A meta-analysis of crash risk factors in freeway entrance and exit areas

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Abstract

Entry and exit areas are considered critical parts of freeways and expressways. In order to meet traffic safety and operation requirements, it is important that ramps and speed change lanes have the appropriate design so that vehicles may complete sequential maneuvers. However, literature on risks associated with these freeway elements is limited and has often demonstrated contradictory results. The present research meta-analyses the effects of ramp and speed change lanes characteristics on crash outcomes. A random-effects meta-analysis was conducted on the effect of ramp length on crash severity and a non-significant overall effect and a significant positive overall effect are observed respectively. Similarly, random-effects meta-analyses regarding deceleration lane length suggested a non-significant effect on road safety (both frequency and severity) at a 95% level of confidence. Overall, there is no indication of strong publication bias in any of the meta-analyses performed. Overall, the results suggest that, although several studies reported significant effects of these design elements on road safety, there is a need for further research especially in a broader geographical context, due to heterogeneous results.

Keywords: speed change lanes; ramps; road crashes; meta-analysis.

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Introduction

Freeways are core parts of the road network in each country. Because of the full control of access on freeways, traffic movement into and out of freeways is allowed only through interchanges. Freeway interchanges are systems of minor roadways designed to connect two or more major roadways. An interchange typically consists of ramps and speed change lanes.

Exit ramps are the only controlled accesses from motorways to secondary or minor roads and they generally include a section of curvature. More specifically, ramps are connected to mainline freeways by speed change lanes that allow entering and exiting vehicles to speed up (acceleration lane) or slow down (deceleration lane) without conflicting with ongoing traffic on the freeway mainline areas. In general, these freeway diverge areas in the vicinity of exit ramps are considered to be critical elements as intensive lane changing maneuvers due to exiting traffic can take place. Merging and diverging traffic at interchanges can result in increasing driver workload and errors (Fatema et al. 2014).

In order to meet traffic safety and operation requirements, it is important that ramps and speed change lanes have the appropriate design and capacity so that entering and exiting vehicles complete sequential maneuvers. Ramp length is the factor most commonly examined in the literature as a risk factor. In general, it is intuitive that short ramps may cause road crashes because in this case the driver does not have the time to adjust the speed appropriately. A recent study found that exit ramps are risk areas where more crashes on freeways tend to occur (Chimba et al. 2006). Although the effect of ramp type is adequately examined in the literature, there is limited available information regarding the impact of ramp length on crash occurrence and severity (Chen et al. 2009 and 2011, Li et al. 2012).

It is also expected that speed change lanes (i.e. acceleration and deceleration lanes) could be more risky than the freeway mainline section (Federal Highway Administration 2010). When traffic approaches the freeway diverge areas, exiting vehicles need to diverge to the deceleration lanes in order to exit the freeway mainlines. Similarly, when traffic enters the freeway mainline areas, entering vehicles have to accelerate in order to meet the operating speed of the freeway. Early literature indicated that increased lengths of deceleration lanes would reduce crashes (Bared et al. 1998, Cirillo 1970, Lundy 1967). Nevertheless, more recent research on this topic indicates the opposite effect (Chen et al. 2009 and 2011, Garnowski and Manner 2011). Another study conducted by Garcia and Romero (2006) found that long deceleration lanes would encourage drivers to further accelerate before they exit the freeway. Mixed or non-significant impacts still exist in recent studies (Cheng et al. 2012, Wu et al. 2014) and thus the overall impact on road safety is unclear.

Therefore, the main objective of the present study is to carry out a thorough review of related studies and to perform meta-analyses where possible on the effects of freeway entry and exit elements on crash outcomes. It is thus aimed to provide overall estimates of the effects of a) ramp length and b) acceleration and/or deceleration lane length on crash frequency and crash severity. To the best of the authors' knowledge, this is the first attempt to carry out such analyses for freeway entrance and exit areas.

The rest of the paper is organized as follows: section 2 concerns the methods and data used in this research; the selection criteria for the considered studies and the related meta-analysis methods are described. In section 3, the selected studies are presented and assessed in terms of their analysis methods and findings, and the results of the meta-analyses performed follow. Detailed tables including quantitative results of each study are also presented in order to complement the meta-analyses. In section 4 the conclusions of the study are presented and discussed.

Data

Literature review and study selection criteria

This paper aims to proceed beyond a typical literature review and to attempt to provide meta-estimates of the effects of the examined risk factors. For that purpose, a dedicated set of study selection criteria were defined, with focus on high quality studies and quantitative effects (SafetyCube 2016):

- Existing meta-analyses were sought.
- Studies with quantitative findings and statistical models reporting standard errors were highly sought.
- Number of crashes or severity of crashes were preferred over other indirect outcomes indicators (e.g. speed measurements).
- Recent and high quality studies reporting estimates of the examined effects were prioritized. More specifically, only recent papers (after 1990) in the field of Engineering were initially considered.
- Journal papers were preferred over conference papers. However, highly informative conference papers and reports were included when necessary.
- No “grey” literature was examined.

It should be underlined that the literature strategy in this paper focused on studies that examined the examined freeway design elements as risk factors. For instance, other literature proposing countermeasures to improve road safety in ramp or diverge areas was not considered, e.g. studies investigating the effects of ramp or deceleration lane treatments.

The databases searched were Scopus and Transport Research International Documentation (TRID). The search terms used for ramp length were *interchange* OR *ramp length* OR *interchange ramp length* AND *casualties* OR *fatalities* OR *traffic safety* OR *crash* OR *crash risk* OR *severity* OR *frequency* OR *collision* OR *incident* OR *accident*. For acceleration and deceleration lane length, the search terms were *acceleration lane* OR *deceleration lane* AND *casualties* OR *fatalities* OR *traffic safety* OR *crash* OR *crash risk* OR *severity* OR *frequency* OR *collision* OR *incident* OR *accident*. The references list of each study was also assessed to find relevant studies that may have not be found during the initial searching. A title and abstract screening was first implemented to identify the relevant studies. A full text screening was then carried out (219 articles in total) to identify the 13 studies meeting the selection criteria for the topics of this research.

Meta-analysis

Meta-analysis is a statistical analysis of a set of numerical research results of studies aiming to develop a 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. In the field of transportation safety several meta-analyses have been carried out (Elvik 1994, 2001, 2011, 2013, Phillips et al. 2011).

There are several techniques for meta-analysis. The theoretical background illustrated here can be found in more detail in (Berkey et al. 1995, Elvik and Bjørnskau 2017, Hedges and Olkin 1985, Van Houwelingen et al. 2002). The most commonly applied technique in road safety is the inverse variance technique. Each estimate of the effect of a risk factor or a safety measure is assigned statistical weight which is inversely proportional to its sampling variance. The reader is encouraged to refer to Elvik (2005), who provides an introductory overview of carrying out meta-analyses and to Elvik (2011) who illustrates issues arising when studies are few when performing a meta-analysis.

The results of meta-analyses are normally reported in terms of one or more summary estimates of effect, i.e. weighted mean estimates using the inverse of sampling variance as weight. The summary estimate of risk or effect based on g individual estimates is:

$$\text{Summary mean} = \bar{Y} = \frac{\sum_{i=1}^{g} Y_i \cdot W_i}{\sum_{I=1}^{g} W_i} \qquad \text{(Eq. 1)}$$

where, $\bar{Y}$ is the summary estimate (estimate of the weighted summary mean), based on i individual estimates, each of which is assigned a statistical weight W_i:

$$\text{Statistical weight} = W_i = \frac{1}{SE_i^2} \qquad \text{(Eq. 2)}$$

In our study, following Elvik (2005) and Elvik and Bjornskau (2017), the term Y_i in Eq. 1 denotes the coefficient estimate in study i, while the term SE_i denotes the standard error of a coefficient.

In general, in fixed effects meta-analyses, if i=1,…,n independent effect size estimates, each is estimating a corresponding true effect size.

$$y_i = \theta_i + \varepsilon_i, \qquad \text{(Eq. 3)}$$

where y_i is the observed effect in the i-th study, θ_i is the corresponding (unknown) true effect, εi is the sampling error (εi~N(0,vi)). As a result, all the y_i's are assumed to be unbiased and normally distributed estimates of their corresponding true effects. Note that the sampling variances vi are assumed to be known.

However, variability (or heterogeneity) can be present among true effects. Elvik (2005) provides a very good overview of dealing with heterogeneity in meta-analyses. One solution to treat potential heterogeneity is by carrying out a random effect meta-analysis model (i.e. genuine differences underlying the results of the studies). Other options include a sub-group analysis or a meta-regression. However, the candidate studies to be included in our paper were few for such types of analysis, and thus the typical random-effects meta-analysis was followed.

In contrast to the traditional fixed effect meta-analysis approach that assumes that the true effect is the same in all studies, the random-effects meta-analysis is a typical approach when significant heterogeneity is present and is frequently applied by researchers (e.g. Elvik, 2016; Elvik and Bjornskau, 2017). This is because when a group of studies is included in a meta-analysis there is generally no indication to assume that they are "identical" in the sense that the true effect size is exactly the same in all these studies. Consequently, instead of assuming that there is one true effect, we allow that there is a distribution of true effect sizes (Borenstein 2007). Under the random effects model the true effect sizes are distributed about a mean with a variance that reflects the actual distribution of the true effects about their mean. Following Borenstein (2007), in random effects meta-analysis each study will be weighted by the inverse of its variance similar to the fixed effects approach, but a core difference is that the variance now includes the original (within-studies) variance plus the between-studies variance, t2.

More specifically, the true effect θ_i is:

$$\theta_i = \mu + u_i, \quad \text{(Eq. 4)}$$

where μ is the mean of all true effects and u_i reflects the distribution of true effects around their mean and follows a normal distribution with mean value zero and (between-studies) variance τ^2. If τ^2 equals zero, then the true effects are assumed to be homogenous (i.e. $\theta_1=\theta_2=\ldots\theta_n=0$).

To determine whether there is systematic between-study variation in results, the following statistical test is performed:

$$Q = \sum_{i=1}^{g} W_i \cdot Y_i^2 - \frac{\left(\sum_{i=1}^{g} W_i \cdot Y_i\right)^2}{\sum_{i=1}^{g} W_i} \quad \text{(Eq. 5)}$$

where Q is an estimate of variance, chi-square distributed with g – 1 degrees of freedom. If Q is significant, the variance between studies is larger than would be expected on the basis of the within-study variation. Whether Q is significant or not depends – next to the heterogeneity – also on the sample size. With a very large sample, Q would practically always be significant and with a very small sample almost never. Therefore, it has been suggested to calculate the percentage of variance that is due to heterogeneity between studies I^2. This expresses the percentage of the variability in effect estimates that is due to heterogeneity rather than sampling error (which is random):

$$I^2 = \left(\frac{Q-(g-1)}{Q}\right) * 100\% \quad \text{(Eq. 6)}$$

Publication Bias in meta-analysis

As Rothstein et al. (2005) state, publication bias occurs whenever the research that appears in the published literature is systematically unrepresentative of the population of completed studies. This could happen if for example researchers avoid to publish insignificant findings or if their findings differ from the initial hypotheses. Consequently, there is danger of making wrong conclusions if the results of the available research differ from the results of all the research that has been done in an area (Rothstein et al., 2005).

A way to test for publication bias is the visual inspection of the funnel plot in order to identify potential asymmetric structure. A funnel plot is a tool used to visualize results of exploratory meta-analyses (Elvik and Bjørnskau 2017), in which the estimate of interest (e.g. slope, odds ratio, relative risk) is plotted on the horizontal axis, while the standard error is plotted on the vertical axis. Therefore, if studies with non-significant or small effect remain unpublished, an asymmetric funnel plot will be generated (Sterne and Egger 2001, Rothstein et al. 2005). Another rather quantitative way to test for publication bias is to test whether the effects are related with their standard errors. This can be tested via the regression test proposed by (Egger et al. 1997).

Then, if publication bias finally exists, the trim-and-fill method which is non-parametric, can estimate the number of studies missing from a meta-analysis due to asymmetric funnel plot, correct for publication bias and produce the new corrected meta-estimates (Duval and Tweedie 2000a and 2000b, Duval 2005). In the present research, the need to control for publication bias is more pronounced, given the small number of studies available in the literature and the presence of rigorous study selection criteria.

Results

Assessment of selected studies on ramp risks

The literature revealed that the crash risk parameter usually explored is “ramp length”. It is normally set as a numerical variable and measured in kilometers, miles, feet or meters. After screening of literature, seven studies were initially selected to be considered for meta-analysis. Three of these studies investigated crash frequency (Chen et al. 2011 and 2014, Garnowski and Manner 2011) and three crash severity (Li et al. 2012, Wang et al. 2009, Zhang et al. 2011). One study (Wang et al. 2015) investigated the probability of crash occurrence.

In crash frequency models, the relationship between ramp length and number of crashes is investigated with Poisson or Negative binomial models, while in crash severity studies the ordered probit models are applied. Crash risk is defined as the probability of crash occurrence and was examined with Bayesian logistic regression models. It is interesting that the vast majority of research concerns the Florida State, US. Therefore, potential transferability of results is questionable.

Two out of three studies (Chen et al. 2011 and 2014), which examine crash frequency, indicate a significant effect on ramp length. More specifically, Chen et al. (2011) developed a Poisson model for crash frequency on one-lane exits and found a negative effect of insufficient ramp length. Chen et al. (2014) investigated only motorcycle crashes and indicated that as ramp length increases more motorcycles crashes tend to occur. Therefore, the effect appears to be different for motorcycle crashes than for all passenger vehicles. On the other hand, Garnowski and Manner (2011) utilized regional data from Germany and found no effect of ramp length on the number of crashes.

All studies that investigated crash severity used regional data in the US, applied the same statistical models (ordered probit models) and found consistent results. They state that increased ramp length causes an increase in crash severity. However, while Wang et al. (2009) and Li et al. (2012) found strong effects at a 95% level, Zhang et al. (2011) did not find strong effect (significant at a 90% level only). Wang et al. (2015) investigated the risk of single- and multi-vehicle crashes in expressways in Central Florida. The authors did not find any significant impact of ramp length. Table 1 illustrates an overview of the main features of the selected studies (sample, method, outcome and results).

Table 1 to be inserted here

On the other hand, Table 2 provides more detailed results for each study (authors, year, outcome indicator, quantitative estimate and effect on road safety). Overall, it is observed that mixed effects of ramp length on road safety exist, especially for crash frequency. On the other hand, increased ramp length seems to cause more severe injuries, however 1 out of 3 studies report a 90% level of significance.

Table 2 to be inserted here

Assessment of selected studies on speed change lane risks

The literature search strategy was the same followed for ramp length. Although journal papers were preferred, conference papers of high quality and other informative reports were considered (e.g. Bauer and Harwood 1998). Usually, there is a clear distinction between acceleration and deceleration lanes. However, most of existing literature has a focus on deceleration lanes on freeway exit areas. One possible explanation is that it is expected that freeway exit areas are of particular risk. The reason is that safety issues can be expected if drivers are forced to reduce speed on the main traffic lanes or to decelerate at a very high rate (El-Basha et al. 2007). Therefore, the complexity is likely to be higher than when entering the freeway via the acceleration lanes.

The influence of acceleration and deceleration lane length on road safety has been mainly investigated on the basis of crash frequency (number of crashes occurred). The influence of deceleration lane length on crash severity (no injury, possible injury, non-incapacitating injury, incapacitating injury, fatality) has also been studied but rarely (Wang et al. 2009 and 2011). A number of studies though examine the frequency of fatal, injury and property damage crashes separately (Bared 1999, Bauer and Harwood 1998, Wu et al. 2014).

In order to examine the underlying relationships between speed change lanes and outcome indicators, studies deployed advanced statistical models. For example, Wu et al. (2014) deployed Generalized estimating equations with temporal correlation to find the relationship between deceleration lane length and number of fatal crashes. However, not all studies developed statistical models but relied on more simple methods instead, such as the Pearson correlation coefficient. On the other hand, crash severity is typically examined by applying ordered probit models. It is noted that a number studies do not report standard errors (Bared 1999, Bauer and Harwood 1998, Sarhan et al. 2008) and could not therefore considered for meta-analysis.

Summing up, ten studies of sufficient quality were selected and considered for potential meta-analysis. Eight of them focused on the number of crashes (Bared 1999, Bauer and Harwood 1998, Chen et al. 2009, Chen et al. 2011, Cheng et al. 2012, Garnowski and Manner 2011, Sarhan et al. 2008, Wu et al. 2014) and two studies on severity of crashes (Wang et al. 2009 and 2011). No studies focusing on the direct relationship between probability of crash occurrence and deceleration/acceleration lane length were found.

The study area in most coded studies were a State in the US. Four studies (Chen et al. 2009 and 2011, Wang et al. 2009 and 2011) examine interchanges in the State of Florida. On the other hand, one study was carried out in Canada (Sarhan et al. 2008), one in German Autobahns (Garnowski and Manner 2011) and one in China (Cheng et al. 2012). Therefore, there is over-representation of US studies. Table 3 illustrates an overview of the main features of coded studies (sample, method, outcome and results). Table 4 provides more detailed results on each study. In general, it can be drawn from Table 4 that speed change lanes have heterogeneous effect on road safety outcomes similar to ramp length. However, it is notable that increased deceleration lengths lead to lower crash injury severity, but 1 out of 2 studies report that the results are significant only at a 90% level.

Table 3 to be inserted here

Table 4 to be inserted here

Meta-analysis of ramp length effects on crash outcomes

Due to the fact that studies of the ramp length influence on crash frequency were too heterogeneous, it was not possible to perform a meta-analysis. More specifically, these studies had applied different statistical models (i.e. Poisson vs negative binomial regression) with different specifications (fixed vs random parameter models). Consequently, effects of these studies could not be combined to produce overall meta-estimates of ramp length on crash frequency.

A meta-analysis has been carried out in order to find the overall estimate of the beta coefficient of ramp length on crash severity. The main reasons for this decision is that:

- A minimum required number of studies (or effects) was achieved (3)
- Studies used the same model (ordered probit model)
- Crash severity was measured in the same way (same 5-point scale)
- The sampling frames were similar.

Studies not reporting standard errors were not considered for meta-analysis. An important note considers the nature of these statistical models. Under the parallel lines assumption (proportional odds), the estimate (beta coefficient) of an independent variable is the same for all categories of crash severity (Washington et al. 2010). Therefore, a meta-analysis on the beta coefficient would make sense.

The studies used in the meta-analysis on the effect of ramp length on crash severity were the following: Li et al. 2012 (1 effect), Wang et al. 2009 (1 effect), Zhang et al. 2011 (1 effect).

Elvik and Bjørnskau (2017) mention a number of potential problems when attempting to carry out a meta-analysis on regression coefficients which are not encountered when meta-analyzing more simple effects such as odds ratios, relative risks etc. Card (2012), provides a list of such problems. Nevertheless, (Elvik and Bjørnskau 2017) argue that many examples of published meta-analyses in international literature do not adhere to restrictions of Card (2012). Following Elvik and Bjørnskau (2017), it was decided to perform a meta-analysis but results should be interpreted with care.

The overall estimate of the random effects meta-analysis showed a non-significant overall effect (estimate=0.1307, 95% CI [-0.0544, 0.3158], p-value=0.1663). This could be attributed to the fact that results in one study were significant only at 90% level. The τ^2 value was 0.1379 indicating the total amount of heterogeneity. I^2 indicates that 74.22% of the total variability in the effect size estimates can be attributed to heterogeneity among the true effects. The Q test is significant (Q=9.0894, p-value = 0.0106) suggesting considerable heterogeneity among the true effects. Therefore, the random-effects meta-analysis is considered appropriate.

The forest plot illustrates an overview of the overall estimates (Figure 1).

Figure 1 to be inserted here

Afterwards, a funnel plot was produced in order to detect potential publication bias. The funnel plot may be consider symmetric suggesting that publication bias is unlikely (see Figure 2). The regression test for funnel plot asymmetry was not significant at a

95% level (p-value = 0.0771), suggesting that despite the small number of studies there is no strong evidence for publication bias.

Figure 2 to be inserted here

Meta-analysis of speed change lane length effects on crash outcomes

In this section, the results of deceleration lane length on crash are illustrated. It was not possible to carry out a meta-analysis on the impact of acceleration lane length on crash frequency. The main reasons were: a) no distinction between acceleration or deceleration lane length was made in most of the available studies, b) when a distinction was made, no standard errors reported or, c) study designs were heterogeneous.

After applying the appropriate transformations, it was attempted to apply separate meta-analyses; a random effects meta-analysis for the effect of deceleration lane length on crash frequency and also a random effects meta-analysis for the effect of deceleration lane length on crash severity. In each meta-analysis, only studies which have similar design, outcome indicator and same model specification (i.e. fixed effects negative binomial models) were considered for further analysis. Studies not reporting standard errors were not included in the meta-analyses. The former meta-analysis revealed the estimate of the beta coefficient of deceleration lane length in the negative binomial model form, whilst the latter revealed the estimate of the beta coefficient of deceleration lane length in the ordered probit model form.

The final list studies included in the meta-analysis for the impact of deceleration lane length on crash frequency were the following: Chen et al. 2009 (2 effects), Chen et al.

2011 (1 effect). This is a typical random effects meta-analysis. The random effect was given to each study, however, a few studies had more than one coefficient, so the random effects meta-analysis can be considered to account for heterogeneity among coefficients.

On the other hand, the final list studies included in the meta-analysis for the impact of deceleration lane length on crash severity were the following: Wang et al. 2009 (1 effect), Wang et al. 2011 (1 effect). The same methodological limitation discussed in section 3.3 applies also to the meta-analysis of deceleration lane length effect. Moreover, although it would be better to have as much homogenous studies as possible, meta-analyses with fewer studies has also been recommended to be carried out (Roshandel et al. 2015) when the topic is of particular importance but less explored.

Effect on crash frequency

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of deceleration lane length on crash frequency (in Km) is 0.2156, while the 95% confidence intervals are -0.2558 and 0.6869 respectively. The p-value (0.3701) indicates a non-significant effect. The Q test is significant (Q= 9.838, p-value = 0.0073) suggesting that considerable heterogeneity exists among the true effects. Figure 3 presents the forest plots for the random effects analyses.

Figure 3 to be inserted here

No publication bias was found. The regression test for funnel plot asymmetry (Figure 4) was not significant at a 95% level (p-value = 0.0892).

Figure 4 to be inserted here

Effect on crash severity

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of deceleration lane length on crash severity (in Km) is -1.9383, while the 95% confidence intervals are -5.3446, 1.4680 respectively. The p-value (0.2647) indicates a non-significant effect. The forest plot is shown in Figure 5.

Figure 5 to be inserted here

The Q test is significant (Q= 10.6481, p-value = 0.0011) suggesting that considerable heterogeneity exists among the true effects. A funnel plot (Figure 6) was firstly produced in order to detect potential publication bias. No publication bias seems to exist. Due to low number of available studies this could not be further tested.

Figure 6 to be inserted here

Discussion

Table 5 summarizes the results of the present research.

Table 5 to be inserted here

The literature suggests that ramp length may increase crash frequency and severity. Concerning crash frequency the number of studies reporting quantitative estimates and their standard errors is limited, and the results are mixed. There appear to be some evidence that the effect is more important for motorcycle crashes compared to other vehicles. Results on crash severity are more consistent, suggesting an increased risk of injury severity on longer ramps, possibly due to higher speeds (possibly allowing for acceleration) on longer ramps.

The effect of acceleration and deceleration lane length on road safety is also rather unclear and needs further investigation. The influence on the number of crashes is unclear as studies show inconsistent findings. It is suggested that increased length of deceleration lanes are associated with lower crash severity, possibly due to smoother deceleration, but the impact of acceleration lanes has not been adequately investigated. Moreover, little is known about various road users; only one study focused on truck-related crashes.

Although in several studies significant effects are reported, none of the meta-analyses performed provided a significant overall estimate. This could be attributed to the fact the studies included in the meta-analysis were relatively few. Consequently, presence of inconsistent and heterogeneous estimates either in terms of magnitude or sign, could have a strong influence on the overall meta-estimate. Moreover, a number of effects considered were significant only for 90% level. However, the results become a basis for further research on these important topics.

Conclusions

Although the performance of freeway entrance and exit geometrical elements is considered critical for road safety, the number of relevant literature in the field is relatively limited, but most importantly has often led to inconsistent findings. The present paper focuses on existing literature examining the relationship between ramp length, acceleration and deceleration length and crash frequency and severity. The approach of the study is multi-dimensional as a qualitative analyses as well as meta-analyses were carried out. Tests for publication bias were also carried out for all performed analyses.

The results suggest that, although several studies found significant risks associated with these elements, the meta-estimates are non-significant and reveal the need for future research in this area. This may also suggest that the design and analysis methods of the existing studies should be thoroughly considered, especially when transferring the results to other contexts. For instance, ramp and diverge areas geometrical characteristics of study designs in the literature are not always the same (e.g. various ramp types, one-lane exits, two-lane exits etc.) and therefore transferability of results is questionable.

The meta-analyses revealed no strong existence of publication bias in the existing estimates; indeed several studies reported non-significant estimates, confirming that these findings are useful when attempting to summarize the knowledge on the overall effects of risk factors, and to transfer the results to other contexts or settings. An in-depth analysis of the study contexts and methods may shed some light to the conditions under which a risk factor is significant, even though the meta-estimate based on several studies may be non-significant.

Authors are aware of the limitations of the study. However, to the best of our knowledge, this was a first of meta-analyses to summarize findings of the selected studies and report the summary estimates of the effects from these analyses. This combined approach is considered by the authors the main contribution of the present study.

More studies investigating crash outcomes in these areas are needed in order to update and strengthen the present meta-analyses, especially with studies from other regions (e.g. Europe, Australia etc.), as well as to address characteristics that have not been sufficiently addressed (e.g. acceleration lane length on crash frequency and severity). However, it is proposed that if some studies are well-designed or are amongst the very few ones that investigate the impact of freeway entrance and exit areas on road safety, their results could potentially be interpreted as conclusive. For instance, Chen et al. (2014), reported that longer ramp lengths lead to more motorcycle crashes. Consequently, even if there could be no clear conclusion on the overall effect of ramp length on crash frequency due to inconsistent results (Chen et al. 2011, Garnowski and Manner 2011), it can be suggested that ramp length is risky for that specific road user type (motorcyclists).

When contradictory findings are present, researchers should carefully consider the evidence and state conclusions or hypotheses about where the weight of the evidence lies. Relying on meta-analysis may be misleading for this type of contradictory findings especially if some heterogeneous studies could not be added to the meta-analysis. Therefore another approach could be sought such as systematic review or best evidence synthesis. For instance, if it is desirable to conclude for the impact of ramp lengths/deceleration lane lengths in road safety overall, the qualitative analysis might be more appropriate to give an insight. On the other hand, if it is desirable to focus on a specific aspect of road safety (e.g. crash severity), the meta-analyses of this study provide some evidence. Therefore, results should be treated with caution.

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Table 1. Description of selected studies for meta-analysis of the effect of ramp length on road safety outcomes.

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Chen et al., 2011	One-lane exit ramps of Interchanges in the state of Florida, US. 352 crashes in 60 sites were considered.	Poisson model	in km	Crash frequency (number of crashes)	Longer exit ramps decrease the number of crashes for all passenger vehicles
Chen et al., 2014	4 exit ramp types in the state of Florida, US. (573 crashes at 419 total exits). Only motorcycles were considered.	Negative binomial model	in miles	Crash frequency (number of crashes)	Longer exit ramps increase the number of motorcycle crashes
Garnowski and Manner, 2011	3,048 crashes at 197 ramps in Germany interchanges.	Random parameter Negative binomial model	in meters	Crash frequency (number of crashes)	Non-significant effect of ramp length
Li et al., 2012	5,538 crashes at 326 segments in the state of Florida.	Ordered probit model	in miles	Crash severity* (5-point scale)	Longer ramps increase severity of crashes
Wang et al., 2009	10,946 crashes at 231 exit segments in the state of Florida, US.	Ordered probit model	in feet	Crash severity* (5-point scale)	Longer ramps increase severity of crashes
Zhang et al., 2011	5539 crashes 326 motorway segments in Florida, US.	Ordered probit model	in miles	Crash severity* (5-point scale)	Longer ramps increase severity of crashes (at a 90% level)
Wang et al., 2015	Crash and non-crash cases in three expressways in Central Florida, US.	Bayesian logistic regression	in miles	Risk of single- and multi-vehicle crashes	Non-significant effect of ramp length

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

Table 2. Summary results selected studies on the effect of ramp length on road safety outcomes.

Author(s), Year	Outcome indicator	Quantitative estimate	Effect on road safety
Bauer and Harwood, 1998	Crash frequency [number of crashes]	All crashes except rear-end: beta coefficient=4.41, CI[90%]=[2.3,6.56]	↑
		Fatal and injury crashes except rear-end: beta coefficient=2.98,CI[90%]=[0.79, 5.13]	↑
		Fatal and injury crashes: beta coefficient=2.9,CI[90%]=[1.21, 4.61]	↑
Chen et al., 2011	Crash frequency [number of crashes]	One lane exits: beta coefficient=-0.7575, p-value=0.0011	↓

Chen et al., 2014	Crash frequency [number of motorcycle crashes]	Beta coefficient=0.35, p-value=0.000	↑
Garnowski and Manner, 2011	Crash frequency [number of crashes]	Not retained in the final model	-
Li et al., 2012	Crash severity [no injury, possible injury, non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.1365, p-value=0.018	↑
Wang et al., 2009	Crash severity [no injury, possible injury, non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.0001, p-value=0.000	↑
Wang et al., 2015	Crash risk [probability of crash occurrence]	Not retained in the final model	-
Zhang et al., 2011	Crash severity [no injury, possible injury, non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.01783, p-value=0.063	↑

Table 3. Description of selected studies for meta-analysis of the effects of speed change lane length on road safety.

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Sarhan et al., 2008	26 interchanges along Highway 417 within the City of Ottawa, Canada for the period 1998-2002	Fixed effects negative binomial models	Acceleration and deceleration lane length (separately) in meters	Crash frequency (number of crashes)	Increased acceleration and deceleration lane lengths leads to reduced number of crashes
Bared, 1999	1452 crashes in Intestates in Washigton State, US., for the period 1993-1995	Fixed effects negative binomial models	Acc/dec lane length in miles	Crash frequency (number of fatal, injury and total crashes)	Increased acceleration and deceleration lane lengths leads to reduced number of crashes (at 90% level only)
Bauer and Harwood, 1998	13706 total crashes in 2000 ramps in Interstates at Washington State, US, for the period 1993-1995	Fixed effects negative binomial models	Acc/dec lane length in miles	Crash frequency (number of fatal, injury and total crashes)	Mixed effects of the effect of acceleration and deceleration lane lengths
Chen et al., 2009	7872 crashes at 424 freeway segments in the State of Florida, US, for the period 2004-2006.	Fixed effects negative binomial models	Logarithm of deceleration lane length in miles	Crash frequency (number of crashes)	Increased deceleration lane lengths leads to increased number of crashes
Chen et al., 2011	Crashes in 74 freeway segments in the State of Florida, US, for the period 2004-2006	Fixed effects negative binomial models	Deceleration lane length in kilometres	Crash frequency (number of crashes)	Increased deceleration lane lengths leads to increased number of crashes
Cheng et al., 2012	7013 crashes on a 200km freeway in China, between 2006 and 2008.	Pearson correlation coefficient	Acc/dec lane length in kilometers	Crash frequency (number of fatal crashes)	Mixed effects of the effect of acceleration and deceleration lane lengths
Garnowski and Manner, 2011	3048 crashes in 197 ramps, between 2003 and 2005) in Autobahns in Germany.	Fixed effects negative binomial models	Deceleration lane length (lower or higher than 180 meters)	Crash frequency (number of fatal crashes)	Deceleration lane lengths higher 180 meters are associated with increased number of fatal crashes
Wang et al., 2009	10946 crashes in Florida state, US for the period 2003-2006	Ordered probit models	Deceleration lane length in feet	Crash injury severity* (5-point scale)	Increased length of deceleration lanes reduces crash injury severity
Wang et al., 2011	4630 crashes in 391 freeway diverge segments in Florida state, US, for 2005-2008	Ordered probit models	Deceleration lane length in miles	Crash injury severity* (5-point scale)	Increased length of deceleration lanes reduces crash injury severity

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

Table 4. Summary results selected studies on the effect of speed change length on road safety outcomes.

Author(s), Year	Outcome indicator	Quantitative estimate	Effect on road safety risk
Sarhan et al., 2008	Crash frequency [number of crashes]	Deceleration lane length for all segments: beta coefficient=-0.0015	↓
		Deceleration lane length for weaving segments: beta coefficient=-0.0016	↓
		Acceleration lane length for all segments: beta coefficient=-0.002	↓
		Acceleration lane length for weaving segments: beta coefficient=-0.0014	↓
Bared, 1999	Crash frequency [number of crashes]	Acceleration/deceleration lane length: beta coefficient=-0.0014	↓
Bauer and Harwood, 1998	Crash frequency [number of crash]	Acceleration/deceleration lane length for fatal and injury accidents: beta coefficient=-4.45, CI[90%]=[-7.21,-1.91]	↓
Chen et al., 2009	Crash frequency [number of crashes]	Logarithm of deceleration lane length for one-lane exit ramps: beta coefficient=0.2345, p-value=<0.001	↑
		Logarithm of deceleration lane length for two-lane exit ramps: beta coefficient=0.3065, p-value=0.0873	↑
Chen et al., 2011	Crash frequency [number of crashes]	Deceleration lane length for one-lane exit ramps: beta coefficient=-0.7575, p-value=0.0011	↓
Cheng et al., 2012*	Crash frequency [number of total, fatal, incapacitating,non-incapacitating, no injury crashes]	Left-turn acceleration lane from crossroad to mainline freeway - Fatal crashes: correlation coefficient=-0.58, p-value=0.066	↓
		Left-turn acceleration lane from crossroad to mainline freeway - No injury crashes: correlation coefficient=0.5210, p-value=0.093	↑
		Left-turn deceleration lane from mainline freeway to crossroad-No injury crashes: correlation coefficient=0.0545, p-value=0.081	↑

Garnowski and Manner, 2011	Crash frequency [number of crashes]	Deceleration lane length>180m: beta coefficient=0.4352, standard error=0.1382	↑
Wang et al., 2009	Crash severity[no injury, possible/visible injury, no-incapacitating injury, incapacitating injury, fatal]	Deceleration lane length: beta coefficient=-0.0001, p-value=0.075	↓
Wang et al., 2011	Crash severity[no injury, possible/visible injury, no-incapacitating injury, incapacitating injury, fatal]	Deceleration lane length: beta coefficient=-2.3838, p-value=0.000	↓
Wu et al., 2014	Crash frequency [number of crashes]	Not retained in the final model	-

* Numerous other non-significant effects are reported in the study, e.g. correlation between left-turn deceleration lane from mainline freeway to crossroad and fatal crashes, correlation between acceleration lane from crossroad to mainline freeway and total crashes etc., but are not shown here for the economy of space.

Table 5. Overview of meta-analysis results.

Risk factor	**Road safety outcome**	**Number of selected studies**	**Number of studies reporting significant effects**	**Random effects meta-analysis estimate**	**Significance at 95% confidence level for random effects model**
Ramp length	Crash frequency	3	2	n.a	-
	Crash severity	3	3	0.1307	no
Deceleration lane length	Crash frequency	2	1	0.2156	no
	Crash severity	2	2	-1.9383	no
Acceleration lane length*	Crash frequency	4	3**	-	-
	Crash severity	n.a	n.a	n.a	-

* Three out of four studies do not distinguish between acceleration and deceleration lane.
** Usually mixed effects exist.
n.a: not available