The impact of traffic flow distribution over arms at junctions on crash risk

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Abstract

In locations where primary and secondary roads cross, the distribution of traffic flow over the arms of a junction can introduce a potential road safety risk. Although the road traffic flow is a frequently considered variable, it is not easy to make a definitive conclusion about the specific effect that the distribution of traffic flow over the arms of a junction has on safety outcomes. This is due to the different variables that published studies use to express the specific risk factor. The aim of the present research is to (i) provide a literature overview of the phenomenon and to (ii) attempt to overcome said uncertainty by conducting a meta-analysis on the effects of traffic flow distribution over arms at junctions. Findings show that where there is an increase in: (i) the traffic volume on the minor or major road, or (ii) the number of turn lanes, crash frequency tends to increase. Where there is a significant flow imbalance between the junction branches (i.e. major and minor roads), mixed results were found in the literature, with crash rates both increasing and decreasing. Meta-analysis findings show that the amount of traffic flow of the secondary road can result in an increase in the number of crashes at a 95% confidence level. This conclusion can be exploited to inform principles of junction design that can consequently improve road safety.

Keywords: Traffic flow distribution; traffic volume split; junction arms; signalized junction; secondary road; meta-analysis.

1. Introduction

Although junctions constitute an important part of any transportation system, they are characterised by a complex nature. Over the years, a substantial effort has been invested to comprehensively review and better understand junctions in order to inform safer and more efficient designs [17]. Such investigations have identified that both geometric features (four-arm, three-arm, or other junction types) and traffic characteristics (e.g. traffic flow), influence the safety at junctions in terms of the number of crashes occurring.

Traffic flow is defined as the number of vehicles passing a point per unit of time; often called volume, when the time unit is one hour. The traffic flow distribution over arms at junctions refers to the allocation of the traffic across the branches of a junction or the traffic volumes on the major versus the minor road and it is usually expressed as AADT (Annual Average Daily Traffic). Traffic flow is relevant for both signalised and non-signalised junctions. Different types of roads (e.g. major or minor) can cross at a junction, and each road presents its own unique traffic flow. This difference between the flows, at the point the roads intersect, constitutes the distribution of traffic flow over arms of junctions. The greatest magnitude of this difference could be when a major road meets a minor one, while the greatest volume of traffic interaction can occur in case two major roads cross.

Road features and traffic characteristics are amongst the most important factors that can influence the number of annual crashes occurring at a particular junction. At road junctions, speeds are typically low, especially in urban areas, which results in traffic characteristics playing the predominant role in crash frequency [32]. Relying on the expected safety benefits of low speeds and underestimating the importance of the traffic flow distribution over arms at junctions could be disastrous.

The relationship between speed and traffic flow is complex. In light traffic conditions, speed is relatively stable while traffic flow increases. High traffic volumes generate more vehicle interactions and conflicts which may result in higher collision rates [4], [34]). In high traffic density, flow and speed decrease, resulting in a reduction in both crash frequency and crash severity due to the lower flow and speed respectively [4], [22]. In the case of an intersection, increased flows of crossing traffic streams can produce increased delays, resulting not only to an increased driving time, but also to a higher crash occurrence probability [13]. A traffic flow imbalance between the approaches of different roads (particularly when a major and minor road cross), the number of turning lanes, the junction control type (i.e. signalised or non-signalised) and a difference between the major and minor road's traffic volume can cause a significant change in crash occurrence and severity [3], [2], [20], [11].

Distribution of flow over arms at junctions constitutes a very specific risk, usually absorbed from the total entering traffic volumes in a junction. Several studies have employed multivariate statistical models with multiple explanatory variables. Across these studies the distribution of flow is examined in several forms, including: natural logarithm of AADT on the major road [17], ratio of major road AADT to minor road AADT [1], flows on the approach streets of an intersection [16], ratio of the minor approach traffic volume to the major approach traffic volume [11], incoming motor vehicle traffic from the primary and secondary direction [15], percentage of minor road traffic [20] and minor approach right-turn lanes traffic volume [24]. Moreover, the studies often compare junction control type (i.e. signalised and non-signalised junctions). A common approach to investigate the relationship between the split of traffic volumes and the number of crashes is to apply Poisson and negative binomial models (e.g. Greibe [15], Kulmala [20], Castro et al. [3] whereas for crash severity a binary probit framework is most commonly employed [17].

Within the literature distribution of flow over arms at junctions is rarely the sole focus of a study. However, there is a growing body of work which considers this risk factor as part of a suit of variables used for crash prediction modelling. Haleem & Abdel-Aty [17] reported that as the natural logarithm of AADT on the major road increases, the severe injury probability reduces. Earlier, Golias [12] tried to establish relationships between the expected number of crashes and the flows of the traffic streams passing through a junction. The main conclusion of the study was that the dominant factor influencing the crash potential of an urban junction is an expression of the interacting traffic stream flows. Moreover, Greibe [15] developed crash prediction models for junctions taking into consideration the traffic flow of major and minor road and stated that motor vehicle traffic volume was the most significant variable. Similar statement was made by Wang and Abdel-Aty [31], who found that the logarithm of the product of conflicting flows was usually the most significant factor in their models. This shows that the crash frequency is associated with the traffic flows to which the conflicting vehicles travel and not to the sum of the entering flows. Furthermore, Ferreira and Couto [11] reported that when the difference between major and minor traffic volume increased or decreased, the crash risk was expected to change significantly. This is supported by another study that proved that a higher imbalance in traffic flow is connected with a lower crash propensity [3]. Agbelie & Roshandeh [1] examined the ratio of the traffic volume on the major road to the traffic volume of the minor road and proved that as this ratio increases, the crash frequency also increases. An increase of road traffic on the minor road was also found to have similar effects on crash rate in the study by Kulmala [20] while similarly, lead to a significant increase in pedestrian-involved crashes; a higher traffic volume on the minor road presents considerable conflicts with pedestrian movements whose attention is mostly on the primary road [33].

There is some evidence to suggest that crash frequency at junctions is associated with the number of right turning lanes on minor street approaches [24], as well as, with the left turning traffic flow on the major approach [16]. For crashes between a left turning vehicle and an opposing vehicle going straight crash frequency tended to increase as (1) the number of opposing lanes increased, (2) the opposing and left-turn ADTs (Average Daily Traffic counts) increased, and (3) the speed limit for the opposing traffic increased [31].

The aim of the present paper is to evaluate the effect of the distribution of traffic flow over arms at junctions. A systematic search and meta-analysis will synthesise findings from the scientific literature. Specifically, the influence of the differences between junction conflicting flows in crash frequency and severity will be considered. To the best of authors' knowledge, there has not been any attempt before to summarise findings regarding the safety effect of traffic volume split at junctions.

2. Methodology

2.1 Literature search strategy

The search strategy focused on identifying the most relevant and recent studies which considered the risk factor distribution of flow over arms at junctions. Two data bases were searched for recent literature on the risk of distribution of traffic flow over arms at junctions: Scopus and TRID. The searches for all the queries were limited to Title-abstract-keywords. The search terms were methodically chosen and combined with the suitable operators to provide all the relevant records.

Within Scopus, after the search was completed papers related to the subject areas Biochemistry, Genetics and Molecular Biology, Neuroscience, Pharmacology, Toxicology and Pharmaceutics, Chemistry, Physics and Astronomy, were excluded. An additional filter was put to exclude papers before 1990. 202 potentially relevant papers were identified. The same search terms and filters were used in TRID, where 22 additional papers were identified.

In total, 224 research studies (202 from Scopus and 22 from TRID) were manually screened (title and abstract) for relevance to the risk factor of interest. However, the risk factor is so specific that often screening of the full text was necessary in order to identify if a paper was truly relevant. 155 studies were excluded after screening due to irrelevance or lack of detail related to the specific topic of distribution of flow over arms at junctions. A full text examination of 35 papers was completed. After full text examination 8 studies were identified as being specifically relevant to the topic and presenting findings to a level of detail necessary for meta-analysis. The present work was carried out within the framework implemented in the SafetyCube project which aimed to create the European Decision Safety Support System (DSS). Further information is available in published studies regarding the full methodology of the study screening process, selection criteria and the DSS are available in published studies [21], as well as regarding the review and comparative assessment of infrastructure related crash risk factors [23], which the present examined topic falls into.

2.2 Meta-analysis and meta-regression methods

The term meta-analysis refers to a statistical analysis of a set of numerical research results of studies aiming to develop a single weighted overall mean result and identify sources of systematic variation in individual results. A meta-analysis can help to combine the results from several studies, if these results are produced under comparable conditions and under a similar framework. A step further is a meta-regression analysis which systematically compares input study characteristics and explains any heterogeneity in present effects by the significance of each study characteristic (e.g. study year, area, unit of analysis etc.).

In systematic reviews, publication bias can occur; publication bias refers to the omission of relevant study results from meta-analyses, which reduces their robustness. The reason for this omission is that these results might be unpublished or counterintuitive [19]. Funnel plots can be used to visualize the presence of heterogeneity and publication bias by contrasting the input estimates by their respective standard errors (described in Rothstein et al. [26]).

There are several techniques for meta-analysis. The theoretical background illustrated here can be found in more detail in Elvik and Bjørnskau [10]; Hedges and Olkin [18]; Van Houwelingen et al. [29]; Viechtbauer [30]. The reader is also encouraged to refer to Elvik [8] and Elvik [9], who provide detailed overview of carrying out meta-analyses. Overall, in the field of road safety several informative meta-analyses already exist (e.g. Elvik [6], [7], [9], [10]; Theofilatos et al. [27]. For detailed information on meta-regression techniques, the reader is also encouraged to refer to Theofilatos et al. [28].

The following is a brief overview of the methods used. To summarize research results in a concise and comprehensive manner, inverse-variance is commonly utilized by assigning to each risk estimate a statistical weight proportional to its sampling variance. The summary mean of g individual estimates is:

$$Summary\ mean = \bar{Y} = \frac{\sum_{i=1}^{g} Y_i * W_i}{\sum_{i=1}^{g} W_i} \qquad ((1)$$

Where $\sum_{i=1}^{g} Y_i * W_i$ is the sum of the products $Y_i * W_i$(effect size multiplied by weight) and $\sum_{i=1}^{g} W_i$ the sum of the weights. The statistical weight W_i is:

$$W_i = \frac{1}{SE_i^2} \qquad (2)$$

Where SE_i^2 is the squared standard error of the combined effect. The inverse-variance technique allows two model specifications: (i) the fixed effects model and (ii) the random effects model.

In fixed effects meta-analyses, if *i=1,…,n* are independent effect size estimates, the true effect θ_i is the (unknown) true effect, and ε_i is the corresponding sampling error, y_i is the observed effect in the i-th study and is given as follows:

$$y_i = \theta_i + \varepsilon_i \qquad (3)$$

Conversely, random effects meta-analyses are used to account for potential heterogeneity. The true effect θ_i has the components of u_i and μ. The parameter u_i follows a normal distribution with mean value μ and variance τ^2.

$$\theta_i = u_i + \mu \qquad (4)$$

If τ^2 equals zero, then the true effects are assumed to be homogenous (i.e. $\theta_1 = \theta_n = \theta_i = 0$). Finally, the Q statistical test is performed to determine whether there is systematic between-study variation in results:

$$Q = \sum_{i=1}^{g} W_i * Y_i^2 - \frac{(\sum_{i=1}^{g} W_i * Y_i)^2}{\sum_{i=1}^{g} W_i} \qquad (5)$$

Where Q is an estimate of variance, chi-square distributed with g – 1 degrees of freedom. The meta-analyses and meta-regression implemented here are conducted in the R software (R Development Core Team, 2008) and specifically following the metafor package [30].

3. Analysis and Results

3.1 Qualitative analysis of studies

The effect of the differences between traffic flow distribution on two or more converging arms at a junction that has been identified can be summarized as follows:

- 1 study with a significant decrease in the number of crashes (when the flow imbalance is higher)

- 5 studies with a significant increase in the number of crashes (when there is an increase to: the minor or major road traffic, the number of turning lanes, the ratio of major road traffic to the minor road traffic)
- 1 study that presents a positive and two negative effects on crash rate (major road through-traffic, major road left turn-traffic, minor road through-traffic)
- 1 study with a weak decrease in crash severity (at a 90% level), (when the natural logarithm of AADT on the major road increases)

It is important to note that there is no fixed variable used to measure the risk factor of distribution of traffic flow over arms at junctions. Instead, the statistical approach to measure the effect varies between studies. Therefore, all studies that referred to the imbalance of traffic flows between the branches of a junction or the primary or secondary road traffic were taken into consideration. An overview of considered studies is provided on Table 1; US studies are reported with the specific state due to possible fluctuations between areas.

The risk factor of distribution of flow over arms at junctions has not been investigated under a broad range of conditions. All the studies use regional data and most of them are from U.S.A. Most of the studies consider the urban environment only and do not take different road users into account. In each case, the effect of distribution of flow over arms at junctions is statistically significant, but there are many other different variables which are also included in the models that affect the final result (region, number of turning lanes, movements, lighting conditions, etc.). Therefore, the transferability of the results can be considered to be limited. Outcomes and main findings of the examined studies are presented on Table 2. Road Safety Impacts are considered to be negative if the risk factor increases either crash occurrence and/or crash severity and positive in the opposite case.

Table 1: Description of considered studies

Author & Year	Country	Risk factor	Method	Measure of effect
Greibe [15]	Denmark	Traffic flow on primary and secondary road	Generalized linear model-Poisson distribution	Elasticity
Kulmala [20]	Finland	Percentage of minor road traffic and overall traffic flow	Generalized linear model-Poisson (and negative binomial distribution)	Elasticity
Castro et al. [3]	USA (Texas)	Flows on the approach streets for each intersection	Generalized ordered-response model	Elasticity
Pulugurtha & Nujjetty [24]	USA (North Carolina)	Minor approach right-turn lanes	Generalized linear model-Negative binomial distribution	Correlation coefficient & Slope
Guo et al. [16]	USA (Florida)	ADT of each intersection approach (major/minor roads) [Signalised junctions]	Bayesian models (Poisson CAR model)	Slope
Ferreira & Couto [11]	Brazil	Ratio of the minor/major approach traffic volumes [Signalised junctions]	Random-effect Poisson model	Slope
Agbelie & Roshandeh, [1]	USA (Illinois)	Ratio of major road AADT to minor road AADT [Signalised junctions]	Random-parameters negative binomial model	Marginal effect
Haleem & Abdel-Aty, [17]	USA (Florida)	AADT on the major road [Unsignalised junctions]	Binary probit model	Marginal effect & difference (%)

3.2 Meta-analysis results

A meta-analysis has been carried out in order to determine the overall estimate of traffic flow distribution over arms at junctions on crash frequency. More specifically, the minor road's traffic for 3-arm and 4-arm junctions was examined for this study in 2 separate meta-analyses. The reasons for this decision are that:

1. A minimum required number of effects for each type of junction is achieved (3). It should be noted that two effects were reported in the same study but were considered separately. The studies finally considered for the meta-analysis are: Greibe [15] and Kulmala [20].
2. The studies have used the same model specifications (Poisson distribution)
3. The sampling frames were similar
4. The measure of effect was the same (elasticity)

Table 2: Main outcomes of considered studies

Author & Year	Outcome variable	Road Safety Impacts	Main outcome description
Greibe [15]	Crash frequency	Negative	Models that relate crash occurrence with traffic flow and road design (95% CI).
Kulmala [20]	Crash frequency	Negative	As minor road traffic portion increases, crash rate increases (95% CI).
Castro et al. [3]	Crash frequency /year/intersection	Positive	Lower crash propensity associated with higher flow imbalance (No CI).
Pulugurtha & Nujjetty [24]	Crash frequency	Negative	The number of turn lanes generally tend to increase crashes at an intersection (95% CI).
Guo et al. [16]	Crash frequency	Positive, Negative, Negative,	(95% CI): (i) For one standardized unit of increase in major through-traffic expected crash rate will drop by a multiplicative factor (ii) For one unit increase the crash rate will increase by a multiplicative factor (iii) For one unit increase for through-traffic per lane on minor roads, the crash rate will increase by a multiplicative factor.
Ferreira & Couto [11]	Crash frequency	Negative	When the difference between major and minor traffic volume increases or decreases, the crash risk is expected to change significantly; when the proportion approaches zero the crash risk is high.
Agbelie & Roshandeh [11]	Crash frequency	Negative	For most of the intersections, increasing the ratio of traffic volume on the major road to this on the minor road will increase accident frequency. A unit increase in this ratio would increase crash frequency by a multiplicative factor (No CI).
Haleem & Abdel-Aty [17]	Crash severity	Positive	As the natural logarithm of AADT on the major road increases, the severe injury probability reduces (90% CI).

The results of the meta-analysis suggest a significant negative effect of secondary road traffic at junctions on road safety (both for 3-and 4-arm junctions) at the 95% confidence level. This means that an increase of secondary road traffic at junctions is translated to an increase on crash numbers. Figures 1 and 2 present the forest plots for the estimates of elasticity for 3-and 4-arm junctions respectively.

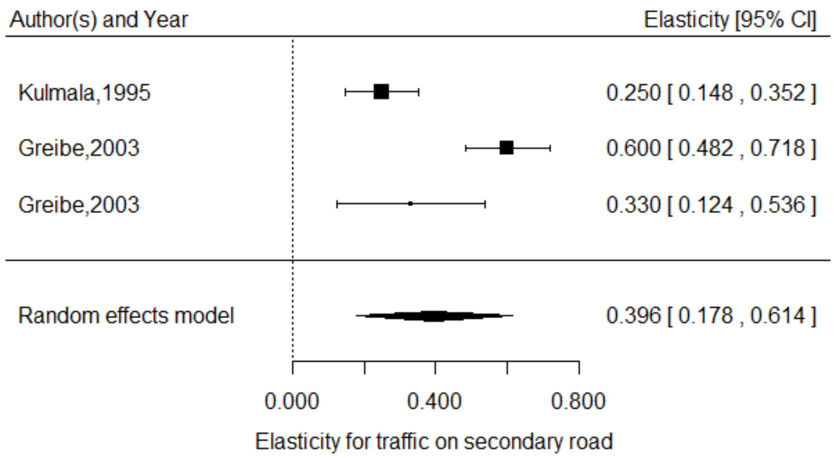

Figure 1: Forest plot for 3-arm junctions

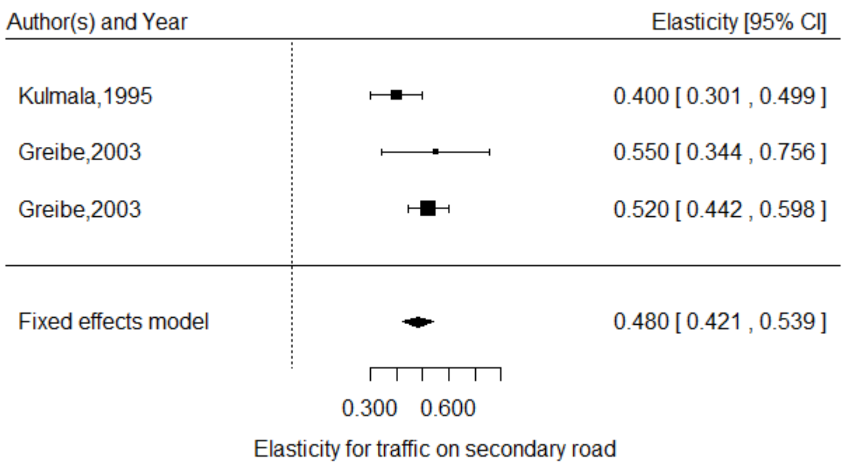

Figure 2: Forest plot for 4-arm junctions

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of secondary road traffic flow at junctions on crash frequency and for 3-arm junctions is 0.396, while the 95% confidence intervals are 0.1775 and 0.6142 (Table 3). The p-value (<0.001) indicates a significant effect referring to an increase in the number of crashes.

Table 3: Random effects meta-analysis on crash frequency for secondary road traffic flow at 3-arm junctions.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Secondary road traffic flow	ADT	0.396	0.1114	<0.001	(0.1775, 0.6142)

The Q test is significant (Q= 19.8804, p-value<0.0001) suggesting that considerable heterogeneity exists among the true effects, and thus the random-effects model was warranted. The value of I^2 indicates that 87.46% of the total variability in the effect size estimates can be attributed to heterogeneity among the true effects. A funnel plot was produced in order to detect potential publication bias. No publication bias was detected. The regression test for funnel plot asymmetry was not significant at a 95% level (p-value = 0.9429), suggesting no publication bias. The funnel plot for 3-arm junctions appears on Figure 3.

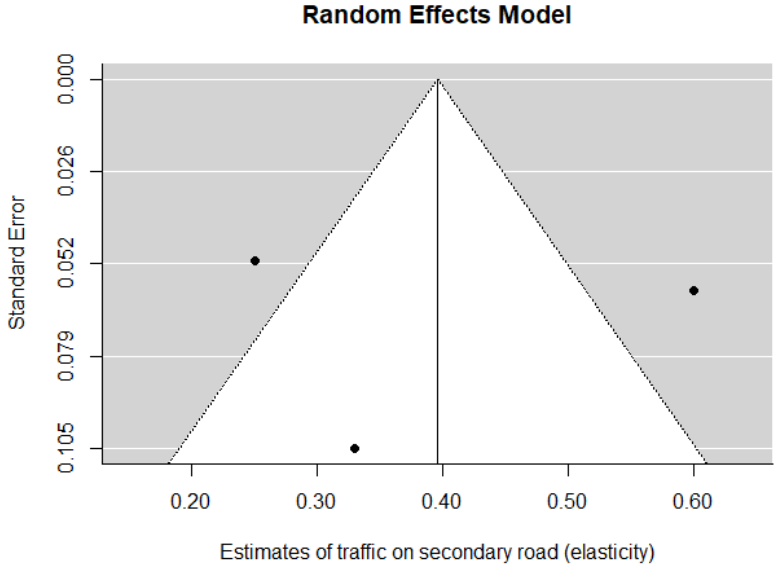

Figure 3: Funnel Plot for crash frequency (effect of secondary road traffic at 3-arm junctions).

Regarding 4-arm junctions, results of the fixed-effects meta-analysis on crash frequency indicate that the overall estimate of the effect of the traffic on secondary road is 0.480, while the 95% confidence intervals are 0.4212 and 0.5390 (Table 4). The p-value (<0.0001) indicates a statistically significant increase in crashes.

Table 4: Random effects meta-analysis on crash frequency for secondary road traffic flow at 4-arm junctions.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Secondary road traffic flow	ADT	0.480	0.0301	<0.0001	(0.4212, 0.5390)

The Q test is not significant (Q= 3.9441, p-value=0.1392) indicating that there is no considerable heterogeneity among the true effects, thus a fixed meta-analysis was warranted. A funnel plot was produced in order to detect potential publication bias. No publication bias was detected. The regression test for funnel plot asymmetry was not significant at a 95% level (p-value = 0.9554), therefore the effects did not show presence of publication bias. The funnel plot for 4-arm junctions is presented in Figure 4.

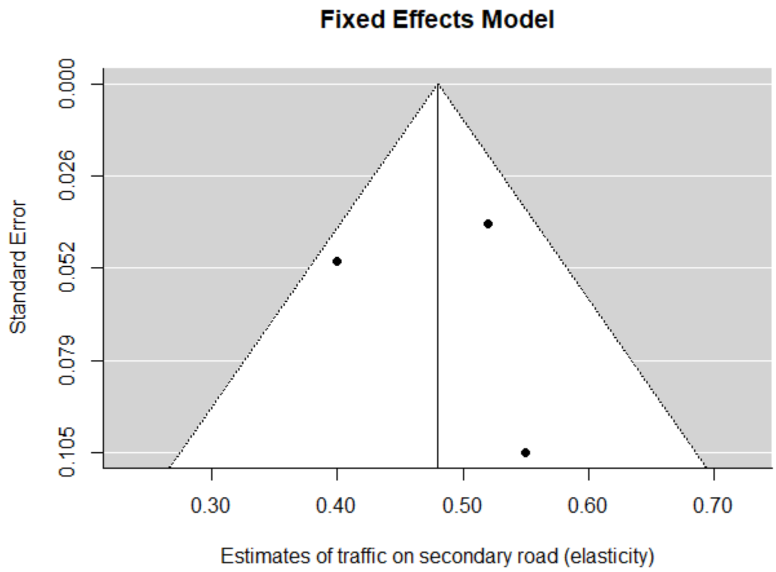

Figure 4: Funnel Plot for crash frequency (effect of secondary road traffic at 4-arm junctions).

Lastly a meta-regression was carried out, in order to identify the impact of individual study characteristics on the overall estimate of traffic. In the meta-regression, the variables “Year” and “Type of Junction” (3- vs 4-arm) were considered as independent variables in the model. However, due to the low number of estimates (6), this analysis should be considered as complementary only and its results should be interpreted with caution. The overall results are illustrated on Table 5. More recent estimates tend to report greater impacts of traffic flow on crash frequency, as the “Year” variable has a positive coefficient (significant at a 95% level). The type of junction was not found to be influential.

Table 5: Meta-regression for the impact of individual study characteristics on the overall estimate of the secondary road traffic flow.

Variable	Estimate	Std. Error	p-value	95% CI
Constant term	-47.5976	20.4029	0.0197	(-87.5866, -7.6086)
Year	0.0240	0.0102	0.0185	(0.0040, 0.0440)

4. Discussion

The current paper employed meta-analysis in order to consolidate findings from the literature related to the safety impact of distribution of flow over arms at junctions. After a systematic search, the most relevant papers were identified, and these providing the appropriate details for the analysis were chosen. The sample size is limited as, while most studies used multivariate methods to estimate the effect of distribution of flow over arms at junctions, the distributions used and variables included differ considerably. As a result, the risk factor is expressed with different variables in different studies. Despite these difficulties, studies of sufficient similarity were selected in order to undertake meta-analysis on 3 arm and 4 arm junctions regarding the secondary traffic flow and crash frequency.

The impact of traffic flow is a critical risk factor for both crash frequency and crash severity. The way that traffic volumes are distributed over the different branches of a junction influences road safety as it affects both the driving time and complexity. A traffic flow imbalance [3] or in other words, a large difference between the major and minor road’s traffic volume (e.g. Ferreira and Couto, [11]) and the number of turning lanes [24] are two factors which are particularly influential for both crash occurrence and severity. In the considered international studies, the effect of traffic distribution over arms at junctions on road safety has been investigated using crash frequency (number of crashes) and crash severity (severity of injuries of occupants given that a crash has occurred).

Ultimately, two meta-analyses were completed, one random effects meta-analysis for 3-arm junctions, and one fixed effects meta-analysis for 4-arm junctions. The results of both meta-analyses suggest that a higher traffic volume of a secondary joining road leads to a significant increase in crash frequency for both 3- and 4-arm junctions at a 95% confidence level. Concerning crash frequency, the estimate of the elasticity for 3-arm junctions was 0.396 (p-value = 0.0004) and for 4-arm junctions was 0.480 (p-value<0.0001).

The risk factor examined here is a special case where the relevant variables, used in different studies to express it, differ. This is the first meta-analysis of studies including the particular risk factor and a first attempt to quantify a part of the widely reported safety effect of traffic flow in junctions. This review included studies that suggest an unequal traffic flow between the branches of a junction or studies examining the effect of increasing or decreasing flow of the major or minor road in a junction. The analysis of the studies showed that the difference in traffic flows between the arms of a junction has a significant effect on road safety. Overall, by reviewing the data available on the distribution of traffic flow over arms at junctions and synthesising the results of the homogenous studies, it is confirmed that the increase on secondary road traffic flow, could lead to a significant increase in the number of crashes.

The limitations of this approach should be mentioned as well. With only two studies, and thus two respective regions in the meta-analysis, results are considered to be of reduced transferability. Furthermore, results from more sophisticated statistical methods (such as CAR models) cannot be meta-analyzed due to a lack of application for the specific topics in the literature. Finally, a fruitful process would be the examination of flow distributions in signalized versus non-signalized junctions, and the comparison of the findings. Unfortunately, the low number of published studies, in these regards, indicates research gaps in the topic of distribution of flow over junction arms, which can be considered as directions for further study. With more relevant research, the meta-analyses results can be improved to be more precise, more robust and more transferable.

5. Conclusions

This study has taken a step further our understanding of the importance of the distribution of traffic flow over arms at junctions regarding road safety. From the review of the considered studies and the synthesis of the results, a more robust conclusion can be drawn about the effect of this special risk factor. It has been confirmed that an increase on the secondary road traffic signifies an increase in crash numbers and that traffic flow imbalance in a junction affects considerably its safety. This knowledge gained can be proved beneficial for the road safety of junctions if applied to future road design and especially, if integrated to junction design principles.

Acknowledgment

The authors would like to thank all the partners involved in the “Infrastructure” work package of the SafetyCube project (WP5) for their valuable comments on earlier drafts of this research.

Funding

This paper was based on work carried out within the SafetyCube research project of the Horizons 2020 programme of the European Commission - INEA (Grant number 633485). The sole responsibility for the content of this publication lies with the authors and does not reflect the opinion of the European Commission.

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