Parameters influencing pedestrian injury and severity – A systematic review and meta-analysis

Abstract

Pedestrians account for 26% of all traffic fatalities worldwide. According to in-depth collision databases, around 3500 temporal variables can affect the outcome of a collision, making it crucial to establish the relationship between each variable and the outcome. To-date, there is no method defined to assess these temporal variables' relevance other than a statistical correlation, which can sometimes lead to reasonable conclusions, but only under specific circumstances. This article addresses this issue by first conducting a literature review to determine all relevant variables, followed by developing a variable selection criterion to select crucial variables, and then conducting a meta-analysis to combine statistical results. Epidemiological studies published between 1990 and 2022 were examined, including 93 papers from 19 different nations, considering 904,655 pedestrian collisions. Of the 204 variables that were extracted from these studies, 152 were examined using the variable selection criterion, and 68 were found to be significant. Of these, 31 were included in the meta-analysis, which combined odds ratio to aggregate the effect of a variable across various studies, thus removing study-specific conclusions. This study is innovative as it proves that statistical correlation alone is insufficient to determine the importance of a variable. The proposed method is an objective way to distinguish the variables for stakeholders and identify the relevant variables. This study provides for the first time the definitive list of the 68 variables that must be included in any pedestrian-to-vehicle accident databases, allowing appropriate actions for safer roads.

1. Introduction

Around the world, traffic accidents continue to be a leading source of fatalities and injuries. They account for the deaths of approximately 1.35 million people each year, and about 26% of those are pedestrians. Road traffic injuries (RTI) are now the leading cause of death for children and young adults aged 5–29 years, and the global economic burden of motor vehicle collisions and pedestrian injuries totals £26 billion (WHO, 2018). Of all the road users, pedestrians are the most affected and are prone to more injuries than any other participant in a vehicle collision. Since 2019, there have been about 36,487 pedestrian casualties in Great Britain (Road safety statistics; Department for Transport, 2021). Pedestrian RTIs can be classified into three categories: primary ones are the injuries that occur at the first contact with a vehicle, like a bumper. Secondary injuries are the ones caused by the second impact, such as windscreen or bonnet. Tertiary injuries are caused by contact with infrastructure, such as the road. The head, torso, and lower extremities are the most injured body regions for pedestrians (Longhitano et al., 2005). The head is the most commonly injured body region in fatal vehicle-to-pedestrian crashes, while lower extremity injuries often result in long-term disability (Maki et al., 2003).

Research has been carried out in order to better understand and determine the temporal variables that influence pedestrian-to-vehicle collisions and the injuries they cause. The data for these studies is either from in-depth collision databases or from generalised demographic data, for example, police and/or medical records. Statistical methods, like logistic regression and ordered probit, are the most common methods used to quantify the relationship between the variables and the severity of the injuries (Li et al., 2019; Zajac & Ivan, 2003). Some studies have also explored the use of advanced machine learning methods like artificial neural networks (Hosseinian et al., 2021). Although there is an agreement that a subset of parameters like impact speed are the most influential, other parameters considered vary across each study. This is particularly important when comparing these studies, since not all parameters are relevant across regions. This discrepancy has led researchers to conduct region-specific analysis and disagree with the findings of others. For example, according to Kim et al. (2008) and Richards & Carroll (2012), the severity of pedestrian injuries increases with age, while Kong & Yang (2010), who used logistic regression to analyse 104 pedestrian accidents in China, disagreed.

The most important aspect while conducting a study to establish a relationship between variables and injury severity is to determine whether these variables are relevant, as statistically, due to the law of large numbers, almost any variable will start to display a statistical link with the dependent variable. As a result, it is very important to establish the relevance of a variable objectively before testing its statistical significance. There are several additional limitations to the previously published literature reviews. For example, they concentrate on the frequency of the parameters under consideration (Moradi et al., 2019). Others restrict the number of studies that are considered and do not assess the odds ratio (i.e., a measure of association between an exposure and an outcome). While a few studies assess the odds ratio and include a sufficient amount of literature, they restrict the study to one parameter. For example, Hussain et al. (2019) performed a meta-analysis of 20 studies but limited his investigation to only one parameter, namely impact speed. To address these limitations, the goal of this research is to:

Step 1: Conduct a literature review and compile a list of all the variables that have been demonstrated to cause pedestrian accidents and influence the severity of resulting injuries.
Step 2: Develop a criterion for determining a variable's relevance to a vehicle-to-pedestrian collision and select relevant variables from the list compiled in step 1.
Step 3: Conduct a meta-analysis of the variables selected in Step 2, which entails comparing research based on effect size and determining their impact regardless of area or sample size.

2. Methods

This study sought to identify all research which investigated the association between temporal variables and their effects on the severity of pedestrian injuries sustained in a vehicle-to-pedestrian collision from 1977 to 2021. The aim of this literature was to answer: which temporal variables were proven to have an influence on the severity of vehicle-to-pedestrian crashes?

Once the list of variables was compiled, a criterion was developed to establish the relevance of each variable with respect to the severity of vehicle-to-pedestrian accidents. This criterion categorises each variable as control-variable, disturbance, not important, or output. The aim of this criterion was to evaluate the relationship between each variable and the injury severity objectively, irrespective of its statistical significance.

After the segregation, variables under control-variable and disturbance are considered for meta-analysis, which is a statistical method to combine the findings of various studies. It is usually performed when there are multiple scientific studies addressing the same question, with each producing conclusions that are expected to be biased in some way. Figure 1 shows the steps followed in this study.

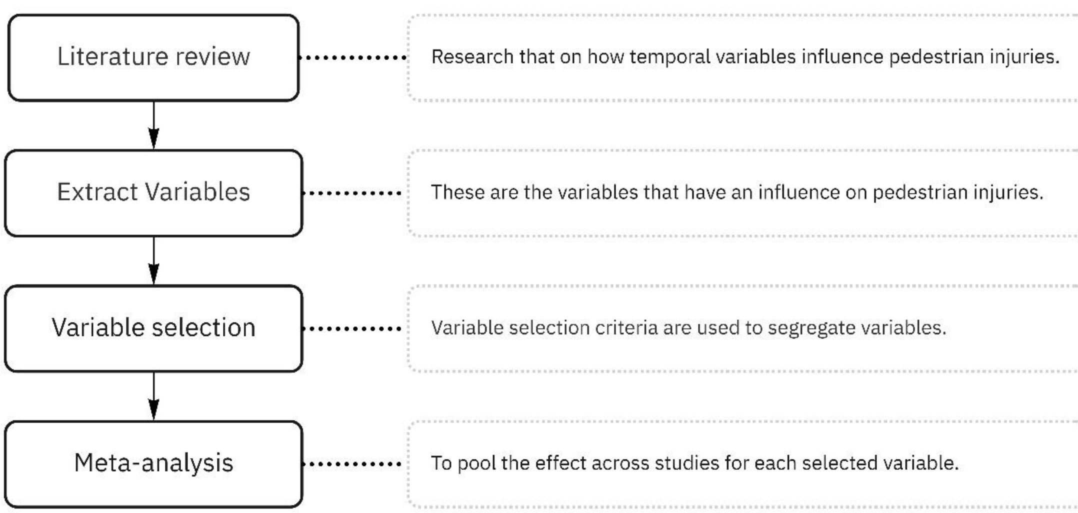

Figure 1: Overview

2.1. Literature review

Protocol and information sources

The literature review was conducted with the view of examining the influence of temporal variables on the severity of pedestrian injuries. Popular databases like PedMed, Scopus, Web of Sciences, ScienceDirect, Google Scholar, and Locate were searched for published articles and reports. References to identified articles were also considered in the selection criteria.

Eligibility criteria

Studies were included if: (1) the study should be focused on assessing pedestrian accidents. (2) The study should have assessed the causation of the accident or the severity of the accident. (3) The study should have considered and assessed at least one parameter. (4) looked into the severity or frequency of a vehicle-to-pedestrian collision as a result. (5) It should be published in English. Each record is assessed twice against inclusion criteria to determine if the study is to be considered for further analysis.

Search strategy

The search string was as follows: (*parameters* or *variables*) AND (*crashes* OR *vehicle collision* OR *injury*) AND (*influencing*) AND (*injury*).

2.2. Variable selection criterion

Despite the established statistical association between the 152 variables from the preceding section and the injuries sustained by a pedestrian in the event of a vehicle-to-pedestrian collision, this relationship may not actually exist; it may simply be a result of the law of large numbers. Consequently, a criterion that is objective and unaffected by statistical connections is required. To develop such a criterion, a system representing the interaction between vehicle and pedestrian in the event of a vehicle-to-pedestrian crash is created. The vehicle and pedestrian kinematics are two attributes of this system, and pedestrian injuries are the outcomes (Figure 2).

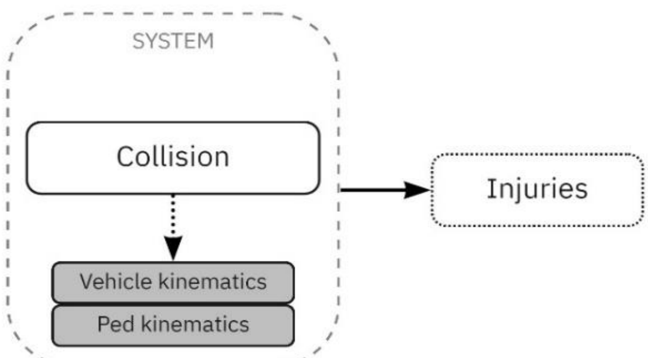

Figure 2: Vehicle-Pedestrian collision system

The criterion is set such that the variable is evaluated based on its ability to influence the system's attributes, i.e., vehicle and pedestrian kinematics, and its output, i.e., injuries sustained. Based on this, each variable is categorised into the following groups:

1. Control-variable: if a variable can influence a system's attributes and has a direct impact on its outcome. For example, a pedestrian's age or gender.
2. Disturbance: if a variable can influence a system's attributes but has no direct impact on its outcome. They have an indirect impact on the outcome of the system by affecting a control-variable. For example, pedestrians' clothing visibility or the driver's age.
3. Not important: If a variable does not influence the system or its outcome, or if it is a derived variable, and its individual components are assessed separately, for example, body mass index (BMI), which is a ratio between a pedestrian's height and weight, or a pedestrian's education level.
4. Output: if a variable quantifies or describes the output of the system. For example, Abbreviated injury score (AIS) or Injury severity score (ISS).

Each variable was assessed based on the format “Does {variable} {column header}?” (Table 1), for example, “Does {pedestrian’s age} {Influence vehicle kinematics}?”, each column is marked 0 (no) or 1 (yes) based on the question.

Table 1: Variable selection criterion

Does	Describe injury?	Influence Vehicle-Kinematics?	Influence Pedestrian-Kinematics?	Influence Injury?
{Variable}	A1	A2	A3	A4

The resulting category is selected based on the following formula:

1. Control-variable: ~(A1) AND (A2 OR A3) AND (A4)
2. Disturbance: ~(A1) AND (A2 OR A3) AND ~(A4)
3. Not important: ~(A1) AND ~(A2) AND ~(A3) AND ~(A4)
4. Output: (A1) AND ~(A2) AND ~(A3) AND ~(A4)

2.3. Statistical analysis by Meta-Analysis

As the literature was already available from section 2.1, the same was carried over for the meta-analysis. The articles which considered control-variables and disturbances were retained and the rest were ignored. From the variable sample, any variable that was not considered in at least 3 studies was not considered. The names of the author(s), the year of publication, the data source, the countries where data was collected, the variable(s) considered for analysis, the sample size, and the outcome measure were all extracted from each study (Table A1 under Appendix A). All outcomes were converted to a common effect size.

A series of hierarchical random-effects models were fitted for each variable for the odds ratios using extracted information. Model 1 was a baseline random-effect model with no moderators. Model 2 included the country of study as a moderator, and Model 3 used the year of publication as a moderator. Publication bias was inspected visually using the funnel plot method. All statistical analyses were performed using metafor (Viechtbauer, 2010), a package for meta-analysis in R (R Core Team, 2013), and meta-analysis was performed using the Review Manager 5.4 (Cochrane Collaboration, Oxford, UK) software package.

Residual heterogeneity was estimated and assessed by tau^2 and I^2. Tau^2 is the between-study variance in the meta-analysis, which is insensitive to the number of studies and precision but is hard to interpret its relevance (Higgins & Thompson, 2002). On the other hand, the index of heterogeneity (I^2) is the percentage of variability in the effect sizes and is not influenced by sampling error. It is also considered to be unaffected by the number of studies but depends heavily on precision (Higgins & Thompson, 2002). Higgins et al. (2003) provided a rule of thumb to interpret it: 25% for low heterogeneity, 50% for moderate heterogeneity, and 75% for substantial heterogeneity. It is important to note that while studies become increasingly large, sampling error tends to zero, resulting in $I^2 \rightarrow 100\%$ (Harrer et al., 2022).

3. Results

The PRISMA flow diagram for reviewed studies is presented in Figure 3. The reviewer examined 600 search results, selecting 252 studies for analysis and 13 from the reference list. Of these, 100 were removed as they did not focus on pedestrians. 23 were not considered as they only compared methods and did not provide details on the influence of variables. Another 49 studies which did not concentrate on collision injuries were also removed. This process concluded that 93 studies met the selection criteria. The final list comprises of studies that were conducted from 1990–2022 and used a variety of methods to establish the influence of variables on the severity of injuries.

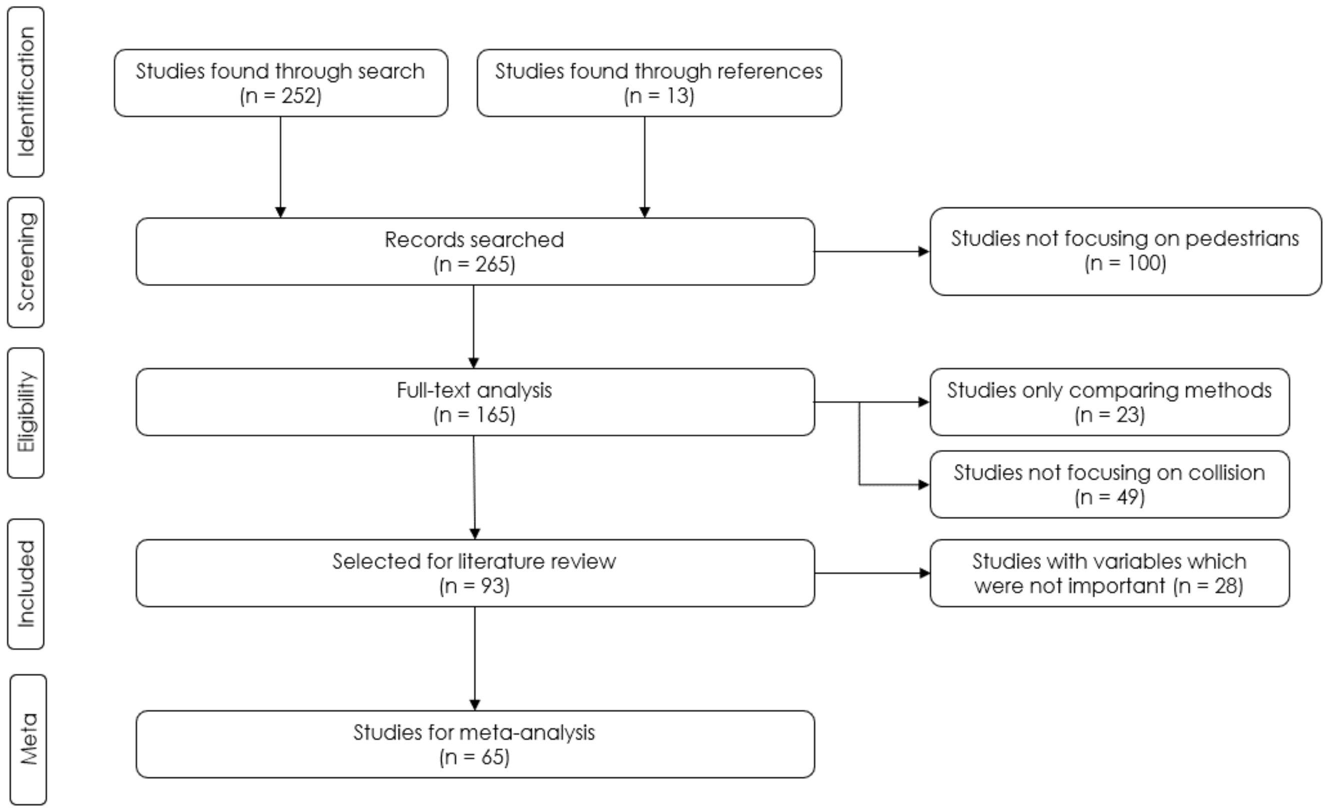

Figure 3: Study inclusion

3.1. Characteristics of the collected studies

Study characteristics, including data source country, sample size, and data period, are summarised in Table A1 under Appendix A. The shortlisted 93 studies analysed 204 different variables that affected the severity of pedestrian injuries. Of these, pedestrian age, gender, and vehicle type were the most common variables considered in 53, 44, and 41 studies, respectively. These studies included 904,655 pedestrian crashes from 19 countries. The outcomes varied from just assessing the binary outcome of fatal or not fatal to a more detailed measure of the KABCO (K-fatal, A-incapacitating, B-non incapacitating, C-possible, O-no injury) injury scale (National Highway Safety Administration, 2008). The data sources varied from in-depth collision databases to police and medical records. The list of all 204 variables and their respective studies is available in Appendix B.

In some cases, the author did not acknowledge the significance of a variable. The reason for this could be that it had no influence on the outcome or the influence could not be determined. 52 such variables were omitted from the list. As a result, 152 variables were taken into consideration for further research. A variable selection criterion was used to classify these 152 variables, and the results showed that 35 of them were control-variables, 33 were disturbances, 2 were outputs, and 82 were not significant. The selection criteria and the resulting category are detailed in Table A2 under Appendix A

Out of the 93 studies that were chosen for the literature review, 16 were discarded because the variables considered were deemed unimportant by the variable selection criteria. Twelve articles presented their findings using injury curves and employed Finite Element (FE) models for their analysis. This made it impossible to quantify how the variables under consideration affected the outcome. Of the 63 control variables and disturbances, 32 were eliminated since at least three studies did not take them into account. Consequently, the final list for the meta-analysis consisted of 31 variables and 65 articles.

3.2. Evaluating heterogeneity and publication bias

A forest plot of odds ratios is shown in Figure 4 with summary estimates for the pedestrian's age variable, as an example. The fitted values were transformed to odds ratios on a log scale for ease of interpretation. None of the moderators improved heterogeneity, indicating the variables' influence is not dependent on when and where the article was published. There was also visual evidence of publication bias from the funnel plot of the final model residuals (see Figure 5) and by the heterogeneity test (τ^2=3.30, p=0.001, I^2=100%).

The odds of pedestrian injuries, AIS1+, will on average increase by two-fold with age (OR = 2.36, 95% CI: 1.39, 3.99) and the odds of pedestrians getting injured will increase by 31% on average based on their behavior (OR = 1.31, 95% CI: 0.44, 3.89). The odds of a pedestrian getting injured vs. all considered variables are summarised in Table 2. A respective plot for each variable is available in Appendix C.

Study or Subgroup	log[Odds Ratio]	SE	Weight	Odds Ratio IV, Random, 95% CI
01 - Holubowycz, 1995	0.5956	0.298	2.1%	1.81 [1.01, 3.25]
02 - Li et al., 2019	0.0247	0.009	2.2%	1.03 [1.01, 1.04]
03 - Zajac & Ivan, 2003	0.9337	0.283	2.1%	2.54 [1.46, 4.43]
04 - Sze & Wong, 2007	0.8713	0.022	2.2%	2.39 [2.29, 2.50]
05 - Kim et al., 2008	0.0129	0.005	2.2%	1.01 [1.00, 1.02]
06 - Kong & Yang, 2010	0.0421	0.0151	2.2%	1.04 [1.01, 1.07]
07 - Richards & Carroll, 2012	0.6408	0.1663	2.2%	1.90 [1.37, 2.63]
08 - Badea-Romero & Lenard, 2013	1.0017	0.2628	2.1%	2.72 [1.63, 4.56]
09 - Islam & Jones, 2014	0.6901	0.2679	2.1%	1.99 [1.18, 3.37]
10 - Li et al., 2017	0.0344	0.009	2.2%	1.03 [1.02, 1.05]
13 - Nishimoto et al., 2019	0.6419	0.083	2.2%	1.90 [1.61, 2.24]
16 - Pitt et al., 1990	0.2351	0.176	2.1%	1.27 [0.90, 1.79]
17 - Zhao et al., 2014	-0.734	1.9751	1.0%	0.48 [0.01, 23.04]
23 - Lee & Abdel-Aty, 2005	2.3792	0.1536	2.2%	10.80 [7.99, 14.59]
24 - Eluru et al., 2008	0.6668	0.1492	2.2%	1.95 [1.45, 2.61]
26 - Al-Ghamdi, 2002	0.1501	0.1436	2.2%	1.16 [0.88, 1.54]
27 - Kim et al., 2010	0.2942	0.0495	2.2%	1.34 [1.22, 1.48]
28 - Aziz et al., 2013	1.6831	0.6213	1.9%	5.38 [1.59, 18.19]
29 - Sasidharan & Menéndez, 2014	2.873	0.215	2.1%	17.69 [11.61, 26.96]
30 - Haleem et al., 2015	2.383	0.431	2.1%	10.84 [4.66, 25.22]
31 - Sun et al., 2019	-1.6195	0.4129	2.1%	0.20 [0.09, 0.44]
34 - Abdel-Aty et al., 2007	1.5261	0.001	2.2%	4.60 [4.59, 4.61]
35 - Pour-Rouholamin & Zhou, 2016	-0.2679	0.104	2.2%	0.76 [0.62, 0.94]
36 - M. Kim et al., 2017	1.1301	0.015	2.2%	3.10 [3.01, 3.19]
37 - Lalika et al., 2022	0.0733	0.0374	2.2%	1.08 [1.00, 1.16]
39 - Nasri et al., 2022	1.5688	0.1463	2.2%	4.80 [3.60, 6.40]
41 - Mohamed (1) et al., 2013	1.245	0.3175	2.1%	3.47 [1.86, 6.47]
43 - Clifton et al., 2009	0.8229	0.1841	2.1%	2.28 [1.59, 3.27]
46 - Song et al., 2020	0.0237	0.0219	2.2%	1.02 [0.98, 1.07]
47 - Helmer et al., 2010	0.7617	0.1848	2.1%	2.14 [1.49, 3.08]
48 - Iragavarapu et al., 2015	0.2359	0.009	2.2%	1.27 [1.24, 1.29]
52 - Roudsari et al., 2004	0.47	0.5004	2.0%	1.60 [0.60, 4.27]
55 - Matsui et al., 1999	0.8264	0.4565	2.0%	2.29 [0.93, 5.59]
57 - Islam & Hossain, 2015	0.48	0.2245	2.1%	1.62 [1.04, 2.51]
58 - Kitali et al., 2017	-1.1712	0.0002	2.2%	0.31 [0.31, 0.31]
59 - Pelet-Del-Toro et al., 2019	3.2007	0.5657	2.0%	24.55 [8.10, 74.40]
60 - Hosseinian et al., 2021	3.405	0.889	1.8%	30.11 [5.27, 171.99]
62 - Wang et al., 2019	0.0227	0.005	2.2%	1.02 [1.01, 1.03]
65 - Zhang et al., 2008	3.1714	0.799	1.8%	23.84 [4.98, 114.14]
66 - Yasmin et al., 2014	2.4296	0.5436	2.0%	11.35 [3.91, 32.95]
67 - Zhao et al., 2013	1.16	0.861	1.8%	3.19 [0.59, 17.25]
74 - Jang et al., 2010	-0.1936	0.06	2.2%	0.82 [0.73, 0.93]
75 - Ma et al., 2018	0.3067	0.0929	2.2%	1.36 [1.13, 1.63]
80 - Uddin & Ahmed, 2018	2.3342	0.0499	2.2%	10.32 [9.36, 11.38]
83 - Šarić et al., 2021	0.375	0.065	2.2%	1.45 [1.28, 1.65]
84 - Kamboozia et al., 2020	1.0389	0.391	2.1%	2.83 [1.31, 6.08]
88 - Rella Riccardi et al., 2022	2.6186	0.092	2.2%	13.72 [11.45, 16.43]
92 - Pour et al., 2016	0.3053	0.3639	2.1%	1.36 [0.67, 2.77]
Total (95% CI)			**100.0%**	**2.36 [1.40, 3.99]**

Heterogeneity: Tau² = 3.30; Chi² = 7188375.00, df = 47 (P < 0.00001); I² = 100%
Test for overall effect: Z = 3.21 (P = 0.001)

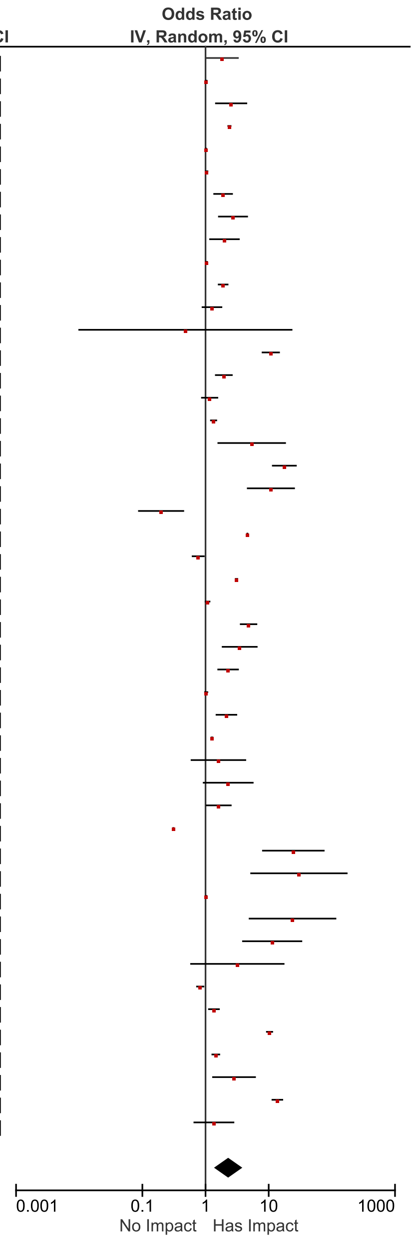

Figure 4: Forest plot

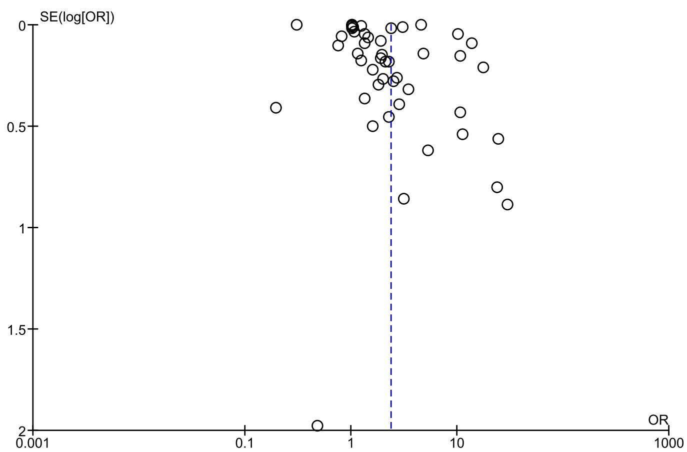

Figure 5: Funnel plot

Table 2: Summary - meta-analysis

#	Variable	# Of Study	OR-	OR	OR+	T^2	I^2	Z	p
1	Age	48	1.39	2.36	3.99	3.31	100%	3.2	0.001
2	Behaviour	20	0.44	1.31	3.89	5.76	100%	0.48	0.63
3	Clothing visibility	3	0.66	1.09	1.81	0.13	88%	0.33	0.74
4	Gender	31	1.02	1.11	1.2	0.03	98%	2.53	0.01
5	Intoxicated	9	1.48	1.83	2.25	0.06	83%	5.63	<0.00001
6	Bonnet angle	3	0.86	1.02	1.19	0.02	80%	0.2	0.85
7	Bonnet leading edge height	6	0.38	1.02	1.06	0	86%	0.8	0.42
8	Bonnet height	3	0.96	1.02	1.08	0	52%	0.57	0.57
9	Driver age	14	1.25	1.43	1.64	0.05	99%	5.23	<0.00001
10	Driver gender	16	0.92	1.05	1.2	0.06	98%	0.68	0.49
11	Driver intoxicated	14	1.21	2.01	3.34	0.89	100%	2.69	0.007
12	Impact Speed	13	1.04	1.1	1.16	0	92%	3.57	0.0004
13	Manoeuvre	16	0.73	0.87	1.04	0.1	99%	1.49	0.14
14	Number of vehicles involved	4	0.55	1.29	3.04	0.1	99%	1.49	0.14
15	Windscreen Angle	3	0.89	0.97	1.06	0	33%	0.69	0.49
16	Area type	15	0.58	1.09	2.04	1.42	100%	0.27	0.79
17	Control type	18	0.91	1.01	1.12	0.03	96%	0.25	0.81
18	Land Use	11	1.04	1.15	1.27	0.01	92%	2.69	0.007
19	Nearby infrastructure	5	0.37	0.7	1.32	0.41	99%	1.1	0.27
20	Number of lanes	9	0.79	1.2	1.81	0.33	100%	0.87	0.39
21	Obstruction	4	0.63	0.93	1.39	0.14	93%	0.34	0.74
22	Road class type	20	0.79	1.04	1.36	0.23	99%	0.26	0.79
23	Road geometry	12	0.53	1.1	2.26	1.46	100%	0.26	0.8
24	Road Network	3	0.82	2.36	6.76	0.85	98%	1.6	0.11

#	Variable	# Of Study	OR-	OR	OR+	T^2	I^2	Z	p
25	Road surface condition	13	0.45	0.85	1.61	1.19	100%	0.49	0.62
26	Road type	14	1.1	1.25	1.42	0.05	97%	3.42	0.0006
27	Shoulder type	3	0.15	0.5	1.71	1.16	100%	1.1	0.27
28	Speed limit	20	1.59	2.42	3.71	0.77	100%	4.09	<0.0001
29	Accident type	4	1.02	1.41	1.94	0.06	93%	2.1	0.04
30	Lighting	34	0.95	1.52	2.43	1.85	100%	1.74	0.08
31	Hit and run	4	0.87	0.99	1.13	0.01	94%	0.15	0.88

4. Discussion

This literature review identified 93 studies and collected 204 variables that might have an influence on the severity of pedestrian injuries in the event of a vehicle-to-pedestrian collision, such as vehicle speed, speed limit, pedestrian's age, gender, lighting conditions, type of road, intoxication of pedestrian, or the driver. Even while they all show a statistical correlation with the assessed outcome, these variables may not actually have any relevance. Due to the effect of the law of big numbers, every variable will start to demonstrate a relationship with the outcome given enough data. Therefore, before considering any statistical analysis, it is imperative to determine their relevance.

This is the first study of its kind to collect temporal variables assessed in literature, analyse them for their relevance, and conduct a meta-analysis to quantify and aggregate their effects on the outcome. The variables are segregated based on their relevance via a variable selection criterion, and the criterion found that out of 152 variables which have statistically proven influence on the severity of pedestrian injury, only 68 are relevant, which is about 50%. To support the criterion, a justification for each variable was provided, and they are as follows: (Justification for 146 other variables can be found in Appendix D.)

- *Pedestrian's Age*, Lockhart et al. (2005) prove that age affects the dynamic equilibrium responsible for recovery in a slip-fall event, implying that older pedestrians' kinematics are impacted as they age. When compared to the 20 to 29 age group, Yamada & Evans (1970) discovered that the mechanical qualities of all bones reduced by 1% in the 30 to 39 age group and by 22% in the 70 to 79 age group, implying that injury severity increased with age. As a result, the age of pedestrians is classified as a control-variable.
- *Pedestrian's gender*, McLean et al. (2004) discovered that females exhibit less hip and knee flexion, hip and knee internal rotation, and hip abduction than their male counterparts, demonstrating the kinematic differences between genders. They also found that these differences in joint kinematics point to higher knee valgus in women, which may raise the risk of anterior cruciate ligament (ACL) injury. As a result, it is categorised as a control-variable.
- *Pedestrian's clothing visibility*, several researchers have found a statistical correlation between clothing visibility and injury severity. We disagree, while a pedestrian's clothes may impact vehicle kinematics, it has no bearing on the severity of an injury. The driver may miss the pedestrian and fail to make the necessary manoeuvres to prevent a collision if the pedestrian's attire does not contrast with the background. We feel that other variables, such as vehicle speed, offer a better explanation for differences in injury severity than garment visibility. As a result, the visibility of pedestrians' clothing is classified as a disturbance.
- *Driver's age*, although it has been determined that the driver's age is statistically significant when compared to the severity of pedestrian injuries in the event of a vehicle-to-pedestrian collision, this may not actually be the case because the driver's age may be associated with careless driving, which may lead to more severe injuries, but the driver's age by itself has no relation to the severity of a pedestrian's injury.
- *Pedestrian's BMI (Body Mass Index)*, although some studies have found this variable to have an influence on the severity of pedestrian injuries, this variable has been excluded since it is a combination of height and weight, both of which are assessed separately.

- *Pedestrian's Education*, although several studies have identified a statistical correlation between a pedestrian's educational level and the severity of injuries incurred in the case of a vehicle-to-pedestrian collision, we believe it has no bearing on the pedestrian's kinematics or injuries. It could be argued that education is linked to socioeconomic status in some circumstances, resulting in a lower quality of life, which may have an impact on the severity of injury cases, but for our analysis, we are interested in whether education has an independent effect on pedestrian-to-vehicle collisions, which it does not. As a result, a pedestrian's level of education is considered irrelevant.

Another indication that the criterion selection is in line with the statistical correlation is that the justification provided during the variable selection process is in line with the findings of the meta-analysis. For example, for the variable 'obstruction', the researcher justified that the speed of the vehicle would be reduced to navigate around obstructions on the road, and a collision at this time would result in less severe injuries. The meta-analysis concluded that the odds of severe pedestrian injuries were reduced by 7% (OR = 0.93, 95% CI: 0.63, 1.39). On the other hand, results showed that inadequate lighting conditions would increase the chances of severe pedestrian accidents by 52% (OR = 1.52, 95% CI: 0.95, 2.43), and this might be the case where the driver is not able to see the pedestrian and fails to make the necessary manoeuvre, which is proven to reduce the severity of injuries sustained by 13% (OR = 0.87, 95% CI: 0.73, 1.04). It is also important to note that these are only indicators that the justification is consistent with the statistical relationship, not proof that these variables behave in this manner.

5. Conclusion

This systematic analysis found 93 articles that examined the impact of temporal variables on the severity of pedestrian injuries between 1990 and 2022. They examined a total of 904,655 pedestrian incidents and came from 19 different countries. In total, 204 different factors were examined in the analyses of these 93 papers. This is the first review of its kind to assess the relevance of a variable regardless of its statistical association using a variable selection criterion and then combine odds ratios from numerous studies using meta-analysis. This rigorous criterion's objective is to determine whether a variable is relevant to the outcome. It is clear that not all variables that display statistical correlation are significant or relevant because 82 out of the 204 variables did not meet the criterion.

We strongly recommend that at least the 68 variables examined in this study, which have been objectively and statistically demonstrated to be significant, should be included in any study or database that tries to collect and analyse vehicle-to-pedestrian collisions. Based on what they represent, the 68 variables were grouped into four groups: pedestrian, vehicle, infrastructure, and environmental. These groups each had 11, 21, 28, and 8 variables, respectively. Which group of variables the stakeholders should concentrate on is also largely determined by the variable selection criterion. While lawmakers or city planners focus on disturbances, automakers and designers should consider the control-variables.

6. Limitations

Although the list of studies considered in this systematic review is extensive, it does not include all published studies; therefore, some key variables might be missing from the database. While the variable selection criterion is designed to be generic and capable of segregating a wide range of variables, it is important to note that the criterion is biased towards the evaluator's opinion on the variable. One way to avoid this is to re-validate the scoring by two independent researchers.

Due to insufficient information in the original article, 12 studies were not considered, and, due to time constraints of the project, the authors of these studies were not contacted. The statistical models used in this meta-analysis assume that effect size is independent between studies. On a few occasions, studies were based on the same database, and a large portion of these studies were from the United States. These studies vary by different inclusion criteria, thus making it difficult to determine the complete dataset. The influence of double counting was also ignored for this study.

A total of 32 variables that were important had to be dropped as very few studies considered them, limiting the ability to assess them in a meta-analysis. There was a high level of residual heterogeneity among the effect sizes in the final model (I2 > 60%). This may have been influenced by unaccounted for differences between the included studies. Although the data was derived from 19 countries, the majority of the studies were based on data from the United States.

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Appendix A

Table A1: Characteristics of included studies

Authors (year)	Study period	Number of variables analysed	Country	Samples
Pitt et al. (1990)	1977-1980	11	United States	1035
Ishikawa et al. (1994)	NA	13	NA	NA
Holubowycz (1995)	1981-1992	3	Australia	400
Miles-Doan (1996)	1988-1990	6	United States	27231
Anderson et al. (1997)	1983-1991	1	Australia	176
Matsui et al. (1999)	1987-1988	5	Japan	82
Al-Ghamdi (2002)	1997-1999	16	Saudi Arabia	638
Liu et al. (2002)	NA	10	NA	NA
Neal-Sturgess (2002)	NA	4	United Kingdom	NA
Zajac & Ivan (2003)	1989-1998	12	United States	278
Ballesteros et al. (2004)	1955-1999	3	United States	2942
Lefler & Gabler (2004)	1995-2000	2	United States	31260
Roudsari et al. (2004)	1994-1998	7	United States	542
Matsui (2005)	1994-1998	7	United States	62
Lee & Abdel-Aty (2005)	1999-2002	15	United States	4351
Simms & Wood (2006)	NA	5	NA	NA
Simms & Wood (2006a)	NA	3	NA	NA
Sze & Wong (2007)	1991-2004	17	Hong Kong	73746
Abdel-Aty et al. (2007)	1999-2003	14	United States	451
Kim et al. (2008)	1997-2000	18	United States	5808
Eluru et al. (2008)	2004	10	United States	60000
Yao et al. (2008)	NA	10	NA	10
Zhang et al. (2008)	1994-1998	9	United States	312
Untaroiu et al. (2009)	NA	4	NA	NA
Clifton et al. (2009)	2000-2004	15	United States	4695
Kong & Yang (2010)	2003-2009	5	China	104
Kim et al. (2010)	1997-2000	18	United States	5808
Helmer et al. (2010)	1994-1998	18	United States	376
Jang et al. (2010)	2002-2007	19	United States	5084
Rosén et al. (2011)	NA	1	NA	NA
Richards & Carroll (2012)	2008-2009; 2008; 2009; 2000-2010	1	United Kingdom	500
Gunji et al. (2012)	2000-2010	57	United Kingdom	205
Lyons & Simms (2012)	NA	2	NA	NA
Watanabe et al. (2012)	NA	5	NA	NA
Peng et al. (2012)	NA	4	NA	NA
Han et al. (2012)	NA	3	NA	NA
Badea-Romero & Lenard (2013)	NA	2	NA	NA
Aziz et al. (2013)	2002-2006	14	United States	4666
Mohamed et al. (2013)	2002-2006	24	United States	6896

Authors (year)	Study period	Number of variables analysed	Country	Samples
Mohamed et al. (2013)	2003-2006	5	Canada	5820
Zhao et al. (2013)	2006-2011	8	China	285
Islam & Jones (2014)	2006-2010	12	United States	1463
Zhao et al. (2014)	2006-2011	10	China	121
Sasidharan & Menéndez (2014)	2008-2012	17	Switzerland	12659
Yasmin et al. (2014)	2002-2006	9	United States	4701
Li et al. (2015)	NA	1	NA	NA
Haleem et al. (2015)	2008-2010	15	United States	3038
Iragavarapu et al. (2015)	2007-2011	17	United States	34620
Chen et al. (2015)	NA	2	NA	NA
Islam & Hossain (2015)	2010-2012	13	United States	2305
Pour-Rouholamin & Zhou (2016)	2010-2013	20	United States	14538
Špička et al. (2016)	2009-2014	2	Czech Republic	NA
Pour et al. (2016)	2004-2013	10	Australia	9872
Li et al. (2017)	2000-2015	13	Germany	594
Yin et al. (2017)	NA	5	NA	315
M. Kim et al. (2017)	2011-2013	9	Korea	137470
Kitali et al. (2017)	2009-2013	17	United States	1397
Wenjun et al. (2017)	2010-2014	2	China	105
Huang et al. (2018)	NA	6	NA	43
G. de Han et al. (2018)	NA	6	NA	18
Ma et al. (2018)	2011-2012	11	United States	2614
Uddin & Ahmed (2018)	2009-2013	10	United States	3184
Li et al. (2019)	2000-2015	6	Germany	1060
Nishimoto et al. (2019)	1096-2016	13	Australia	6868
Sun et al. (2019)	2006-2015	11	United States	14236
Hussain et al. (2019)	NA	1	NA	20
Pelet-Del-Toro et al. (2019)	2000-2014	4	United States	2093
Wang et al. (2019)	2000-2012	8	Germany	404
Y. Han et al. (2019)	NA	2	NA	NA
Moradi et al. (2019)	NA	27	NA	NA
Chakraborty et al. (2019)	2011-2016	7	India	NA
Mokhtarimousavi (2019)	2010-2014	11	United States	8573
Mokhtarimousavi et al. (2020)	2010-2014	13	United States	10146
Song et al. (2020)	2007-2018	17	United States	27091
Tang et al. (2020)	NA	3	NA	NA
Malin et al. (2020)	2014-2017	18	Finland	281
Kamboozia et al. (2020)	2014-2019	11	Iran	484
Su et al. (2021)	2011	22	Hong Kong	14884
Hosseinian et al. (2021)	2017-2019	12	Iran	6123
Y. Zhang et al. (2021)	NA	4	NA	NA
Rodionova et al. (2021)	2015-2021	8	Russia	13888

Authors (year)	Study period	Number of variables analysed	Country	Samples
Šarić et al. (2021)	2015-2018	11	Croatia	7155
Guo et al. (2021)	2006-2016	18	United States	856
Zhu (2021)	2016-2018	7	Hong Kong	3054
Chang et al. (2022)	2012-2019	8	Korea	147026
Lalika et al. (2022)	2016-2018	15	United States	913
Olowosegun et al. (2022)	2010-2018	10	United Kingdom	5156
Nasri et al. (2022)	2010-2019	16	Australia	10040
Darus et al. (2022)	2009-2014	15	Malaysia	2518
Tao et al. (2022)	1989-2021	9	Australia	52843
Rezapour & Ksaibati (2022)	NA	7	NA	811
Rella Riccardi et al. (2022)	2016-2018	28	United Kingdom	67356
Pineda-Jaramillo et al. (2022)	2009-2016	25	Colombia	27956

Table A2: Variable selection

Does	Describe Injury?	Influence Vehicle - Kinematics?	Influence Pedestrian - Kinematics?	Influence Injury?	Variable Category
Age	0	0	1	1	Control Variable
Age effect	0	0	0	0	Not Important
Behaviour	0	0	1	1	Control Variable
BMI	0	0	0	0	Not Important
Clothing visibility	0	1	0	0	Disturbance
Face direction angle	0	0	1	1	Control Variable
Gait	0	0	1	1	Control Variable
Gender	0	0	1	1	Control Variable
Education	0	0	0	0	Not Important
Height	0	0	1	1	Control Variable
Hip height	0	0	0	0	Not Important
IMD decile	0	0	0	0	Not Important
Injury location	1	0	0	0	Output
Intoxicated	0	0	1	1	Control Variable
ISS	1	0	0	0	Output
Job	0	0	0	0	Not Important
Language	0	0	0	0	Not Important
Nationality	0	0	0	0	Not Important
Number of pedestrians involved	0	0	1	1	Control Variable
Ratio height shoulder / ground rear hood op.	0	0	0	0	Not Important
Ratio body height / ground rear hood opening	0	0	0	0	Not Important
Ratio body height / ground base windshield	0	0	0	0	Not Important
Ratio body height / hood length	0	0	0	0	Not Important

Does	Describe Injury?	Influence Vehicle - Kinematics?	Influence Pedestrian - Kinematics?	Influence Injury?	Variable Category
Size	0	0	0	0	Not Important
Speed	0	0	1	1	Control Variable
Weight	0	0	1	1	Control Variable
Age	0	0	0	0	Not Important
Bonnet angle	0	0	1	1	Control Variable
Bonnet leading edge angle	0	0	1	1	Control Variable
Bonnet leading edge height	0	0	1	1	Control Variable
Normalised Bonnet leading edge height	0	0	0	0	Not Important
Bonnet end depth	0	0	0	0	Not Important
Bonnet length	0	0	1	1	Control Variable
Bonnet stiffness	0	0	1	1	Control Variable
Bumper bottom Height	0	0	0	0	Not Important
Bumper central Height	0	0	0	0	Not Important
Normalised Bumper central Height	0	0	0	0	Not Important
Bumper lower depth	0	0	0	0	Not Important
Bumper lower height	0	0	0	0	Not Important
Normalised Bumper lower height	0	0	0	0	Not Important
Bumper upper depth	0	0	0	0	Not Important
Bumper upper height	0	1	1	1	Control Variable
Normalised Bumper upper height	0	0	0	0	Not Important
Bumper stiffness	0	0	1	1	Control Variable
Bumper wrap around	0	0	0	0	Not Important
Driver age	0	1	0	0	Disturbance
Driver gender	0	1	0	0	Disturbance
Driver home area	0	0	0	0	Not Important
Driver IMD Decile	0	0	0	0	Not Important
Driver intoxicated	0	1	0	1	Control Variable
Driver Job	0	0	0	0	Not Important
Driver License Condition	0	1	0	0	Disturbance
Driver nationality	0	0	0	0	Not Important
Driver journey purpose	0	0	0	0	Not Important
Ground to base of windshield (wrap)	0	0	0	0	Not Important
Ground to top of windshield (wrap)	0	0	0	0	Not Important
Impact location	0	1	1	1	Control Variable
Impact Speed	0	1	1	1	Control Variable
Impact Speed (squared)	0	0	0	0	Not Important
Kinetic energy	0	0	0	0	Not Important
Manoeuvre	0	1	1	1	Control Variable

Does	Describe Injury?	Influence Vehicle - Kinematics?	Influence Pedestrian - Kinematics?	Influence Injury?	Variable Category
Number of vehicles involved	0	1	1	1	Control Variable
Rear hood opening distance	0	0	0	0	Not Important
Registration year	0	0	0	0	Not Important
Speed Ratio (Impact speed/Speed limit)	0	0	0	0	Not Important
Travel speed	0	1	0	0	Disturbance
Vehicle Engine (CC)	0	1	0	0	Disturbance
Vehicle propulsion	0	0	0	0	Not Important
Vehicle type	0	0	0	0	Not Important
Weight	0	1	1	1	Control Variable
Windscreen Angle	0	0	1	1	Control Variable
Windscreen stiffness	0	0	1	1	Control Variable
Year of manufacture	0	1	0	1	Control Variable
Area type	0	1	1	0	Disturbance
Clear roadway width	0	1	0	0	Disturbance
Control type	0	1	0	0	Disturbance
Crosswalk type	0	1	0	0	Disturbance
Hazard	0	1	1	0	Disturbance
Intersection type	0	1	1	0	Disturbance
Land Use	0	1	1	0	Disturbance
Nearby infrastructure	0	1	1	0	Disturbance
Node type	0	1	1	0	Disturbance
Number of lanes	0	1	1	0	Disturbance
Number of roads	0	1	1	0	Disturbance
Obstruction	0	1	1	0	Disturbance
On-street parking	0	1	1	0	Disturbance
Park lane	0	1	1	0	Disturbance
Pavement type	0	1	1	1	Control Variable
Pavement surface condition	0	0	1	1	Control Variable
Road class type	0	1	0	0	Disturbance
Road geometry	0	1	0	0	Disturbance
Road marking	0	1	1	0	Disturbance
Road Network	0	1	0	0	Disturbance
Road surface condition	0	1	1	1	Control Variable
Road surface material	0	1	1	1	Control Variable
Road type	0	1	0	0	Disturbance
Road width	0	0	1	0	Disturbance
Shoulder type	0	0	1	0	Disturbance
Special circumstance	0	1	1	0	Disturbance
Speed limit	0	1	1	0	Disturbance
Traffic aids	0	0	0	0	Not Important
Traffic congestion	0	1	1	0	Disturbance
Population age	0	0	0	0	Not Important
Accident Location	0	0	0	0	Not Important

Does	Describe Injury?	Influence Vehicle - Kinematics?	Influence Pedestrian - Kinematics?	Influence Injury?	Variable Category
Accident type	0	1	1	1	Control Variable
Alcohol involvement	0	0	0	0	Not Important
Average annual daily traffic	0	0	0	0	Not Important
Contributory factor	0	0	0	0	Not Important
Day of week	0	0	0	0	Not Important
Direction of impact	0	1	1	1	Control Variable
Education	0	0	0	0	Not Important
Ethnicity	0	0	0	0	Not Important
Fault	0	0	0	0	Not Important
First harmful event	0	1	1	1	Control Variable
Household income	0	0	0	0	Not Important
Household size	0	0	0	0	Not Important
Humidity	0	1	1	1	Control Variable
Lighting	0	1	1	0	Disturbance
Month	0	0	0	0	Not Important
Population	0	0	0	0	Not Important
Road Density	0	0	0	0	Not Important
Time of day	0	0	0	0	Not Important
Visibility	0	0	0	0	Not Important
Weather	0	0	0	0	Not Important
Temperature	0	1	1	1	Control Variable
Year	0	0	0	0	Not Important
Zone area (km2)	0	0	0	0	Not Important
Ambulance Rescue	0	0	0	0	Not Important
Avenue	0	0	0	0	Not Important
Borough/District	0	0	0	0	Not Important
Camera distance	0	1	0	0	Disturbance
Camera land use	0	0	0	0	Not Important
Contrecoup pressure	0	0	0	0	Not Important
Coup pressure	0	0	0	0	Not Important
Cumulative strain damage measure	0	0	0	0	Not Important
Dilatational damage measure	0	0	0	0	Not Important
Distance from GPO	0	0	0	0	Not Important
Hit and run	0	1	0	0	Disturbance
Number of bus stops	0	0	0	0	Not Important
Number of hotels	0	0	0	0	Not Important
Number of metro exits	0	0	0	0	Not Important
Number of non-signalized intersections	0	0	0	0	Not Important
Number of restaurants	0	0	0	0	Not Important
Number of schools	0	0	0	0	Not Important
Number of shopping malls	0	0	0	0	Not Important

Does	Describe Injury?	Influence Vehicle - Kinematics?	Influence Pedestrian - Kinematics?	Influence Injury?	Variable Category
Number of signalized intersections	0	0	0	0	Not Important
Percentage of trucks	0	0	0	0	Not Important
Shear stress	0	0	0	0	Not Important
Total crashes	0	0	0	0	Not Important
Trip generation (per day)	0	0	0	0	Not Important
Von Mises stress	0	0	0	0	Not Important
Walking frequency (per day)	0	0	0	0	Not Important

Appendix B
Appendix_A-Variable_Vs_Study.xlsx

Appendix C
Appendix_B-Meta-analysis.docx

Appendix D
Appendix_C-Variable_Selection_Criterion_Justification.docx