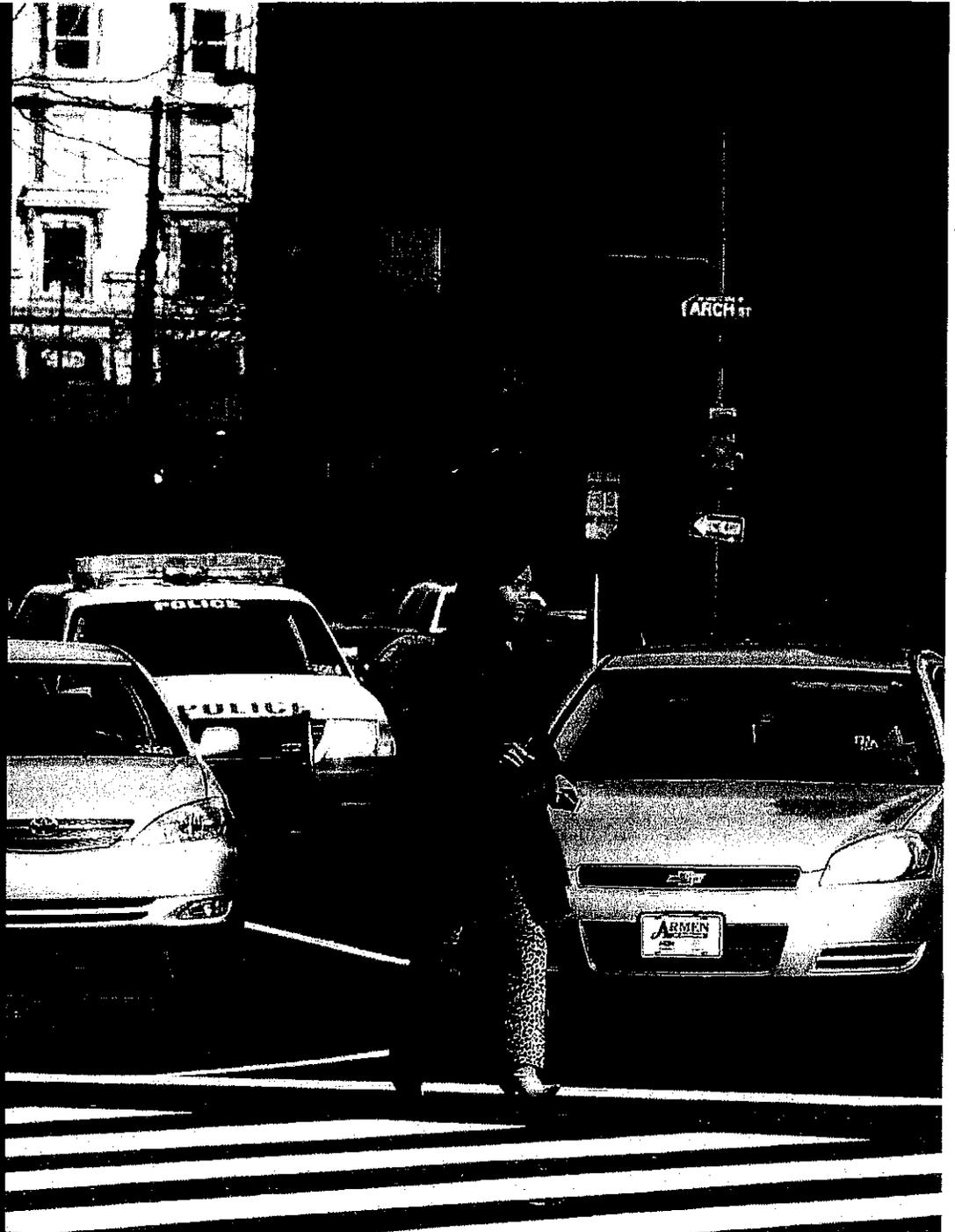Car crashes rank among the leading causes of death in the United States

Impact Speed and a Pedestrian's Risk of Severe Injury or Death

September 2011

Author

Brian C. Tefft
Senior Research Associate
AAA Foundation for Traffic Safety
607 14th Street NW, Suite 201
Washington, DC 20005
btefft@aaafoundation.org

Acknowledgment

About the Sponsor

Abstract

The relationship between impact speed and a pedestrian's risk of death has been studied extensively; however, past studies of data from the United States are now several decades old. Older studies of data from the United States may not be generalizable to the present situation because of changes in the composition of the walking population, vehicle design, and medical care over the past several decades. Similarly, the ability to generalize from recent European studies to the United States is unclear due to differences in the types and sizes of vehicles driven in Europe versus in the United States.

This study estimates of the risk of severe injury or death for pedestrians struck by vehicles in the United States using data from a federal study of crashes that occurred in the United States in years 1994 – 1998 in which a pedestrian was struck by a forward-moving car, light truck, van, or sport utility vehicle. The data were weighted to correct for oversampling of pedestrians who were severely injured or killed. Logistic regression was used to adjust for potential confounding related to pedestrian and vehicle characteristics. Risks were standardized to represent the average risk for a pedestrian struck by a car or light truck in the United States in years 2007 – 2009.

Results show that the average risk of severe injury for a pedestrian struck by a vehicle reaches 10% at an impact speed of 16 mph, 25% at 23 mph, 50% at 31 mph, 75% at 39 mph, and 90% at 46 mph. The average risk of death for a pedestrian reaches 10% at an impact speed of 23 mph, 25% at 32 mph, 50% at 42 mph, 75% at 50 mph, and 90% at 58 mph. Risks vary significantly by age. For example, the average risk of severe injury or death for a 70-year-old pedestrian struck by a car travelling at 25 mph is similar to the risk for a 30-year-old pedestrian struck at 35 mph.

These results could be used to inform efforts to improve pedestrian safety, for example, by limiting traffic speeds to levels that are unlikely to result in severe injury or death in places where pedestrians and vehicles may encounter one another, creating physical separation of pedestrians and vehicles in places where higher traffic speeds are desired, and developing vehicle-based systems that detect pedestrians and warn the driver or brake automatically when a collision is imminent.

Introduction

In 2009, 4,092 pedestrians were killed in motor vehicle crashes and an estimated 59,000 were injured in the United States (National Highway Traffic Safety Administration [NHTSA], 2010). It is well established that the risk that a pedestrian struck by a vehicle will be injured or killed is related to the impact speed (Rosén *et al.*, 2011). Thus, one way to reduce the number of pedestrians injured or killed in crashes is to restrict traffic speeds, in areas where vehicles and pedestrians may encounter one another, to speeds at which a pedestrian is unlikely to be seriously injured or killed if struck by a vehicle. This requires understanding of the relationship between crash impact speed and pedestrian injury risk, as well as other factors that may influence that relationship.

Although there is a general understanding that a pedestrian's risk of injury or death increases as crash impact speed increases, there is substantial disagreement over the actual risks at any given speed. Rosén et al. (2011) reviewed all studies of the relationship between crash impact speed and pedestrian fatality risk published prior to 2010. Of the 11 studies that Rosén et al. identified, five were based on data collected prior to 1980 (including three different studies of the same data), and nine likely were biased due to over-representation of crashes that resulted in severe injury or death, the authors noted. Although the two remaining studies identified by Rosén et al. were methodologically sound, one (Davis, 2001) was based on data collected in the United Kingdom from years 1966–1979, and the other (Rosén & Sander, 2009), based on German data collected from years 1999–2007, excluded crashes that involved pickup trucks, vans, or sport utility vehicles (SUVs). One additional study not included in the review of Rosén et al. analyzed British data from years 2000–2009 (Richards, 2010); this study also did not include pedestrians struck by pickup trucks, vans, or SUVs. Given the age of the data analyzed by Davis and the prevalence of pickup trucks, vans, and SUVs in the present vehicle fleet in the United States, the degree to which the results of these three studies may be generalized to the current situation in the United States is unknown.

The objective of this study was to estimate the risk of severe injury or death in relation to impact speed for a pedestrian struck by a car, pickup truck, van, or SUV, using the most recent data available from the US.

Methods

Data

The data analyzed in this study were from the NHTSA's National Automotive Sampling System (NASS) Pedestrian Crash Data Study (PCDS) (PCDS, 2008). The PCDS compiled data from on-scene and follow-up investigations of crashes that occurred in Buffalo, NY; Fort Lauderdale, FL; Dallas, TX; Chicago, IL; Seattle, WA; and San Antonio, TX from July 1994 through December 1998 and involved a pedestrian struck by a forward-moving car, pickup truck, van, or SUV (pickup trucks, vans, and SUVs hereafter are referred to collectively as *light trucks*) with the first point of contact forward of the top of the vehicle's A-pillar. The sample was restricted to vehicles manufactured within 5 years of the study period (model years 1989–1999). Crashes were excluded from the PCDS if the pedestrian was sitting or lying in the roadway, the striking portion of the vehicle had been modified or damaged previously, the vehicle was involved in other impacts besides that with the pedestrian, or vehicle damage measurements were not obtained within 24 hours of the crash. Data available in the PCDS includes information about the crash, roadway, vehicle, pedestrian, and specific injuries sustained by the pedestrian. Measures of injury severity available in the PCDS included *police-reported injury severity* (killed, incapacitating injury, non-incapacitating injury, possible injury, no injury, injured-severity unknown, died prior to accident), *treatment-mortality* derived by PCDS investigators from police medical data (no treatment, fatal, fatal-ruled disease, hospitalized, transported and released, treated on scene – not transported, treated later, other treatment), and *Abbreviated Injury Scale (AIS)* (Association for the Advancement of Automotive Medicine, 1990) score for each specific injury (NHTSA, 2002).

The data file contained 549 records of pedestrians struck by vehicles. Pedestrians younger than 15 years of age (n=126) were excluded because the number of deaths of pedestrians younger than 15 was too small for analysis (n=5). Age 15 was selected as the cutoff because both males and females typically have exceeded 95% of their adult height by this age (McDowell *et al.*, 2008). One additional pedestrian was excluded because all three measures of injury severity were unknown. The sample analyzed for this study comprised 422 pedestrians ages 15 years and older who were struck by a single forward-moving car or light truck model year 1989–1999 and whose injury severity was known.

Main outcome measure

The main outcome measures were the risk of severe injury and risk of death in relation to impact speed. For this study, severe injury was defined as an AIS score of 4 or higher and included death irrespective of AIS score. The outcome of death was defined as death that occurred within 30 days of the crash as a result of injuries sustained in the crash.

Potential confounding variables

Potential confounding variables considered in the study were pedestrian age (years), sex, height (inches), weight (pounds), body mass index (BMI) (weight [in kilograms] divided by height [in meters] squared); vehicle type (car vs. light truck), curb weight (pounds), and bumper height (inches, measured from the ground to the top of the bumper at the location of contact with the pedestrian).

Weighting

The PCDS was not designed as a representative sample and thus did not contain sampling weights (Chidester & Isenberg, 2001). To assess the representativeness of the sample, the distribution of injury severity in the sample was compared to that in national data from a census of all fatal crashes in the United States (Fatality Analysis Reporting System [FARS], 2010) and a representative sample of all police-reported crashes (General Estimates System [GES], 2011). To match the study sample as closely as possible, the national data used for weighting were restricted to pedestrians struck between July 1994 and December 1998 by a single forward-moving car or light truck model year 1989–1999.

The only measure of injury severity common to the PCDS, GES, and FARS was police-reported injury severity. For comparison of the study sample to the national data, police-reported injury severity was collapsed into three categories: fatal, incapacitating injury, and non-incapacitating/possible/no injury. The PCDS variable police-reported injury severity contained 11 discrepancies with the variable treatment-mortality, and 22 values coded as unknown. Thirteen values of police-reported injury severity were re-coded to fatal on the basis of treatment-mortality (originally 11 incapacitating and 2 unknown). To assign values of police-reported injury severity to the remaining 20 pedestrians, the risk of police reported incapacitating injury vs. non-incapacitating/possible/no injury was estimated using logistic regression with explanatory variables of treatment-mortality, maximum AIS score, and a set of dummy variables representing each jurisdiction. Police-reported injury severity was imputed as incapacitating injury if the estimated risk was 0.5 or greater; otherwise it was imputed as non-incapacitating/possible/no injury. Note that these imputed values of police-reported injury severity were used only to compare the study sample to national data and to derive weights (described below) for the study sample; the outcome measures were not imputed.

Pedestrians who sustained incapacitating or fatal injuries were over-represented in the study sample (Table 1). To mitigate potential bias due to this over-representation, the data were post-stratified (Gelman & Carlin, 2002) by police-reported injury severity, and every pedestrian in each post-stratum (row of Table 1) was assigned a post-stratification weight equal to the total number of struck pedestrians in the post-stratum nationwide divided by the number in the sample.

Table 1. Comparison of injury severity distribution in study sample vs. among all pedestrians ages 15+ years struck by a forward-moving car or light truck model year 1989–1999, United States, 1994–1998.

Injury severity[b]	Study sample (N = 422)		All struck pedestrians[a] (N = 85,809)	
	N	(%)	N	(%)
None/possible/non-incapacitating	216	(51.2)	57,265	(66.7)
Incapacitating	140	(33.2)	21,433	(25.0)
Fatal	66	(15.6)	7,111	(8.3)

a. Derived from number of pedestrians killed in Fatality Analysis Reporting System (FARS, 2010) and weighted estimate of number of struck pedestrians not killed in General Estimates System (GES, 2010).

b. Police-reported injury severity; 13 values in the study population were re-coded to fatal and 20 missing values were imputed on the basis other injury measures derived from medical data.

Missing data

Impact speed and/or a potential confounder was missing (unknown) in 25% of all records (n=107). Impact speed was missing in 67 records, weight in 61 records, height in 59 records, age in 1 record, and curb weight in 1 record. Missing values were imputed using multiple imputation (Rubin, 1987) with the method of chained equations (van Buuren *et al.*, 1999). The imputation models included both outcome measures (severe injury and death), all potential confounding variables, and the post-stratification weights. Twenty imputed data sets were created.

To determine the most appropriate form of model for the effect of impact speed, logistic regression models were fitted to the complete cases using only a linear term; first- and second-order fractional polynomials (powers -2, -1, 0 [natural logarithm], ½ , 1, 2, 3); and linear, quadratic, and cubic splines (Greenland, 1995). Separate models were fitted for the outcomes of severe injury and death. None of the additional terms (polynomials or splines) was significant at the 95% confidence level in either model, thus the effect of speed was modeled as linear.

To select the form of model for each of the other continuous variables (age, height, weight, BMI, curb weight, and bumper height) logistic regression models were fitted with two explanatory variables: impact speed and one potential confounding variable. Separate models were fitted for each of the potential confounders for both outcomes. In these models, the effect of speed was modeled as linear, and the confounder was modeled using a linear term, fractional polynomials, and splines, as described previously. More complex models (fractional polynomials or splines) were used only if the additional polynomial or spline terms were significant at the 95% confidence level. Age was modeled using both linear and squared terms; BMI was modeled using a linear spline with knots at 25 kg/m² and 30 kg/m², the cutoff values for overweight and obese as defined by the World Health Organization (World Health Organization, 2000). BMI was imputed separately rather than calculated from imputed values of height and weight (Von Hippel, 2009).

In addition to the outcome measures and potential confounders described previously, the imputation model for impact speed also included the posted speed limit and a dummy variable for the jurisdiction in which the crash occurred, because inspection of the data revealed that both were strongly associated with impact speed being missing (92% of missing values of impact speed were from the same jurisdiction [p<0.001]; 73% were from roads with a speed limit of 30 mph [p=0.003]).

Statistical analysis

The risks of severe injury and death in relation to vehicle impact speed were estimated using multivariable logistic regression, performed using the weighted, imputed data. The selection of confounders to include in the final model was performed via an iterative backward elimination process. After fitting the full model with all potential confounding variables, the model was re-estimated with each of the potential confounding variables deleted. The variable whose deletion had the smallest effect on the estimated odds ratio for the variable of primary interest—impact speed—was eliminated. This process continued until no further variables could be eliminated without changing the odds ratio for speed by more than 1% relative to its value in the full model. This process was performed separately for the outcomes of severe injury and death.

After this elimination process, the model for the risk of severe injury included impact speed, age, and type of striking vehicle. The model for risk of death included impact speed, age, age squared, height,.

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weight, BMI, number of BMI units above 25 (0 if BMI ≤ 25), and number of BMI units above 30 (0 if BMI ≤ 30). There was no *a priori* hypothesis that the factors that confound the relationship between impact speed and risk of severe injury would differ from those that confound the relationship between impact speed and risk of death, thus any variable retained in either model after the elimination process was included in the other model as well. Thus, the final models for both outcomes included impact speed, age, age squared, height, weight, BMI, number of BMI units above 25, number of BMI units above 30, and type of striking vehicle.

The risks of severe injury and death were estimated at various impact speeds using the fitted logistic regression model. Risks presented in this paper are average marginal predictions (Graubard & Korn 1999), that is, risks averaged over all struck pedestrians in the study sample. The average marginal prediction at a given impact speed was estimated as follows. The fitted logistic regression model was used to estimate each individual pedestrian's risk if struck at that speed using each individual's own values of all other variables in the model except speed (i.e., age, height, weight, BMI, and type of striking vehicle). The average marginal prediction for the sample is a weighted average of each individual's predicted risk. Average marginal predictions presented here were standardized using the distribution of pedestrian age and type of striking vehicle in the population of pedestrians struck in the United States in years 2007–2009 (FARS 2010, GES 2010). Average marginal predictions were also estimated separately for pedestrians struck by cars vs. light trucks and for pedestrians aged 30 years vs. 70 years. Standard errors of the average marginal predictions were estimated using Taylor series approximation (also known as the delta method).

For comparison to previous studies that estimated unadjusted risk of death for pedestrians struck by cars (Davis, 2001; Richards, 2010; Rosén & Sander, 2009), unadjusted risks of death were also estimated at selected speeds using data from pedestrians struck by cars only. Adjusted average marginal predictions were also estimated at the mean age in the sample of Rosén & Sander (45 years) for pedestrians struck by cars for comparison of adjusted estimates in the current study to those of Rosén & Sander.

All analysis was conducted using Stata statistical software (StataCorp, 2009). Imputations were performed using an imputation by chained equations algorithm (van Buuren *et al.*, 1999) implemented in Stata by Royston (2004, 2005, 2009). Standard errors accounted for the variability between imputed data sets as well as the variability within each imputed data set using the method of Rubin (1987) implemented in Stata by Carlin *et al.* (2008). All analyses were performed using the weighted data except where noted otherwise.

Sensitivity analysis
Several additional analyses were conducted to assess the extent to which the main results of the study were influenced by major decisions about study design. Sensitivity was assessed in terms of changes in the speeds at which estimated risks of severe injury and death reached levels of 10%, 25%, 50%, 75%, and 90%.

To assess the sensitivity of the main results to post-stratification adjustment of the injury severity distribution, risks were estimated using a logistic regression model fitted to unweighted data.

To assess the sensitivity of the results to the use of multiply-imputed values of speed and other variables, risks were estimated using a logistic regression model fitted to complete cases only.

To assess the sensitivity of the results to the accuracy of the speed measurements, speed estimates not derived from crash reconstruction (e.g., based on estimates by the driver, witnesses, or police) were treated as unknown and were imputed using only data from crashes in which the speed estimate was derived from crash reconstruction; risks were estimated from a logistic regression model fitted to these data. As an additional test of sensitivity to the accuracy of the speed measurements, reconstruction-based speed estimates with a high degree of uncertainty (error range greater than 5 mph) were also treated as unknown and imputed using only data from crashes in which the speed estimate was derived from crash reconstruction and calculated to have an error range of 5 mph or less.

To assess the sensitivity of the results to possible under-reporting of lower-severity crashes in the national data used to develop the post-stratification weights, new weights derived under the assumption that the true number of pedestrians who sustained incapacitating injuries was 10% greater, and the number struck but uninjured or sustaining only non-incapacitating injury was 50% greater than reflected in the GES database. Risks were estimated using a logistic regression model fitted to data with these weights instead of the original weights.

The main results are based on models fitted to the weighted data from all crashes including those in which missing values were replaced by multiply-imputed values, using the original impact speed estimates and the original post-stratification weights. Results of the various sensitivity analyses are presented and discussed briefly.

Results

The majority of pedestrians in the sample were struck at relatively low impact speeds: 280 of 422 were struck at speeds slower than 20 mph, while only 81 were struck at speeds of 30 mph or faster (Table 1). Of the 30 pedestrians struck at speeds of 40 mph or faster, 4 were struck at speeds of 50 – 60 mph, and 7 were struck at speeds faster than 60 mph. The median impact speed was 12 mph for all crashes in the sample and 35 mph for crashes in which the pedestrian was killed. The proportion of pedestrians who were severely injured or killed increased as impact speed increased across all categories of impact speed examined. The proportion of struck pedestrians who were male was greater among pedestrians struck at higher speeds than at lower speeds.

Table 1 also illustrates the effect of the post-stratification weighting adjustment. Severely and fatally injured pedestrians were over-represented in the original sample, thus they were given lower weights and consequently contributed less to weighted results than did pedestrians with less severe injuries. For example, although 19 of 30 (63.3%) pedestrians struck at speeds of 40 mph or faster were killed, the estimated proportion of pedestrians killed in this group was 54.6% when weighting was used.
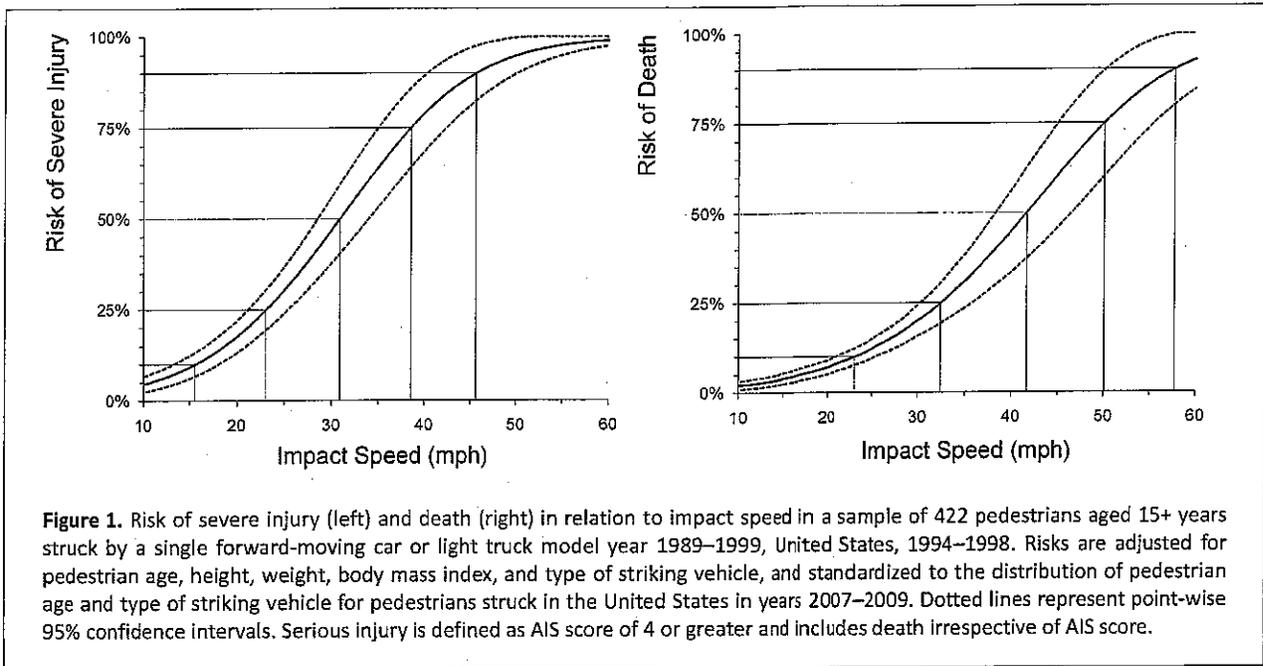
Adjusted for age, height, weight, BMI, and type of striking vehicle, and standardized to the distribution of pedestrian age and type of striking vehicle for pedestrians struck in the United States in years 2007–2009, the average risk of severe injury reached 10% at an impact speed of 16 mph, 25% at 23 mph, 50% at 31 mph, 75% at 39 mph, and 90% at 46 mph (Figure 1). Risk of severe injury increased approximately linearly with speed for speeds between 23 mph and 38 mph, with an average increase of 3.2 percentage points (95% Confidence Interval [CI]: 2.7 – 3.8) for each 1 mph increase in impact speed for speeds within this range.

Table 2. Characteristics of study population, pedestrians ages 15+ years struck by forward-moving car or light truck model year 1989–1999, United States, 1994–1998. N's are averaged from 20 independent imputations[a]; percents are weighted to reflect nationwide distribution of struck pedestrians with respect to police-reported injury severity.

	Impact speed (miles per hour)									
	< 10.0 (N = 163)		10.0 – 19.9 (N = 117)		20.0 – 29.9 (N = 61)		30.0 – 39.9 (N = 51)		40.0+ (N = 30)	
Pedestrian characteristics	Unweighted N (weighted column %)									
Mortality										
Non-fatal (n=356)	161	(99.5)	112	(97.7)	45	(84.5)	27	(64.6)	11	(45.4)
Fatal (n=66)	2	(0.5)	5	(2.3)	16	(15.5)	24	(35.4)	19	(54.6)
Maximum severity injury										
AIS 0 – 3 non-fatal (n=315)	158	(98.1)	102	(89.5)	39	(75.1)	13	(32.9)	4	(17.2)
AIS 4 – 6 or fatal (n=107)	5	(1.9)	15	(10.5)	22	(24.9)	39	(67.1)	26	(82.8)
Age (years)										
15 – 34 (n=180)	65	(40.8)	54	(48.4)	32	(55.9)	20	(38.6)	10	(33.8)
35 – 59 (n=150)	60	(37.0)	42	(35.9)	18	(30.2)	17	(37.1)	13	(44.9)
60+ (n=92)	38	(22.2)	21	(15.7)	12	(14.0)	15	(24.3)	7	(21.4)
Sex										
Female (n=200)	99	(60.7)	52	(42.7)	25	(40.2)	16	(33.8)	8	(26.4)
Male (n=222)	64	(39.3)	65	(57.3)	36	(59.8)	35	(66.2)	22	(73.6)
Height (inches)										
< 64.0 (n=90)	44	(25.8)	23	(20.0)	15	(22.8)	6	(11.9)	2	(6.3)
64.0 – 69.9 (n=214)	77	(48.4)	62	(51.3)	31	(48.9)	30	(57.6)	14	(46.5)
70.0+ (n=118)	43	(25.8)	31	(28.8)	15	(28.3)	15	(30.4)	14	(47.2)
Weight (pounds)										
< 135.0 (n=118)	51	(31.0)	37	(31.7)	15	(25.4)	9	(17.4)	6	(20.2)
135.0 – 179.9 (n=200)	76	(47.2)	53	(45.7)	28	(45.8)	27	(56.1)	16	(53.0)
180.0+ (n=104)	36	(21.8)	27	(22.7)	18	(28.7)	15	(26.5)	8	(26.7)
Body mass index (kg/m^2)										
< 25.0 (n=249)	95	(57.3)	77	(67.2)	34	(59.4)	25	(54.2)	18	(62.1)
25.0 (n=173)	68	(42.7)	40	(32.8)	27	(40.6)	26	(45.8)	12	(38.0)
Vehicle characteristics										
Vehicle type										
Car (n=280)	104	(64.5)	78	(67.4)	38	(64.3)	39	(75.9)	21	(70.7)
Light truck (n=142)	59	(35.6)	38	(32.6)	23	(35.7)	12	(24.1)	9	(29.3)
Bumper height (inches)										
< 20.0 (n=93)	30	(19.1)	30	(26.5)	11	(19.4)	14	(26.5)	8	(26.9)
20.0 – 23.9 (n=251)	98	(60.5)	67	(57.3)	39	(67.4)	32	(61.5)	15	(50.8)
24.0+ (n=78)	35	(20.3)	20	(16.2)	10	(13.2)	5	(12.1)	7	(22.3)
Curb weight (pounds)										
< 2,500 (n=100)	33	(20.2)	35	(30.2)	13	(21.6)	10	(20.2)	9	(31.8)
2,500 – 3,499 (n=194)	76	(47.5)	48	(41.7)	33	(53.2)	25	(44.5)	12	(40.5)
3,500+ (n=128)	54	(32.3)	34	(28.1)	15	(25.2)	17	(35.3)	9	(27.7)

a. Number (weighted %) of values imputed: impact speed: 67 (15%); body mass index: 64 (14%); weight 61 (13%); height: 59 (13%); age: 1 (0.3%); curb weight: 1 (0.3%).
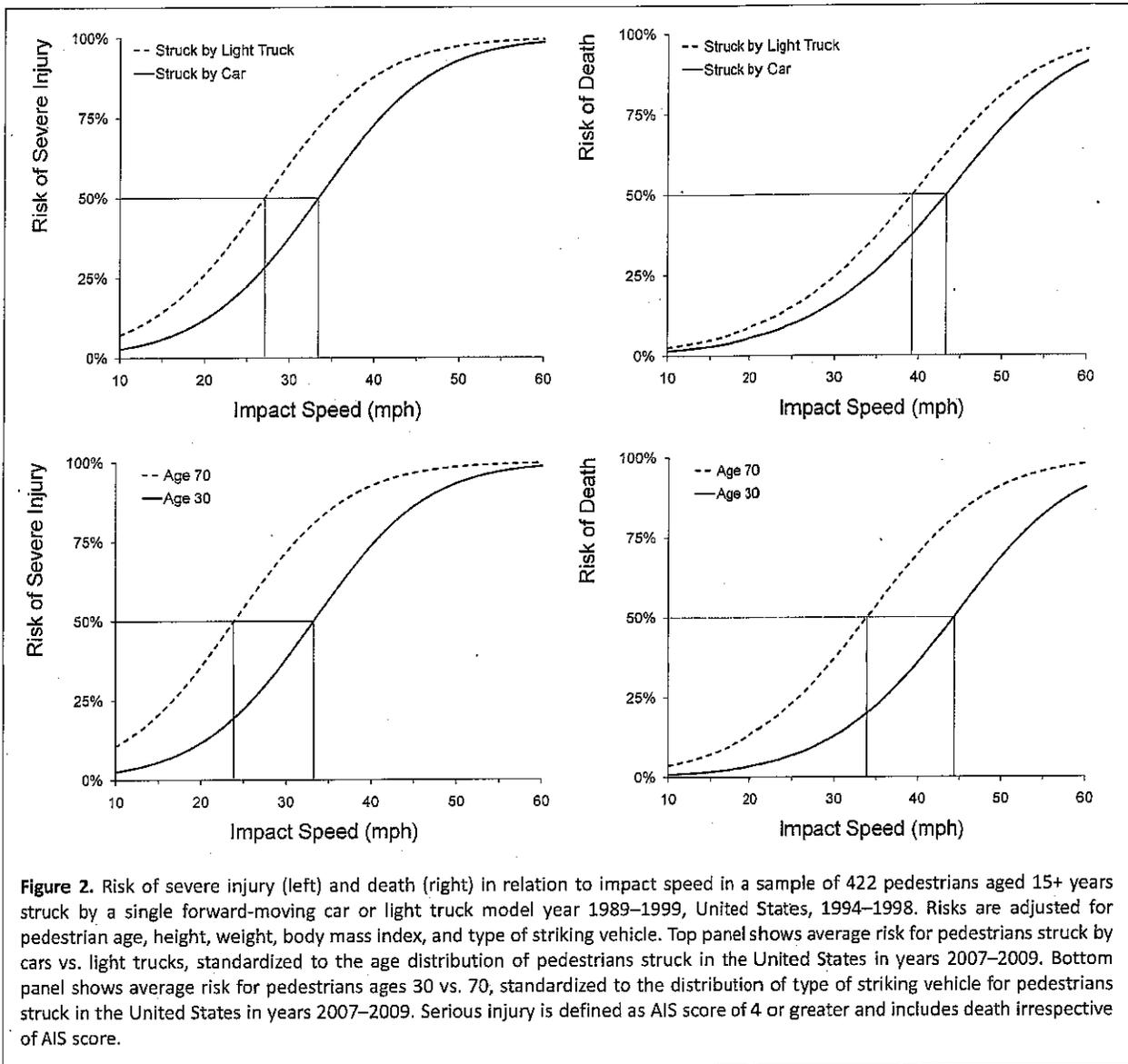
b. N's reflect averages from 20 imputed data sets and are rounded. Totals should add to N and column percents to 100.0% but may not due to rounding.

Figure 1. Risk of severe injury (left) and death (right) in relation to impact speed in a sample of 422 pedestrians aged 15+ years struck by a single forward-moving car or light truck model year 1989–1999, United States, 1994–1998. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle, and standardized to the distribution of pedestrian age and type of striking vehicle for pedestrians struck in the United States in years 2007–2009. Dotted lines represent point-wise 95% confidence intervals. Serious injury is defined as AIS score of 4 or greater and includes death irrespective of AIS score.

The average adjusted, standardized risk of death reached 10% at an impact speed of 23 mph, 25% at 32 mph, 50% at 42 mph, 75% at 50 mph, and 90% at 58 mph. Risk of death increased approximately linearly with speed for speeds between 32 mph and 50 mph, with an average increase of 2.8 percentage points (95% CI: 2.2 – 3.4) for each 1 mph increase in impact speed for speeds within this range.

Risks were higher for pedestrians struck by light trucks than for pedestrians struck by cars (Figure 2, top panel). The average adjusted, standardized risk of severe injury for a pedestrian struck at any given speed by a light truck was approximately equal to the average risk if struck by a car travelling 6.3 mph faster (95% CI: 2.1 – 10.6 mph). The average risk of death for a pedestrian struck at any given speed by a light truck was approximately equal to the average risk if struck by a car travelling 4.1 mph faster (95% CI: -1.4 – 9.5 mph).

Risks were also higher for older pedestrians than for younger pedestrians (Figure 2, bottom panel). The average adjusted, standardized risk of severe injury for a 70-year-old pedestrian struck at any given speed was approximately equal to the average risk for a 30-year-old struck by a vehicle travelling 9.3 mph faster (95% CI: 5.3 – 13.4 mph). The average risk of death for a 70-year-old pedestrian struck at any given speed was approximately equal to the average risk for a 30-year-old pedestrian struck by a vehicle travelling 10.4 mph faster (95% CI: 5.4 – 15.4 mph).

Figure 2. Risk of severe injury (left) and death (right) in relation to impact speed in a sample of 422 pedestrians aged 15+ years struck by a single forward-moving car or light truck model year 1989–1999, United States, 1994–1998. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle. Top panel shows average risk for pedestrians struck by cars vs. light trucks, standardized to the age distribution of pedestrians struck in the United States in years 2007–2009. Bottom panel shows average risk for pedestrians ages 30 vs. 70, standardized to the distribution of type of striking vehicle for pedestrians struck in the United States in years 2007–2009. Serious injury is defined as AIS score of 4 or greater and includes death irrespective of AIS score.

Sensitivity analysis

Risks of severe injury and death were higher at any given speed when estimated from the unweighted data than from the weighted data. Risk of severe injury reached 10%, 25%, 50%, 75%, and 90% at impact speeds 2-3 mph lower, and risk of death reached each of these levels at impact speeds 2-4 mph lower when estimated from the unweighted data than when estimated from the weighted data (Table 3).

Risk of severe injury was lower, but increased slightly more rapidly, when estimated from complete cases only than when estimated from all of the data; each level of risk was reached at a speed 1-2 mph higher when estimated from complete cases only. Risk of death was slightly lower at low speeds, but increased more rapidly above approximately 32 mph and was higher at higher speeds, when estimated from complete cases only than when estimated from all of the data.

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Table 3. Impact speed at which estimated average risk for struck pedestrian reaches 10%, 25%, 50%, 75%, and 90%, main results vs. sensitivity analyses. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle, and standardized to the distribution of pedestrian age and type of striking vehicle for pedestrians struck in the United States in years 2007–2009.

	Risk of severe injury (%)					Risk of death (%)				
	10	25	50	75	90	10	25	50	75	90
					Impact speed (mph)					
Main results	16	23	31	39	46	23	32	42	50	58
Sensitivity analyses										
Unweighted data	13	21	29	37	44	19	29	39	48	56
Complete cases only[a]	17	25	33	40	47	24	33	41	48	54
Impact speed from crash reconstruction only[b]	16	23	31	38	45	23	32	41	49	56
Impact speed accurate to within 5 mph only[c]	16	23	30	37	44	24	32	40	48	55
Weights adjusted for under-reporting[d]	17	25	33	40	47	26	34	43	51	58

a. Estimated from logistic regression model fitted to complete cases only (N=315).
b. Impact speed estimates not derived from crash reconstruction (e.g., based on police, driver, or witness estimates; n=26) were treated as missing values and were imputed.
c. Impact speed estimates not derived from crash reconstruction (n=26) and speeds derived from reconstruction with error range greater than 5 mph (n=11) were treated as missing values and were imputed.
d. Separate post-stratification weights were derived assuming that the true number of struck pedestrians sustaining non-incapacitating injury or no injury was 50% greater and the number sustaining incapacitating injury was 10% greater than reflected in national statistics used to derive the weights.

There was little change in the estimated risks of severe injury and death at low speeds, but risks increased slightly more rapidly at higher speeds, when impact speeds derived from driver, witness, or police estimates (vs. crash reconstruction) were treated as unknown and were replaced with imputed values, compared to risks estimated from the original data. When the least accurate reconstruction-based estimates (those with an error range of greater than 5 mph) were also treated as unknown and replaced with imputed values, risks of serious injury and death both increased even more rapidly at higher speeds (Table 3).

Risks of severe injury and death were lower at lower speeds, but increasingly similar at higher speeds, when estimated using weights adjusted for potential under-reporting of non-fatal crashes (in the national statistics used to derive the weights) than when estimated using the original weights (Table 3).

Discussion

It is well known that the risk that a pedestrian struck by a vehicle will be seriously injured or killed increases as impact speed increases. This study provides estimates of the risk of severe injury or death in relation to impact speed for the pedestrian population and vehicle fleet of the United States.

At low speeds (e.g., below about 15 mph), risks are low and increase relatively slowly with small increments in speed. At impact speeds below 15 mph, most pedestrians who are struck (about 91%) do not sustain AIS 4 or greater injuries, and very few (about 2-5%) die. However, as speeds increase beyond this range, small changes in speed yield relatively large increases in risk. At an impact speed of 25 mph, an estimated 30% of pedestrians sustain AIS 4 or greater injury, and about 12% die. Nearly half of all pedestrians (47%) struck at 30 mph sustain AIS 4 or greater injury, and one in five (20%) die. At 40 mph, 79% of struck pedestrians sustain AIS 4 or greater injury and 45% die. Risks for a pedestrian struck at any given speed by a light truck are higher than if struck at the same speed by a car, and are higher for an older pedestrian struck at any given speed than for a younger pedestrian struck at the same speed.

Relation to other research

Most past studies of the relationship between crash impact speed and a pedestrian's risk of death were based on samples in which the proportion of pedestrians seriously injured or killed was substantially greater than in the general population, and did not account for potential bias that could result from this (Rosén *et al.*, 2011). Exceptions are Davis (2001), Rosén & Sander (2009), and Richards (2010).

Davis (2001) analyzed a sample of British data that included pedestrians struck by the front of a car from years 1966–1979 (data described in Ashton [1980]), post-stratified the sample by age (0–14 years, 15–59 years, and 60+ years) and injury severity (slight, serious, and fatal), weighted the data using corresponding national statistics, and estimated unadjusted risks for pedestrians in each of these three age groups separately. Rosén & Sander (2009) analyzed German data from years 1999–2007 that included pedestrians ages 15–96 struck by the front of a car, post-stratified the sample by injury severity (ambulant, in-patient, and fatal), weighted the data using national statistics, and estimated both unadjusted risks and risks adjusted for pedestrian age. Richards (2010) analyzed a sample British data from years 2000–2009 that included pedestrians struck by the front of a car, post-stratified the sample by injury severity, weighted it using national statistics, and estimated unadjusted risks of death in relation to impact speed.

The shape of the curve relating risk of death to impact speed in the current study was very similar to that of Rosén & Sander. In the current study, unadjusted risks increased from 25% to 75% with a 16 mph increase in impact speed and from 10% to 90% with a 32 mph increase in impact speed; in Rosén & Sander (2009), unadjusted risks increased from 25% to 75% with a 15 mph increase in impact speed and from 10% to 90% with a 31 mph increase in impact speed. However, the speed at which any given level of risk was reached was approximately 3-4 mph lower in the current study than in Rosén & Sander (2009) (Table 4). The incremental increase in risk for a given increase in speed appeared to be somewhat steeper in Davis (2001) and Richards (2010) than in the current study; however, there was no evidence that differences observed were larger than plausible variation

Table 4. Impact speed at which estimated risk of death reaches 10%, 25%, 50%, 75%, and 90%, and odds ratio for change in odds of death given 5 mph increase in impact speed, previous studies and current study.

Study	Data	Confounders adjusted	Odds Ratio (95% CI)	Risk of death (%)				
				10	25	50	75	90
				Impact speed (mph)				
Davis (2001)	United Kingdom, 1966-1969 & 1973-1979	None	2.78 (2.09-3.69)	33	38	43	49	54
Rosén & Sander (2009)	Germany, 1999-2007, pedestrians ages 15+ years struck by front of car	None	2.06 (1.60-2.66)	32	40	48	55	63
		Age	2.15 (1.67-2.76)	33[a]	41	48	55	63
Richards (2010)	United Kingdom, 2000-2009, pedestrians struck by front of car	None	2.41 (1.79-3.24)[b]	33	38	45	51	62
Current Study	United States, 1994-1998, pedestrians ages 15+ years struck by forward-moving car or light truck	None	1.99 (1.60-2.49)	28[c]	36	44	52	60
		Age, height, weight, BMI, vehicle type	2.18 (1.78-2.67)	30[d]	38	46	53	61
				23[e]	32	42	50	58

a. Adjusted risks for age = 45 years (mean age in sample).
b. Richards did not report standard error of odds ratio; standard error estimated using information in Table A2.2 of Richards (2010).
c. Unadjusted model, pedestrians struck by cars only, pedestrians struck by light trucks excluded.
d. Average marginal prediction for pedestrian aged 45 struck by cars, adjusted for age, height, weight, BMI, and vehicle type.
e. Average marginal predictions for pedestrians struck by cars and light trucks, standardized the distribution of age and type of striking vehicle for pedestrians struck in the United States in years 2007–2009, adjusted for age, height, weight, BMI, and vehicle type.

attributable only to chance. A global test of homogeneity of the unadjusted odds ratios of Davis (2001), Rosén & Sander (2009), Richards (2010), and the current study produced no evidence that the effect of a given change in impact speed varied across studies (p=0.29).

The shape of the adjusted risk curve in the current study was very similar to that of Rosén & Sander (2009) when both were estimated for the same values of age and risks in the current study were estimated for pedestrians struck by cars only (Table 4, second row from bottom). Adjusted risks increased from 25% to 75% with a 15 mph increase in impact speed in the current study vs. a 14 mph increase in Rosén & Sander (2009), and increased from 10% to 90% with a 31 mph increase in impact speed in the current study versus a 30 mph increase in Rosén & Sander (2009). The speed at which any given level of risk was reached was approximately 2-3 mph lower in the current study than in Rosén & Sander (2009). A test of homogeneity of the adjusted odds ratios of Rosén & Sander (2009) and the current study produced no evidence that the effect of a given change in impact speed differed between the two studies (p=0.95).

The last row of Table 4 shows the estimates presented as the main results of the current study— average risks for pedestrians of all ages, struck by cars or light trucks, standardized to the distribution of age and type of striking vehicle for all pedestrians struck in the United States in 2007–2009. These risks reach any given level at a lower speed than do the risks for 45-year old pedestrians struck by cars, because these are a weighted average that also includes pedestrians whose risks are higher than average, e.g., older pedestrians and pedestrians struck by light trucks. Arguably these are the most

representative estimates of risks—they represent risks averaged over the entire population of struck pedestrians in the United States (i.e., pedestrians of all ages and sizes struck by cars or light trucks) rather than only for pedestrians of a certain age struck by a certain type of vehicle. The inclusion of light trucks was a unique contribution of this study relative to other studies reviewed here.

Limitations

The study sample was not designed as a representative sample of all struck pedestrians in the US (Chidester & Isenberg, 2001). Inspection of the data revealed that pedestrians who were severely injured or killed were over-represented in the sample. When the proportion of events sampled varies according to their outcome, as was the case with the PCDS data, appropriate weighting is required to produce valid estimates of the risk of the outcome (e.g., death) (Hsieh *et al.*, 1985). Thus, the data were post-stratified by injury severity and were weighted so that the distribution of injury severity in the weighted sample reflected the injury severity distribution of all struck pedestrians in the US over the study period.

The weighting procedure entailed additional limitations. Pedestrians included in this study were sampled from six specific jurisdictions, not the entire US. Data on the injury distribution of all pedestrians struck by vehicles during the study period in these specific jurisdictions was not available, so weights were derived using national data instead. If the injury severity distribution of pedestrians struck in these jurisdictions during the study period differed from the injury distribution in the US as a whole, then the post-stratification weights derived from the national data could have introduced a bias. It was assumed that the distribution of injury severity among struck pedestrians nationally was a reasonable approximation of that in the jurisdictions from which the sample was derived.

Additionally, while the study sample excluded pedestrians who were sitting or lying in the roadway, pedestrians struck by vehicles that had modifications or prior damage to the impact area, and pedestrians whose initial point of contact with the vehicle was not forward of the A-pillar (Chidester & Isenberg, 2001), it was not possible to identify and exclude such cases from the national data used to derive the weights. It was assumed that the number of pedestrians included in the national totals used for weighting that should have been excluded was small.

Of the 422 pedestrians in the study sample, 107 had missing data on impact speed and/or one or more confounding variables included. To reduce potential bias associated with analyzing complete cases only, missing data were imputed. For imputed values to be unbiased, they must be missing at random, e.g., the probability that speed was unknown must be independent of the actual speed, after controlling for the other variables included in the imputation model. If missing values were related to other variables not included in the model, bias could still be present.

Another potential limitation of the study is that the results are dependent upon the accuracy of the estimated impact speed. Sensitivity analysis showed that if the relationship between speed and risk observed in crashes in which the estimated impact speed was believed to be most accurate was applied to all crashes, risks were similar to those reported in the main results for low speeds but increased more rapidly at higher speeds.

The risks of injury and death estimated in this study are somewhat sensitive to under-reporting of crashes in the national data that was used to derive the post-stratification weights. Sensitivity analysis found that for a hypothetical scenario in which the true number of struck pedestrians sustaining non-incapacitating injury or no injury was 50% greater and the number sustaining incapacitating injury was 10% greater than reflected in national statistics, risks of severe injury were lower than reported in the main results; risks of death were lower at low speeds but similar at higher speeds.

The results of this study are not generalizable to children under the age of 15. Children younger than 15 years of age were excluded from the study because of concerns that the dynamics of a crash in which a small child is struck by a vehicle might differ in important ways from a crash in which an adult is struck, and estimating the risk of death for children over a the full range of speeds was not feasible because there were only 5 fatally-injured children under the age of 15 in the PCDS database.

Finally, although the data analyzed for this study is the most recent available data from vehicle-pedestrian crashes in the United States, it was from years 1994–1998. Changes in medical care, vehicle design, or the composition of the vehicle fleet could impact the relationship between impact speed and risk of severe injury or death. The proportion of all injured pedestrians who were struck by light trucks increased from 21% in 1994 to 40% in 2009 (NHTSA, 1994; NHTSA, 2009). To account for this change, risks presented in this study were adjusted for type of striking vehicle and were standardized to the distribution of vehicles that struck pedestrians in the United States in 2007–2009. However, it is possible that risks estimated from a more recent sample might differ if changes in vehicle design, medical care, or other factors have changed the risks of pedestrian injury or death at a given impact speed even after controlling for vehicle type.

Conclusion

To reduce the number of pedestrians seriously injured and killed in crashes with motor vehicles, it is necessary to reduce the risk of crashes occurring, the risk of severe or fatal outcomes in crashes, or both. This study can inform strategies to reduce the risk of severe or fatal outcomes when pedestrians are struck. Specifically, the results of this study highlight the importance of limiting the exposure of pedestrians to vehicles travelling at high speeds.

In places such as residential streets and urban areas designed to allow pedestrians and vehicles to be in close proximity to one another, examples of measures to reduce vehicle speeds include traffic calming techniques such as speed bumps, lane narrowing, and changes in roadway curvature, as well as increased enforcement or reduction of speed limits. In places designed to for higher vehicle speeds, pedestrians can be separated from traffic through the use of sidewalks and safe crossing facilities such as overpasses, underpasses, or traffic signals timed to reduce or eliminate conflicts between pedestrians and vehicles. Retting et al. (2003) provides a review of traffic engineering measures to improve pedestrian safety.

Vehicle-based systems that detect when a collision with a pedestrian is imminent and brake automatically may be able to help to reduce the frequency and severity of collisions with pedestrians; however, Jermakian and Zuby (2011) noted that such systems would need to function in low-light conditions and at speeds above 40 mph to prevent a large proportion of pedestrian fatalities.

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