted a literature review of 11 studies, where they assessed the data sampling procedures and methods of statistical analysis. Their study showed that, although there is a direct relationship between estimated impact speed and risk of a fatality reported in those studies, earlier studies provided much higher risk estimates. That is, in earlier studies the probability of a fatality at for example, 60 km/h was around 80-90%, whereas Rosen et al. estimated it to be about 20%. The authors argue the discrepancy is the result of earlier studies adopting an outcome-based sampling scheme, which did not adjust for sample bias. For instance, assume a hypothetical case where the national fatality rate was 10 out of 100 crashes between pedestrians and vehicles. Now suppose a study used a subset of those crashes with a higher fatality rate, e.g., 3 out of 20 crashes. This outcome-based sampling problem may result in an analytical bias towards overestimating the fatality risk in earlier studies. Therefore, sample weights, derived on the basis of national or regional traffic fatality rate, were then used to adjust for selection bias. Therefore, sample weights, derived on the basis of the national or regional traffic fatality rate, were then used to adjust for selection bias. Similarly, in another review, Kroyer et al. [12] claimed that past studies were incorrect in regards to determining the risk of a fatality versus estimated impact speed due to sample bias. They excluded studies that did not adjust for bias, leaving only 5 studies for their review.

In the third review, Pok et al. [13] focused on pedestrian injury severity rather than pedestrian fatality. The authors used the Abbreviated Injury Scale (AIS 1 to 6) codes [14] and the Injury Severity Score (ISS) [15] to calculate the risk of injury versus estimated impact speed. They then summarized the findings of 6 studies to estimate the pedestrian injury curves for AIS 1-6 as functions of impact speed. For pedestrians sustaining AIS 1 to 6 injuries, the 50th percentile of impact speeds were 19, 25, 31, 40, 53 and 71 km/h, respectively.

The previous published reviews have some further limitations. For instance, Kroyer et al. and Pok et al. only included a limited number of studies (5 and 6 respectively). Pok et al. plotted risk curves for AIS2-5 using mathematical theoretical curves instead of estimates from actual real-world collision data, due to the lack of published studies. All three previous reviews did not evaluate odds ratios using a clear statistical methodology (i.e., meta-analysis) and did not provide mathematical details about how their risk curves were plotted. Finally, yet importantly, many new studies have been published focusing on determining the relationship between the risk of pedestrian injury and fatality versus estimated impact speed.

None of the three previous reviews followed the PRISMA [16, 17] statement for reporting systematic reviews which is often required by journals. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is an evidence-based minimum set of items designed to enable the production of a wide array of systematic reviews and meta-analyses of the benefits and harms of healthcare interventions. PRISMA consists of a checklist and a flow diagram, which provides transparency to the process of selecting papers for systematic reviews. The PRISMA flow diagram maps out information about the number of records identified in the literature search, the number of studies included and excluded and the reasons for exclusion.

In addition to impact speed, many other factors could contribute to an increased risk of a pedestrian fatality during a vehicle-pedestrian crash. These include the age of the victim [18], vehicle designs [19, 20], emergency response time, e.g., crashes occurring in rural areas compared to urban areas [21], and the roadway-built environment [22]. However, the main contribution of this systematic review and meta-analysis is to further increase the accuracy of the estimated relationship between pedestrian fatality or injury risk and impact speed.

2. METHODS

Four electronic databases (MEDLINE, EMBASE, COMPENDEX and SCOPUS) were searched to identify relevant studies. An initial search was performed on 12 May 2017, which was updated on 24 March 2019. In order to include as many studies as possible, broad search terms were used such as ((pedestrian* or walk*) AND (accident* or fatal*)). The searches were not restricted by language, location of the data collection, publication date or any other criteria that might increase the probability of missing any relevant study. Reference lists from the included studies and previously published reviews [11-14] were searched to identify additional records. Two review authors independently assessed every record retrieved against inclusion criteria to determine which study should be included in a meta-analysis. Discrepancies were resolved either through discussion or adjudicated by a third author. Study authors were contacted when additional information was required to resolve conflicts or determine eligibility.

The PRISMA flow chart (see Figure 1) was used to present the number of records included or excluded at each stage. Full text studies were included if they reported the results of a logistic regression of pedestrian fatality (including non-fatal injuries) and the impact speed of motor vehicles. Studies which did not provide logistic regression results but provided sufficient summary statistics were also included. Pedestrians of all ages who had injuries from a frontal impact with a motor vehicle were included. Studies based on data for other travel modes (i.e., cyclists or motorists), studies that only reported speed limits or speed zones, and reviews of other studies were excluded.

Data from each included study was extracted and summarized by one author and checked by a second author. Again, any discrepancies were resolved through discussion and/or by a third author. The information extracted from each study included: the name(s) of the author(s), the year of publication, the data source, the countries where data was collected, injury type (fatal, AIS2+, or AIS3+), the sample size, the age categories of the included pedestrians (child, adult or all), the data type (on-scene or collision report), the vehicle type, and the outcome measures (the estimated values of the logistic regression and their variance).

A series of hierarchical random-effects models were fitted for the odds ratio using the extracted information. Model 1 was a baseline random-effects model with no moderators, Model 2 included injury type as a moderator and Model 3 included injury types as a moderator and random effects for the study. A final model was chosen using the likelihood ratio test (LRT) and Akaike's information criterion (AIC). Study-level moderators were added individually and assessed for inclusion in the final model. Residual heterogeneity was estimated and assessed by Cochran's Q and the index of heterogeneity I^2. Publication bias was inspected visually using funnel plot methods and numerically by the rank correlation test. Time trend bias was examined through leverage points by plotting estimated odds ratios against publication year. All statistical analyses were performed using the R metafor package [23].

3. RESULTS

The PRISMA flow diagram for reviewed studies is presented in Figure 1. The initial and the updated searches identified a total of 1479 records including 469 duplicates, which were removed. Screening of titles

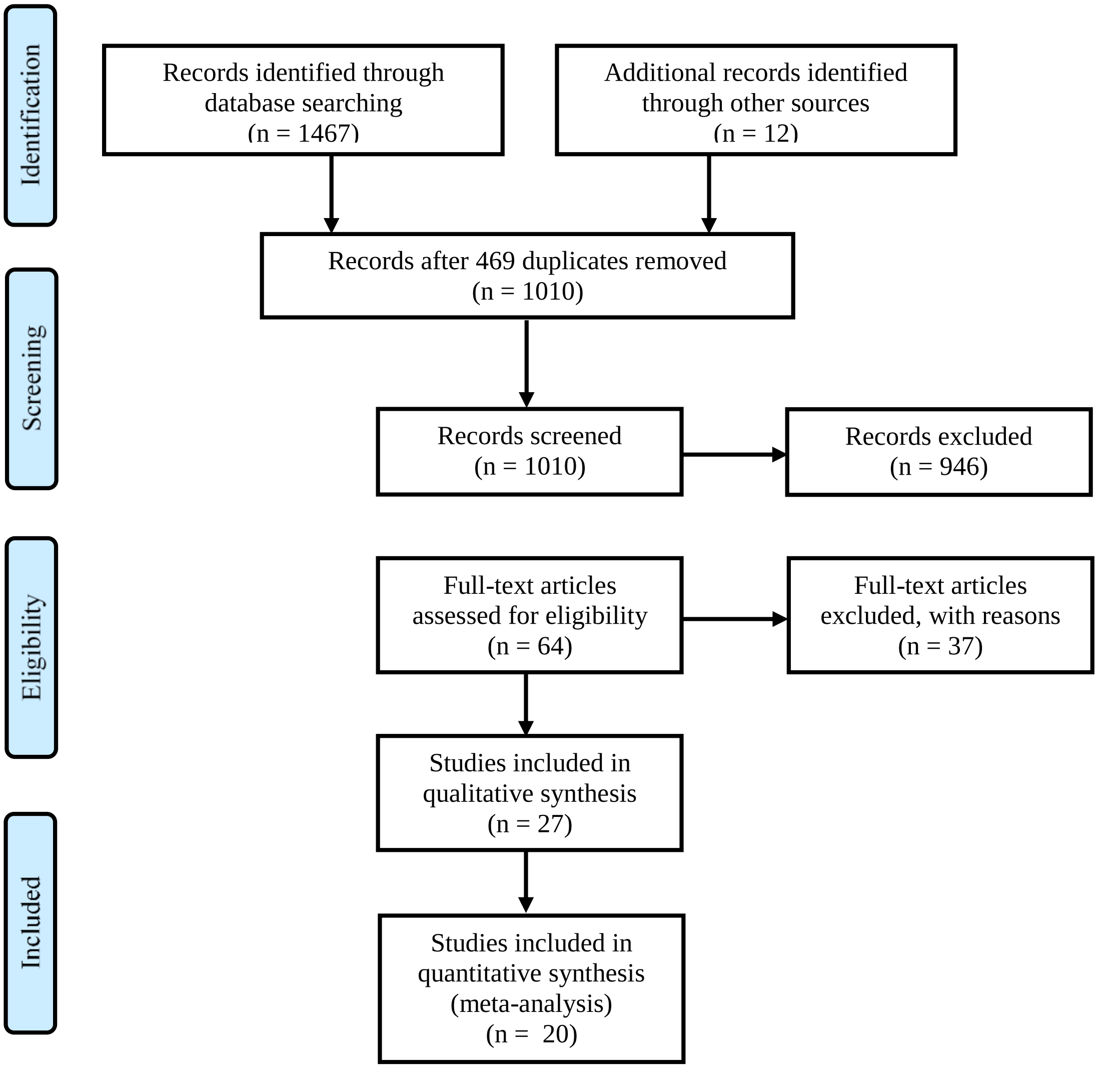

Figure 1: PRISMA flow diagram of included studies

and abstracts eliminated a further 946 records leaving 64 articles for a full-text assessment. After excluding a further 37 articles for various reasons, 27 articles met the inclusion criteria.

The primary reasons for excluding studies were as follows: the collected data was based on speed limits or speed zones only [24-30], the data was limited only to head impacts [31] or ground contact injuries [32], no injury or fatality data was used [33, 34], the inability to compute an S-shaped risk curve [35-40], the study data was a subset of another included study [41-46], the collected data consisted of only fatal cases [47-49], the original full-text of the study was unavailable [50-52], the study was not focused on frontal impacts [53-55], the study used experimental data [56, 57], the impact speed was not measured or included [58, 59], and the impact speed was unknown for most of the cases which was imputed from other information and crashes were not limited to only frontal impact [60]. A further seven studies were excluded from the meta-analysis because the information in the original articles were insufficient. The study authors were contacted for additional information, but the study authors either did not respond to the request or they did not provide relevant information. The exact reasons were: the raw data or regression results were not presented or not clear [61-65], the original data was no longer available [66] and the study data was a subset of another included study [67].

Characteristics of the studies included for the meta-analysis are given in Table 1. Within the 20 included studies, 15 provided information concerning the relationship between estimated impact speed and pedestrian

TABLE 1: Characteristics of studies meeting selection criteria

Authors	Year	Country	Study size	Injury type	Age	Data type	Weighted analysis
Ashton	1980	UK	358	Fatal	All	Report	
Garrett & John	1981	US	494	Fatal	All	On-scene	
Cuerde *et al.*	2007	UK	108	Fatal	All	On-scene	
Oh et al	2008	Korea	101	Fatal	All	Report	
Rosen & Sander	2009	Germany	490	Fatal	Adult	On-scene	Yes
Fredriksson *et al.*	2010	Germany	161	AIS3+	All	On-scene	Yes
Kong & Yang	2010	China	104	Fatal	Adult	On-scene	Yes
Nie et al.	2010	China	110	Fatal, AIS3+	All	On-scene	
Richards	2010	UK	197	Fatal	All	On-scene	Yes
Zhao *et al.*	2010	China	184	Fatal	All	Report	
Helmer *et al.*	2011	US	376	Fatal	All	On-scene	
Peng *et al.*	2012	Germany	22	AIS2+, AIS3+	Adult	On-scene	
Matsui *et al.*	2013	Japan	32614	Fatal	All	Report	
Peng *et al.*	2013	Germany	43	AIS2+, AIS3+	Adult	On-scene	
Tefft	2013	US	315	Fatal	Adult	On-scene	Yes
Zhang *et al.*	2014	China	207	Fatal	All	On-scene	
Li *et al.*	2015	China	109	Fatal, AIS3+	Adult	Report	
Nie *et al.*	2015	China	371	Fatal	Adult	Report	
Wang *et al.*	2016	Germany	404	AIS2+	Adult	On-scene	
Li *et al.*	2017	Germany	489	AIS2+	All	On-scene	

fatality [68-82]. These studies included crash data from 36,138 pedestrians struck by the front of a motor vehicle. The other five studies focused on injury severity (i.e., AIS2+ and/or AIS3+) and included 1,119 injured pedestrians [83-87]. The included studies span 38 years (1980-2017), representing six countries (China, Germany, Japan, South Korea, UK and US).

Data from 14 studies were collected from in-depth on-the-scene collision investigations, while data from six studies were from police and medical reports. In five of the included studies, a weighting procedure was used to analyse the data comparing it against national or regional fatality rates, while the other 15 studies did not use such an approach.

The results from the multivariate meta-regression models are given in Table 2. Model 3 was chosen as a final model which includes injury type as a moderator and random effects for the study. Study-level random effects were included to account for dependence as some of the included studies reported both pedestrian fatality risk and AIS3+ risk using the same samples. The inclusion of injury type improved model fit by AIC and the likelihood ratio test, while the inclusion of a random intercept did not. Study-level moderators for age, publication year, country, data type and whether the data was weighted, were individually added to

TABLE 2: Summary of the multivariate meta-regression models

Multivariate models					
Model	**AIC**	**I^2**	**LRT**	**Df**	**P-value**
(Model 1) Baseline	-125.7	63.7%	-	-	-
(Model 2) +injury type	-151.9	48.4%	30.3	2	<0.0001
(Model 3) +random intercept	-151.1	-	1.2	1	0.273
Model 3 with moderators					
Model	**AIC**		**LRT**	**Df**	**P-value**
Model 3	-151.1		-	-	-
Model 3 +age	-149.6		4.4	3	0.218
Model 3 +year	-158.4		9.3	1	0.002
Model 3 +country	-144.1		3.0	5	0.700
Model 3 +data type	-149.7		0.5	1	0.464
Model 3 +weighted or not	-152.3		3.2	1	0.074

Model 3. None of these moderators improved model fit except for publication year. This potentially indicates time trend bias, which refers to changes in study findings over time.

To verify time trend bias, publication years were plotted against the estimated log-odds ratios (Figure 2). The dashed lines represent the estimated log-odds ratios while the solid red line is the fitted linear regression for fatal cases. According to Hoaglin & Welch [88], points with $h_{ii} > 2p/n$ are leverage points (h_{ii} are the values of the projection matrix). In this case, the four observations lying on the left are leverage points. These leverage points help explain the high significance of publication year as a moderator. There was also visual evidence of publication bias from the funnel plot of the final model residuals (see Figure 3) and by the rank correlation test ($\tau = 0.31$, $p = 0.005$).

A forest plot of odds ratios by injury type is given in Figure 4 with summary estimates taken from Model 3. For ease of interpretation, the fitted values were transformed to the odds ratio scale through exponentiation. The odds of pedestrian fatality, AIS3+ injury, or AIS2+ injury will on average increase by 11% (OR = 1.11, 95% CI: 1.10-1.12), 9% (OR = 1.09, 95% CI: 1.07-1.11) and 7% (OR = 1.07, 95% CI: 1.05-1.10) respectively, as the estimated impact speed increases by 1 km/h. From this meta-analysis, the risk of a pedestrian fatality will reach 5%, 10%, 50%, 75% and 90% when the estimated impact speed reaches 30 km/h, 37 km/h, 59 km/h, 69 km/h and 80 km/h respectively.

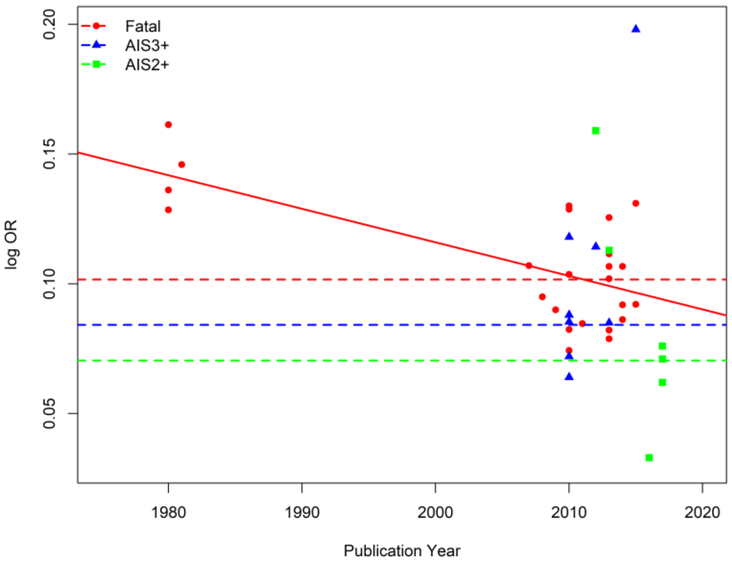

FIGURE 2: Estimated log-odds ratios versus publication year

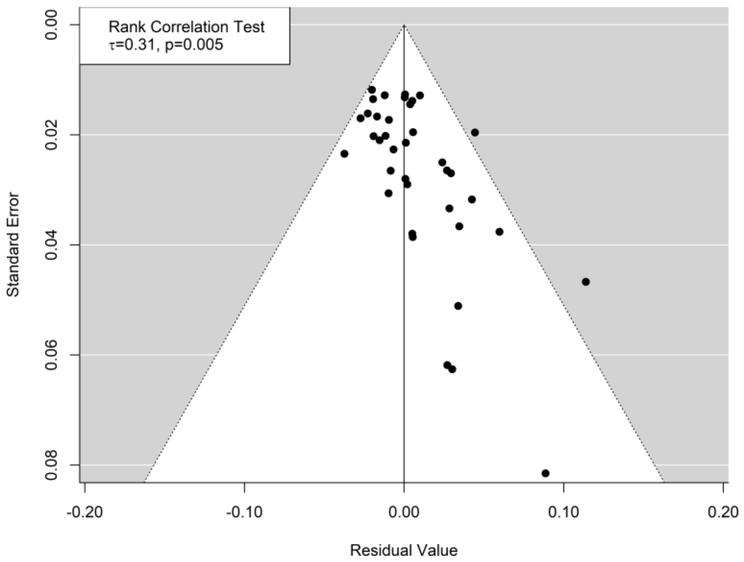

FIGURE 3: Funnel plot of residuals from multivariate meta-regression model

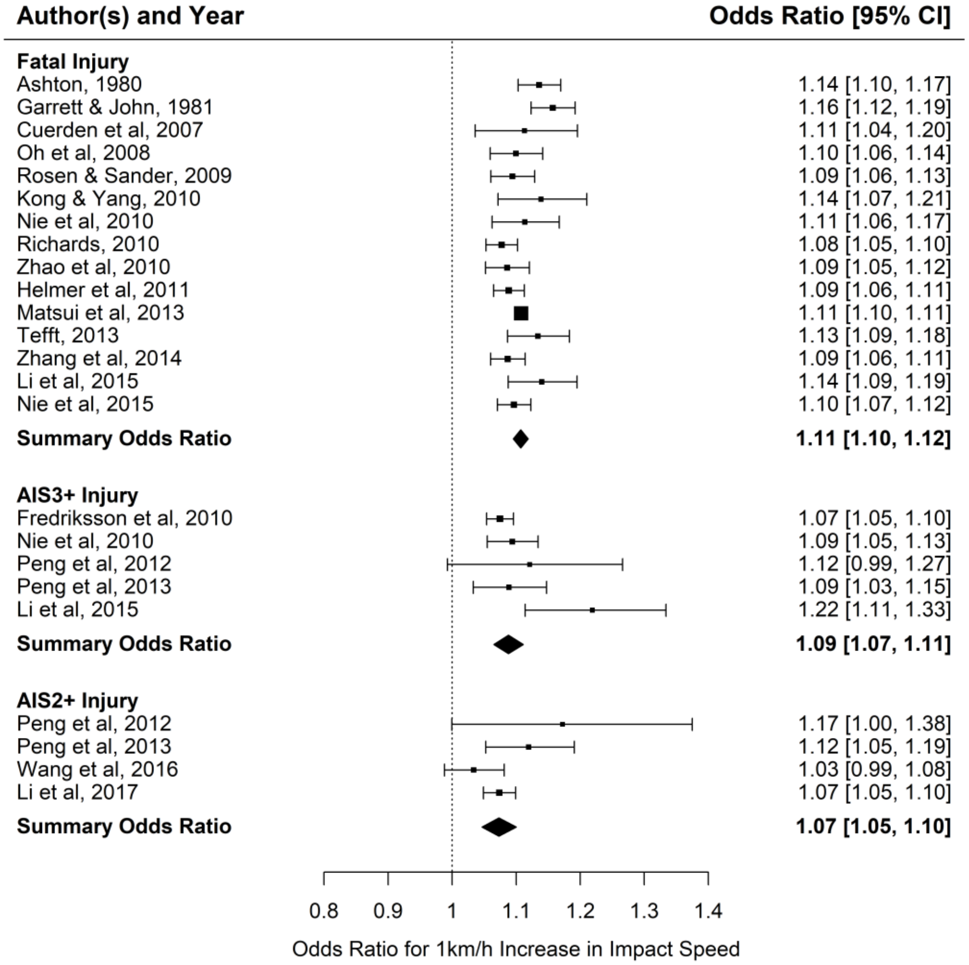

FIGURE 4: Forest plot of study and summary odds ratios by pedestrian injury type (95% CI)

An overview of S-shaped curves synthesizing all 15 included studies for pedestrian fatality risk is given in Figure 5. The thicker red curve is plotted according to the results from the multivariate meta-regression model while black curves represent study estimates of the 15 included studies.

A series of sensitivity analyses were performed to assess the influence of analytic decisions made (see Table 3). Since time trend bias was found among the included studies in the final model, the analysis was restricted to studies published since 2010. The estimated log-odds ratios for fatal, AIS2+ and AIS3+ all reduced, though by a small amount.

Two previous studies investigated differences in risk of pedestrian fatality due the vehicle types [74, 80]. The frontal shape of a vehicle is possibly a crucial factor. The relative vehicle-pedestrian geometry influences the trajectory of pedestrians in a crash, such as throw distance or impact location of the head strike. However, for our analysis (Model 3), we included studies that restricted samples for vehicle types, as well as those that did not make that restriction. Therefore, only the five studies which did not restrict the

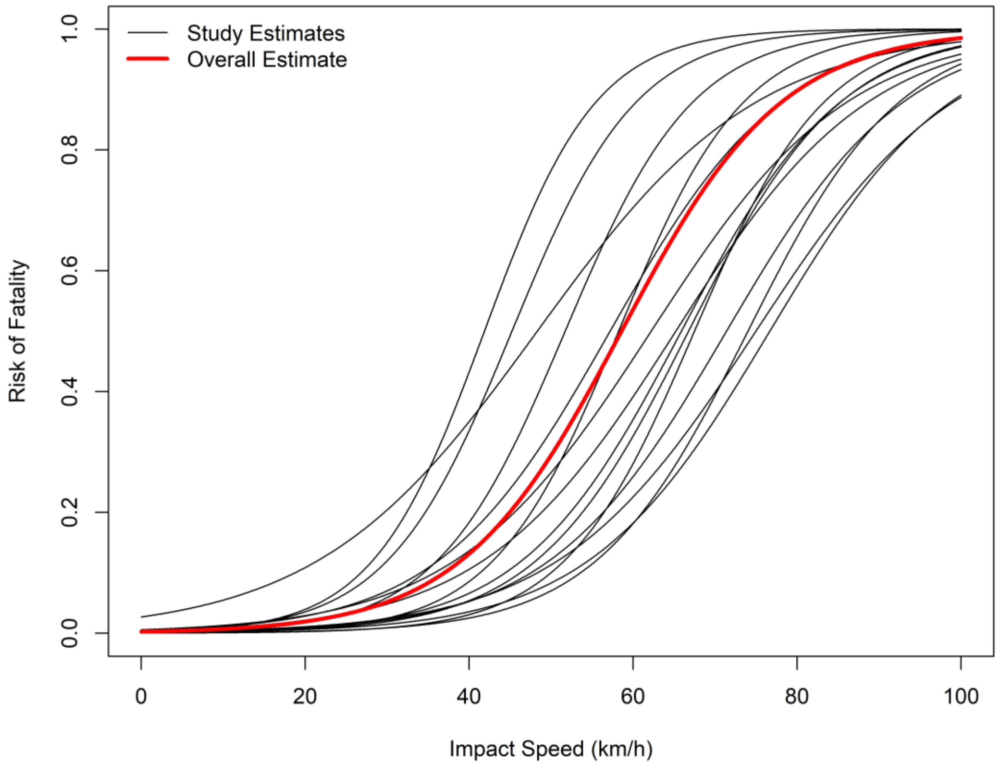

FIGURE 5: Plot for S-shaped curves for pedestrian fatality risk by impact speed

TABLE 3: Comparison of odds ratios from final model and sensitivity analyses

Injury type	Final model	Publications since 2010	Without vehicle type restriction	Exclusion of Matsui et al. (2013)	Weighted Estimates	Random effects logistic regression
Fatal	1.107	1.105	1.103	1.107	1.094	1.107
AIS3+	1.088	1.079	1.076	1.089	1.075	---
AIS2+	1.073	1.072	1.079	1.074	---	---

sample for the vehicle types, but considered all types of vehicles in their analyses, were considered for the sensitivity analysis. The fitted odds ratios were similar for fatal, AIS3+ and AIS2+ injuries.

Among all included studies, the sample size for Matsui et al. [78] was much larger than all other studies (n=32,614). It is possible that this study may have dominated the summary results. The analysis was repeated without the data from Matsui and colleagues and the fitted values were similar to the final model.

Recent research has been critical of likely selection biases in earlier studies and recommend performing analyses weighted against the national fatality rate. We limited our analysis to only studies with weighted analyses [72, 73, 75, 79, 83]. The analysis did not consider the AIS2+ injury as none of the included studies used weighted data. The estimated odds ratios reduced by a little amount for both fatal and AIS3+ injuries.

Meta-analyses are often performed on summary statistics instead of raw data from each study. There is a potential for some information loss in those situations. We reanalysed the data for studies that provided raw data using a logistic regression model with study level random effects. Only one study provided raw data for serious injury while 11 studies reported raw data on fatalities. The estimated odds ratio for fatality was identical to our final model to three decimal places.

4. DISCUSSION

This systematic review identified 27 relevant studies that assessed motor vehicle impact speed and pedestrian fatality or injury. Of these studies, 20 were included in a meta-analysis with 15 contributing data on when a pedestrian fatality occurs. This includes 8 studies not included in previous reviews [69, 74, 77-82]. Data from these studies estimate an increase in the odds of 11% for a pedestrian fatality (95% CI: 1.10-

1.12), 9% for AIS3+ injuries (95% CI: 1.07-1.11), and a 7% increase in AIS2+ injuries (95% CI: 1.05-1.10) for a 1 km/h increase in estimated impact speed.

This is the first systemic review to combine odds ratios from individual studies using a meta-analysis method and the first systematic review to adhere to the PRISMA protocol. This study, therefore, provides a more accurate estimate of the relationship between impact speed and pedestrian fatality risk in a crash. Moreover, these results provide support for prescribing speed limits of 30 and 40 km/h for high pedestrian active roads. For instance, the results of the meta-analysis indicate that the risk of a fatality reaches 5% at an estimated impact speed of 30 km/h and 10% at 37 km/h.

Drivers usually do not adapt [10] and drive faster than the posted speed limits [89], and travel based on the design and features of the road and its surroundings [90]. In this study, the risk of pedestrian fatalities increases more rapidly for any small increase in the impact speed between 30-70 km/h compared to the other speed regimes. To keep drivers' traveling speed under the set speed limits, appropriate speed management (e.g., speed calming measures, enforcement) is also essential in areas with high pedestrian traffic.

Past research has recommended adjustment for sample bias by weighting data against the national fatality rate. However, the above analysis indicates that adding a study-level moderator for whether the data was weighted (or not) does not markedly change the results. The results from our sensitivity analysis are somewhat in line with the previous authors [11, 12] who argue that studies which did not adjust for sample bias overestimated pedestrian fatality risk for any given impact speed. Moreover, the distribution of fatalities across estimated impact speeds is not known in national fatality statistics and can be significantly different from the study sample. So, it is not clear whether weighting is needed in the analysis and, if weighting is needed, it is unclear if estimated weights accurately represent all fatalities for the population being studied.

The estimated odds ratios reduced towards a null effect for studies published since 2010. This is possibly due to the development of the frontal design of vehicles resulting from pedestrian impact consumer test ratings, which have progressively improved crash severity mitigation [91]. Moreover, improvements in medical emergency response and treatments have also helped reduce fatality risk.

5. LIMITATIONS

Despite the value of this study several limitations should be considered. Seven relevant studies [61-67] were not included due to insufficient information in the original articles. The authors of these studies were contacted, but study authors did not supply relevant information, or they did not respond to the request. Many of the included studies were published more than 10 years ago and contact information for study authors was difficult to obtain, thus potentially explaining the poor response rate. Another three studies [50-52] were not included because the original full-texts could not be located. The earliest one of these three studies was published in 1964, which is more than 50 years ago. The articles were also requested from the interlibrary loans services of UNSW and UHasselt, but research librarians at these institutions could not locate these reports.

The statistical models used in this meta-analysis assumes the effect sizes are independent between studies. On a few occasions, more than one study used participants from the same database. For example, six included studies used the sample from GIDAS (German In-Depth Accident Study). Different inclusion criteria were applied in their studies such as year of the sample, age groups of the pedestrians, and car types. Therefore, it was difficult to determine the most complete dataset. The influence of double counting was minimized by excluding obvious sample repetitions such as when data used in a published study was a subset of the data from another study. Nevertheless, it is still possible that in a few instances double counting may have inadvertently occurred.

There are likely factors other than impact speed that influence the risk of a pedestrian fatality or serious injury such as age, vehicle type, the response time of emergency assistance, and characteristics of the roadway design. However, very few studies if any have investigated these factors, which limits the ability to assess them in a meta-analysis.

There was a moderate level of residual heterogeneity among the effect sizes in the final model (I^2 = 48.4%). This may have been influenced by unaccounted for differences among the included studies. For instance, crash data types used in some of the included studies are from in-depth on-the-scene investigations while other studies used data from police and medical reports. Some of the included studies weighted data against national fatality data and, some of them filtered the data for adult pedestrians only. The included studies used data from only six countries (China, South Korea, Japan, Germany, UK, US) and the emergency and medical services can be highly variable among those counties. The summary estimates could greatly be improved if more relevant studies are included and especially those from countries not represented in this review.

Another sensitivity analysis was performed for studies published since 2010 to assess the impact of older studies. It was decided that the years of data collected for each study is perhaps a better indicator than publication year. However, a sensitivity analysis on publication years was conducted since two studies did not mention years of data collection [74, 78], two studies used combination of datasets collected at different time intervals [84, 85], and three studies used data collected over a 10 year span [68, 86, 87].

6. CONCLUSION

Speed limits are an important regulation that can help reduce the kinetic energy and consequential injury severity in a crash. It is important for policy makers to prescribe speeds that are safe, i.e. survivable, for all road users. For pedestrians, it is not possible to fully eliminate the risk of a fatality. However, our results suggest an impact speed of 30 km/h has on average a risk of a fatality of around 5%. The risk increases to 13% for an impact speed of 40 km/h and 29% at 50km/h. Speed limits should be set lower in areas of poor visibility and thus slower reaction times. Furthermore, such speed limits could be supported by appropriate speed calming approaches such as physical measures (e.g., roadway design, pedestrian islands, and speed humps), surface treatments (e.g., road markings, rumble strips, and perceptual countermeasures), and traffic enforcement (e.g., speed cameras) to motivate drivers lowering their traveling speeds. Such speed limits and speed calming approaches are already commonly used by best practice countries that have the lowest road fatality rates and that practice a Safe System Approach to road safety.

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