Effect of traffic volume on road safety

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Please note: The studies included in this synopsis were selected from those identified by a systematic literature search of specific databases (see supporting document). The main criterion for inclusion of studies in this synopsis and the DSS was that each study provides a *quantitative effect estimate*, preferably on the number or severity of crashes or otherwise on road user behaviour that is known to be related to the occurrence or severity of a crash. Therefore, key studies providing qualitative information might not be included in this synopsis.

1 Summary

Hesjevoll, I.S., Elvik, R., August, 2016

1.1 COLOUR CODE: RED

Most of the reviewed studies find higher traffic volumes to be associated with a net increase in crashes. However, the crash increase is less than proportional to traffic volume increases, indicating a lower risk for each road user. The effect of traffic volume on crash occurrence appears to differ between crash types. The studies reviewed concern motorways.

1.2 KEYWORDS

Traffic flow; traffic volume; hourly volume; AADT; annual average daily traffic

1.3 ABSTRACT

Traffic volume, or traffic flow, denotes the number of vehicles passing a given point or section of a road for a given time unit. The relationship between crashes and traffic volume appears to be non-linear. Most reviewed studies find that higher traffic volumes are associated with a net increase of crashes. However, the number of crashes increases less than proportional to traffic volume. This indicates that an increase in traffic volume is associated with a lower risk for each road user (since risk = crashes/exposure). Several studies find that the effect of traffic volume on crash occurrence differs between crash types. For multi-vehicle crashes, most studies indicate that both the frequency *and* the risk of such crashes increase at higher traffic volumes. While it seems clear that traffic volume is related to crash occurrence, the form of this relationship (which might differ for different crash types), and the mechanism explaining these relationships remain somewhat unclear. It is also not clear how traffic volume affects road safety on different road types. The current results are mostly based on motorways, as this is what is currently available in the literature.

1.4 BACKGROUND

1.4.1 What is traffic volume, and how is it measured?

Traffic volume is the number of vehicles passing a cross section during a certain period (e.g. one hour, 5 minutes, or a day). Average annual daily traffic (AADT) is the number of vehicles passing a road in a year, divided by 365. Traffic volume estimates can be based either on continuous counting (traffic sensors), or short-term data collection adjusted for relevant variations (e.g. seasonal, weekday and hourly variations).

1.4.2 How does traffic volume affect road safety?

The mechanism relating traffic volume to crash occurrence is not clear. That is, while an increased traffic volume may lead to a net increase in crashes due to the presence of more vehicles (i.e. more crash candidates), it is not clear how the risk for each individual road user is affected by the total traffic volume. It has been proposed that it is not the number of vehicles per se, but the number of events (e.g. encounters) that is responsible for an association between exposure and crash occurrence (Elvik, 2015). Alternatively, driver alertness could be affected by traffic volume.

1.4.3 What road safety outcomes are affected by traffic volume?

Most reviewed studies investigate how traffic volume relate to crash counts, which is in some cases differentiated for different crash types (e.g. single-vehicle and multi-vehicle, or different severities). Other studies address how crash risk (the number of crashes divided by traffic volume) is affected by traffic volume.

1.4.4 How is the effect of traffic volume on road safety studied?

Two main types of methodologies are used to investigate the relationship between traffic volume and road safety. First, studies investigating the association between traffic volume and crash frequency are generally observational, cross-sectional studies employing multivariate models. The reviewed studies that fall into this category rely on aggregate traffic volume measurements (mostly AADT). A second main category of studies use a case-control design, comparing traffic conditions directly before crash occurrence (cases) to traffic conditions of non-crashes (controls). These studies typically rely on disaggregated, real-time data, and investigate both traffic volume and other traffic characteristics (e.g. occupation, speed). Most studies are based on motorways.

1.5 OVERVIEW OF RESULTS

Seven studies were coded for this risk factor. Among these were two meta-analyses based on studies comparing traffic volumes directly prior to crashes with volumes of non-crash controls.

1.5.1 Main results

The meta-analyses report contradictory results: One finds that higher volume downstream is associated with increased risk of crash occurrence, while the other finds the opposite. The main findings of the remaining studies are:

- Increased traffic volume is generally associated with increased crash occurrence, when all crashed are considered jointly.
- Most studies find increased traffic volume to be associated with a crash increase that is less than proportional to the traffic volume increase, which translates to a lower risk per road user at higher traffic volumes.
- The relationship between traffic volume and crash occurrence is different for different types of crashes. Results for Single-vehicle crashes are mixed. Multi-vehicle crashes appear to increase more than proportional to traffic volume (increased risk).
- Both the direction and the form of the relationship between traffic volume and crash numbers might differ between crash types.

Additionally, relevant results from studies primarily dedicated to other risk factors find that a higher AADT in work zones is associates with negative road safety outcomes, and in ramp/merging/ diverging areas, higher AADT on both the mainline and on the ramp is associated with increased crash occurrence, although in many cases lower risk.

1.5.2 Transferability

Most studies are based on major roads, leaving uncertainty regarding the effect of traffic volume on road safety for different road types. The summarized studies are mainly concerned with motor vehicles (all considered jointly), and the present tendencies might not hold for different road users (the volumes of (conflicting) flows of cyclists, pedestrians, and cars are dealt with in a synopsis on traffic composition). One might expect the effect of traffic volume on road safety to depend on factors such as road type, road capacity, weather, and other traffic characteristics (e.g. density, speed). The effect of AADT on road safety might also depend on how the traffic is distributed (e.g. if it is concentrated in peak-hours, or more continuous throughout the day).

1.6 NOTES ON ANALYSIS METHODS

While it seems clear that traffic volume is related to road safety, some limitations in the reviewed studies should be noted. Many studies rely on aggregate measures, which cover different levels of other risks (e.g. weather, lighting) that are often not accounted for. Furthermore, many studies do not distinguish between different crash types that are shown to relate differently to traffic volume, which could give a simplified or distorted picture of the actual associations of interest. The effect of traffic volume on real-time crash risk remains unclear, and more research in this area would be beneficial.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 On the measurement of traffic volume.

Traffic volume has been investigated on several levels of aggregation, including hourly and daily volumes, and 5-minute intervals. In investigating relationships between crashes and traffic volume, average, aggregated measures such as AADT (and to a lesser degree hourly averages), could be problematic in the sense that they "smooth out" variations and differences that could contribute to the actual crash. For instance, traffic variations over days, weeks, seasons and also over shorter time periods are covered up, and average traffic volumes will often differ from volumes at crash occurrence(s). Additionally, average daily traffic includes variations in other variables known to affect road safety (i.e. that are associated with different levels of risk), such as lighting conditions and weather. The distribution of traffic, e.g. if a given AADT is concentrated in peak hours or spread out more continuously, could also have different implications for road safety, but this is often not accounted for. In sum, this means that average daily measurement does not necessarily capture relevant traffic conditions, and this aggregation of traffic states and levels of other risk factors could produce biased results in investigating the relationship between traffic volume and road safety. For an in-depth explanation of issues arising in averaging traffic volume, see e.g. Mensah & Hauer (1998)

On the other hand, real-time traffic data is associated with different issues and potential biases, e.g. related to the placement of measurement devices (varying distances could mean one has to estimate traffic conditions, and could introduce statistical noise), missing or erroneous data, and temporal placement of crashes from imprecise police reports.

2.1.2 On mechanisms relating traffic volume to road safety

There seems not to be any generally accepted theory relating traffic volume, or exposure, to road safety. Elvik (2015) proposes that it may not be traffic volume as such, but rather the number of events (e.g. encounters, lane changes, overtaking) that is important for road safety. According to Elvik, the number of encounters will increase more rapidly than the AADT, and the repeated experience of a certain type of traffic event will be associated with learning, so that road users become increasingly competent in understanding and controlling the events. Another probable mechanism is the influence of traffic volume on driver alertness: on roads with higher traffic flows, drivers are constantly reminded of the presence of other vehicles, and more easily pay attention to them.

It might also be that for traffic volumes approximating congestion, reduced speed could mean that crashes become less severe. For instance, Golob et al. (2008) find that controlling for whether the traffic state is congested or free flow, a higher traffic volume is associated with a lower likelihood of crashes being injury crashes (vs PDO), which they suggest might be explained by lower speed as traffic becomes denser. This has not been investigated by any other of the reviewed studies. Congestion as a risk factor is treated in a separate synopsis (most congestion studies are conducted on motorways, where speed could remain high even in congested states, and so there is limited evidence for congestion reducing crash severity in studies reviewed for congestion), and with the exception of case-control studies, the studies reviewed for traffic volume generally do not take congestion or speed into account.

More generally, two identified reviews note that the effect of traffic volume could depend on weather conditions (Theofilatos & Yannis, 2014) and other traffic characteristics (such as speed and density) (Wang, Quddus, & Ison, 2013), which is not taken into account in most reviewed studies.

2.2 DESCRIPTION OF STUDIES

2.2.1 How is the effect of traffic volume studied?

Two types of original studies are found among the articles in this review. First, one type of study aims to identify traffic conditions associated with increased crash occurrence by comparing traffic conditions prior to crashes with those of non-crash control periods. These studies typically rely on real-time traffic data, aggregated to 5-minute intervals. The majority of primary studies on which the meta-analyses are based, as well as one section of an original study, fall into this category. Both meta-analyses focus on general/all crashes, and neither distinguished between different crash severities, and they include some of the same studies. One meta-analysis applies Bayesian meta-analysis methods (several varieties, including Bayesian meta-regression), while the other applied inverse variance meta-analysis, with fixed and random effects.

The second category of studies are cross-sectional studies that rely on multivariate crash prediction models to explain variation in crash numbers between locations (and in some instances across time units) by traffic volume, and the models often include other factors as well. The analyses applied are mostly count regression models (negative binomial, generalized negative binomial, zero-inflated Poisson, and Bayesian bivariate Poisson-lognormal). All five original studies coded primarily for traffic volume fall into this category. Three out of five studies model single-vehicle (SV) and multi-vehicle (MV) crashes separately (Lord et al., 2005; Yu & Abdel-Aty, 2013; Qin et al., 2004), and one of these also draw distinctions between different types of MV crashes. Two studies provide estimates of crash frequency per crash severity (Caliendo et al., 2007; Lord et al., 2005), and one study also looks into crash involvement for different driver demographics (Abdel-Aty & Rawdan, 2000). Most of these studies investigate AADT, but some make distinctions between AADT per lane and/or direction while others do not (or do not report if they do). One study investigates hourly volumes. Finally, one study reports both crash frequencies and a case-control analysis (Yu & Abdel-Aty, 2013).

2.2.2 How well has the effect of traffic volume been studied?

Most of the studies on which the meta-analyses are based are from the United States, and some are from Asian countries (e.g. Korea, China). They are all based on data from motorways, with a focus on general crashes (not specific types). Three of the five original studies are from the United States, one from Canada and one from Italy. All but one of these, which is based on a principal arterial, are based on data from motorways. While several studies indicate that different functional forms describe the relationships between traffic volume and different crash types, this was not done in all studies, and findings were somewhat mixed.

It should be noted that the study designs of the reviewed studies (mostly cross-sectional, or case-control) identify associations between traffic volume and crash numbers. However, their results do not in and by itself reveal whether this relationship is causal or not, i.e. whether the number of vehicles causes a change in risk or crash frequency, or if the association is better explained by some other mechanism.

2.2.3 Transferability

From the reviewed studies it is not clear how (/if) the effect of traffic volume on crash counts differ between road types, countries, and crash types. While many recent studies investigate how traffic volume, in addition to other traffic flow characteristics, relate to crash risk, the contradictory results of the two meta-analyses indicate that the relationship between crash risk and real-time traffic volume could benefit from further research. Reviews note that the effect of traffic volume is likely to depend on weather conditions and other traffic characteristics (such as speed and density), which is not taken into account in all reviewed studies. More research might be needed to establish this.

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

Results of seven studies reviewed for traffic flow, of which two meta-analyses, are summarized below. Additionally, many studies with main focus on other risk factors (reviewed for other SafetyCube topics) are summarized briefly. More details on these studies and their results can be found in the supporting document.

2.3.1 Results from meta-analyses

Two meta-analyses were identified, both concerned with studies assessing real-time crash risk of different traffic characteristics (e.g. speed variation and occupancy), including traffic volume. One of the meta-analyses only reports one summary estimate for volume, measured downstream of the crash (and non-crash control case) (Xu et al., 2015), while the other also includes studies in which it was not specified which sensor was used (could be either upstream or downstream, or nearest) (Roshandel et al., 2015).

Table 1. Overview of summary estimates for traffic volume from meta-analyses.

Detector placement	Summary estimates	Effect on crash risk	
		↗	↘
All	1	1	
Upstream	2	1	1
Not distinguished	1	1	

No non-significant results were reported. The meta-analyses report contradictory results for upstream volume. There is some overlap between the primary studies on which the meta-analyses are based, but also a few differences between the meta-analyses, such as the number of studies included, and the criteria applied for including primary studies (see supporting document for details). It is, however, not clear what best explains the conflicting results.

Issues related to the type of study included in the meta-analyses are noted by Roshandel, Zheng, and Washington (2015): First, the time intervals chosen to measure traffic appears to be chosen arbitrarily in most cases, which might have an impact on the estimated results. Second, most studies do not validate their models, and those who do show inconsistent performance and high prediction errors. Third, as most studies are not guided by a theoretical approach relating traffic characteristics to crash occurrence, it is not clear what traffic states should be associated with increased risk, which might lead to data-mining approaches identifying spurious relationships.

A more general issue with the two meta-analyses is that neither clearly specifies what types of models the estimates on which they are based were taken from. More specifically, it is not clear to what extent the traffic volume estimates origin from models controlling for other traffic characteristics, or if this could be an issue in estimating (and interpreting) a summary estimate. As an example, one might imagine that an effect estimate for traffic volume *controlled for* speed and occupancy could differ form an estimate in a model without these variables. While it is evident that the primary studies control for different confounding factors and focus on different traffic characteristics, it is not made clear if the summary estimates are the effect of volume *controlled for* e.g. occupancy and speed variation or not, or to what degree this could affect the results. This also means that it is not clear if the results are the effect of traffic volume *given* i.e. speed or not.

2.3.2 Vote-count analysis

Among the five original studies reviewed, none used the same (or largely similar) analyses, outcomes, and traffic volume indicators, rendering a meta-analysis infeasible. The results are therefore presented in the form of a vote-count analysis, in which each estimate gets one vote on the effect of traffic volume. The estimates included are one per main listed condition in each study. In this vote-count analysis, a vote could take four different values:

- An increase in crash frequency that is less than proportional to the volume increase, indicating a *higher number of crashes* in total, but *lower risk* per road user (↗).
- An increase in crash frequency proportional to, or more than proportional to the volume increase (↗↗), indicating *increased frequency and increased risk*
- A non-significant relationship (-)
- A decrease in crash frequency (which would also correspond to lower risk) (↘)

However, no studies showed increased volumes to be associated with a net decrease in crash frequency. The majority of estimates are for crash frequencies, and one set of estimates is based on real-time crash risk.

Table 2. Effects of traffic volume on road safety by crash type and traffic volume measurement.

	Estimates	Results (n estimates)			Results (% of estimates)		
		↗	↗↗	-	↗	↗↗	-
All crashes*							
Total	**7**	**7**			**100%**		
AADT	5	**5**			100%		
Hourly	2	**2**			100%		
Multi-vehicle							
Total	**7**	**2**	**4**	**1**	**28 %**	**57%**	**14 %**
AADT	4	2	2		50 %	50 %	
Hourly	2		2			100 %	
Single-vehicle							
Total	**4**	**3**		**1**	**75 %**		**25 %**
AADT	2	1		1	50 %		50 %

*Note: * refers to model results where all crashes are considered jointly. MV and SV estimates outlined in table are not included in "all crashes". The level of traffic volume aggregation is not presented for categories with one estimate only. Percentages could sum to less than 100 due to rounding effects.*

For the impact of traffic volume on all crashes considered jointly, all studies report that as traffic volume increases, the total number of crashes increases as well, but that this increase is less than proportional to the traffic volume increase, which translates to lower risk per road user (coefficient estimates range from 0.25-0.62). One of the studies finding such a result is Lord and colleagues (2005) who also report that the numbers of single-vehicle crashes decline at increasing volumes, but that multi-vehicle crashes increase more than proportional to the volume increase (increased risk).

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All studies that investigate crash frequency for SV and MV crashes separately find different relationships for multi- and single-vehicle crashes: SV crashes increase less than proportional to volume increase, but the results for MV crashes are more mixed. This is in part because Qin et al. (2004) report different results for different MV crashes: intersecting crashes are found to increase less than proportional to, opposite direction crashes increase proportional to, and MV crashes between oncoming vehicles increase more than proportional to volume increases.

There are a number of plausible reasons why the results would differ. First, differences in the level of aggregation at which traffic is measured could explain some between-study variation. For instance, Yu and Abdel-Aty find that increased AADT is related to a higher MV crash frequency, but unrelated to SV frequency. However, for a case-control analysis of real-time crash risk, volume is not related to MV crash risk, but a higher (downstream) volume increases the probability of SV crash risk. It may also be that the types of crashes considered or not considered (all/SV and MV; different types of MV), or actual differences in the investigated samples, for instance differences between countries, road types or other factors, could have contributed to the findings. While these explanations are not mutually exclusive, based on the reviewed studies it is not possible to say for certain which is most relevant.

One study finds that while heavy traffic volume increases the risk of crash involvement for all drivers, this effect is larger for females than for males, and also larger for young and older drivers than for middle-aged drivers (Abdel-Aty & Radwan, 2000).

2.3.3 Other findings

Results for the effect of traffic volume on road safety were also reported in studies reviewed for other SafetyCube risk factors. The results are presented in greater detail in the supporting document. The main findings are:

- In work zones, a higher AADT is associated with higher frequencies of both PDO and injury crashes. The same is found for crash rates (3 studies).
- A higher accumulated ADT over the construction period is related to a higher crash frequency, but crash frequencies increase at a decreasing rate (1 study)
- For ramp areas, a higher AADT both on the ramp and mainline is associated with an increased crash frequency (4 studies).
- A higher AADT is associated with increased crash severity in merging and diverging areas/exit ramp segments (3 studies).

5 studies with other main focus areas find less comparable results. Generally, most of the studies in which crash frequency is the outcome variable, higher volumes are associated with crash increases that are less than proportional to the volume increase.

2.4 CONCLUSION

Five primary studies and two meta-analyses were reviewed and summarized. The effect of traffic volume on crash frequency seems to be non-linear, with increased volume corresponding to more crashes, but lower risk. This means, for example, that if traffic volume increases from 5,000 to 10,000 vehicles per day, the number of crashes will not be doubled, but increase from, for example, 4 to 6. However, the results are somewhat inconsistent, and it remains unclear how traffic volume relates to real-time crash risk, and if differences in results are due to differences in studies areas, degree of aggregation, crash types considered or methodology. Thus, the effect of traffic volume on different types of crashes, as well as on different levels of crash severities, could benefit from more research. Additional results provided from studies dedicated to other risk factors mostly indicate that crash frequencies increase less than proportional to volume increases.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

The databases Science Direct, TRID and Taylor & Francis were used to identify relevant studies for traffic volume. Due to paper titles not being sufficiently informative, abstracts of potentially relevant papers were screened during the search, and potentially relevant studies were retrieved for full-text screening.

In addition to this focused search, the work on other risk factors also returned estimates for traffic volumes, identified and coded by other SafetyCube partners for other primary topics. While providing relevant results, these studies are mainly focused on factors other than traffic volume, and the results of these 21 studies are dealt with under a separate heading at the end of this document.

3.1.2 Principles

Limitations/exclusions for search in all databases:

- Title-ABSTR-KEY
- Journal articles and reports
- 2000-2016
- English language

3.1.3 Search terms and hits

Database: Science Direct **Date:** 15th of March 2016

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY ("AADT" OR "annual average daily traffic" OR "traffic volume" OR "hourly volume") AND TITLE-ABSTR-KEY(road OR accident* OR crash* OR injur* OR incident* OR risk OR safety)	482

Database: TRID (trid.trb.org) **Date:** 17th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(AADT OR "annual average daily traffic" OR "traffic volume" OR "hourly volume") AND (accident* OR crash* OR incident* OR injur* OR risk OR safety) [2000 onwards, only articles and reports, english only]	1407
#2	(accident* OR crash* OR incident* OR injur* OR risk OR safety) [+index terms AADT or traffic volume]	817

Database: Taylor & Francis **Date:** 17th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(AADT OR "annual average daily traffic" OR "traffic volume" OR "hourly volume")AND (accident* OR risk OR safety OR crash* OR injur* OR incident*)	1467

3.1.4 Screening and eligibility

A total of 23 studies were obtained and full-text screened. The following elimination criteria was applied:

- Included in meta-analyses identified
- Results not compatible with coding (i.e. unusual analysis)
- No crash data

3.1.5 Screening and prioritizing coding

Among the studies remaining, a lower priority for coding was assigned to those who:

- Had a main topic other than traffic flow/volume
- Grouped AADT (loss of information)
- Lack of reporting of methodological detail made interpretation of results difficult

Finally, a higher priority was given to meta-analyses, and studies from European countries. In the end, seven of the studies with the highest priority were coded and reviewed.

3.2 LIST OF CODED STUDIES

Studies coded primarily for AADT

Abdel-Aty, M. A., & Radwan, A. E. (2000). Modeling traffic accident occurrence and involvement. Accident Analysis & Prevention, 32(5), 633–642. doi:10.1016/S0001-4575(99)00094-9

Caliendo, C., Guida, M., & Parisi, A. (2007). A crash-prediction model for multilane roads. Accident; Analysis and Prevention, 39(4), 657–70. doi:10.1016/j.aap.2006.10.012

Lord, D., Manar, A., & Vizioli, A. (2005). Modeling crash-flow-density and crash-flow-V/C ratio relationships for rural and urban freeway segments. Accident Analysis and Prevention, 37, 185-199. doi: 10.1016/j.aap.2004.07.003

Qin, X., Ivan, J. N., & Ravishanker, N. (2004). Selecting exposure measures in crash rate prediction for two-lane highway segments. Accident Analysis & Prevention, 36(2), 183–191. doi:10.1016/S0001-4575(02)00148-3

Roshandel, S., Zheng, Z., & Washington, S. (2015). Impact of real-time traffic characteristics on freeway crash occurrence: systematic review and meta-analysis. Accident; Analysis and Prevention, 79, 198–211. doi:10.1016/j.aap.2015.03.013

Xu, C., Wang, W., Liu, P., & Li, Z. (2015). Calibration of crash risk models on freeways with limited real-time traffic data using Bayesian meta-analysis and Bayesian inference approach. Accident; Analysis and Prevention, 85, 207–18. doi:10.1016/j.aap.2015.09.016

Yu, R., & Abdel-Aty, M. (2013). Multi-level Bayesian analyses for single- and multi-vehicle freeway crashes. Accident; Analysis and Prevention, 58, 97–105. doi:10.1016/j.aap.2013.04.025

Studies coded for other topics (not fully integrated in synopsis, see final part of this document for details)

Bared, J., Giering, G. L., & Warren, D. L. (1999). Safety evaluation of acceleration and deceleration lane lengths. *Institute of Transportation Engineers. ITE Journal*, *69*(5), 50.

Chen, E., & Tarko, A. (2012). *Analysis of Work Zone Crash Frequency with Focus on Police Enforcement.* Paper presented at the Transportation Research Board 91st Annual Meeting.

Chen, E., & Tarko, A. P. (2014). Modeling safety of highway work zones with random parameters and random effects models. *Analytic methods in accident research*, *1*, 86-95.

Chen, F., Ma, X., & Chen, S. (2014). Refined-scale panel data crash rate analysis using random-effects tobit model. *Accident Analysis & Prevention*, *73*, 323-332.

Chen, H., Lee, C., & Lin, P.-S. (2014). Investigation Motorcycle Safety at Exit Ramp Sections by Analyzing Historical Crash Data and Rider's Perception. *Journal of transportation technologies, 2014*.

Chen, H., Liu, P., Lu, J. J., & Behzadi, B. (2009). Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. *Accident Analysis & Prevention*, *41*(3), 543-551.

Chen, H., Zhou, H., Zhao, J., & Hsu, P. (2011). Safety performance evaluation of left-side off-ramps at freeway diverge areas. *Accident Analysis & Prevention*, *43*(3), 605-612.

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Choi, J., Kim, S., Heo, T.-Y., & Lee, J. (2011). Safety effects of highway terrain types in vehicle crash model of major rural roads. *KSCE Journal of Civil Engineering, 15*(2), 405-412.

Daniel, J. R., & Maina, E. (2011). Relating Safety and Capacity on Urban Freeways. Procedia - Social and Behavioral Sciences, 16, 317–328.

Garnowski, M., & Manner, H. (2011). On factors related to car accidents on German Autobahn connectors. *Accident Analysis & Prevention, 43*(5), 1864-1871.

Khattak, A. J., Khattak, A. J., & Council, F. M. (2002). Effects of work zone presence on injury and non-injury crashes. *Accident Analysis & Prevention, 34*(1), 19-29.

Mergia, W. Y., Eustace, D., Chimba, D., & Qumsiyeh, M. (2013). Exploring factors contributing to injury severity at freeway merging and diverging locations in Ohio. *Accident Analysis & Prevention, 55*, 202-210.

Milton, J. C., Shankar, V. N., & Mannering, F. L. (2008). Highway accident severities and the mixed logit model: an exploratory empirical analysis. *Accident Analysis & Prevention, 40*(1), 260-266.

Montella, A., & Imbriani, L. L. (2015). Safety performance functions incorporating design consistency variables. *Accident Analysis & Prevention, 74*, 133-144.

Ozturk, O., Ozbay, K., Yang, H., & Bartin, B. (2013). *Crash frequency modeling for highway construction zones.* Paper presented at the Transportation Research Board 92nd Annual Meeting.

Rahman, M. M., Katan, L., & Tay, R. (2011). *Injury risks in collisions involving buses in Alberta.* Paper presented at the Transportation Research Board Annual Meeting, 90th, 2011, Washington, DC, USA.

Wang, Z., Cao, B., Deng, W., Zhang, Z., Lu, J. J., & Chen, H. (2011). Safety evaluation of truck-related crashes at freeway diverge areas. *Transportation Research Board*.

Wang, Z., Chen, H., & Lu, J. (2009). Exploring impacts of factors contributing to injury severity at freeway diverge areas. *Transportation Research Record: Journal of the Transportation Research Board*(2102), 43-52.

Wang, C., Quddus, M., & Ison, S. (2013b). A spatio-temporal analysis of the impact of congestion on traffic safety on major roads in the UK. Transportmetrica, 9935(July 2015), 1–25.

Wu, W.-q., Wang, W., Li, Z.-b., Liu, P., & Wang, Y. (2014). Application of generalized estimating equations for crash frequency modeling with temporal correlation. *Journal of Zhejiang University SCIENCE A, 15*(7), 529-539.

Yang, H., Ozbay, K., Ozturk, O., & Yildirimoglu, M. (2013). Modeling work zone crash frequency by quantifying measurement errors in work zone length. *Accident Analysis & Prevention, 55*, 192-201.

Studies screened full text, not coded based on elimination and/or prioritization criteria

Ayati, E., & Abbasi, E. (2011). Investigation on the role of traffic volume in accidents on urban highways. Journal of Safety Research, 42(3), 209–14. doi:10.1016/j.jsr.2011.03.006

Chen, C., & Xie, Y. (2016). Modeling the effects of AADT on predicting multiple-vehicle crashes at urban and suburban signalized intersections. Accident; Analysis and Prevention, 91, 72–83. doi:10.1016/j.aap.2016.02.016

Christoforou, Z., Cohen, S., & Karlaftis, M. G. (2012). Integrating Real-Time Traffic Data in Road Safety Analysis. Procedia - Social and Behavioral Sciences, 48, 2454–2463. doi:10.1016/j.sbspro.2012.06.1216

Haleem, K., Alluri, P., & Gan, A. (2015). Analyzing pedestrian crash injury severity at signalized and non-signalized locations. Accident; Analysis and Prevention, 81, 14–23. doi:10.1016/j.aap.2015.04.025

Jonsson, T., Ivan, J. N., & Zhang, C. (2007). Crash Prediction Models for Intersections on Rural Multilane Highways: Differences by Collision Type. Transportation Research Record, 2019, 91–98. doi:10.3141/2019-12

Karlaftis, M. G., & Golias, I. (2002). Effects of road geometry and traffic volumes on rural roadway accident rates. Accident Analysis & Prevention, 34(3), 357–365. doi:10.1016/S0001-4575(01)00033-1

Kononov, J., & Durso, C. (2012). Relationship Between Traffic Density, Speed, and Safety and Its Implications for Setting Variable Speed Limits on Freeways. Transportation Research Record: Journal of the Transportation Research Board, 2280, 1–9. doi:10.3141/2280-01

Kononov, J., Hersey, S., Reeves, D., & Allery, B. K. (2012). Relationship Between Freeway Flow Parameters and Safety and Its Implications for Hard Shoulder Running. Transportation Research Record: Journal of the Transportation Research Board, 2280(-1), 10–17. doi:10.3141/2280-02

Lee, C., Hellinga, B., & Saccomanno, F. (2003). Real-Time Crash Prediction Model for Application to Crash Prevention in Freeway Traffic. Transportation Research Record, 1840(03), 67–77. doi:10.3141/1840-08

Pande, A., & Abdel-Aty, M. (2009). A novel approach for analyzing severe crash patterns on multilane highways. Accident; Analysis and Prevention, 41(5), 985–94. doi:10.1016/j.aap.2009.06.003

Qin, X., Ivan, J. N., Ravishanker, N., Liu, J., & Tepas, D. (2006). Bayesian estimation of hourly exposure functions by crash type and time of day. Accident; Analysis and Prevention, 38(6), 1071–80. doi:10.1016/j.aap.2006.04.012

Roque, C., & Cardoso, J. L. (2014). Investigating the relationship between run-off-the-road crash frequency and traffic flow through different functional forms. Accident; Analysis and Prevention, 63, 121–32. doi:10.1016/j.aap.2013.10.034

Theofilatos, A., & Yannis, G. (2014). A review of the effect of traffic and weather characteristics on road safety. Accident; Analysis and Prevention, 72, 244–56. doi:10.1016/j.aap.2014.06.017

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Xu, C., Liu, P., Wang, W., & Li, Z. (2012). Evaluation of the impacts of traffic states on crash risks on freeways. Accident; Analysis and Prevention, 47, 162–71. doi:10.1016/j.aap.2012.01.020

Xu, C., Wang, W., Liu, P., & Zhang, F. (2014). Development of a real-time crash risk prediction model incorporating the various crash mechanisms across different traffic states. Traffic Injury Prevention, 16(1), 28–35. doi:10.1080/15389588.2014.909036

Zheng, Z., Ahn, S., & Monsere, C. M. (2010). Impact of traffic oscillations on freeway crash occurrences. Accident; Analysis and Prevention, 42(2), 626–36. doi:10.1016/j.aap.2009.10.009

3.3 DESCRIPTIONS OF CODED STUDIES AND SAMPLING FRAMES

3.3.1 Meta-analyses

Two studies were coded in which a meta-analysis was carried out for the effect of traffic volume on road safety. Both meta-analyses were based on studies with disaggregated traffic data (mostly 5-minute intervals), and two primary studies were included in both meta-analyses. Table 3 lists main differences between the meta-analyses. Both meta-analyses included only studies that considered all crashes jointly, and excluded studies with very aggregated data.

Table 3. Comparison of (traffic volume aspects of) meta-analyses.

Characteristics	Xu et al, 2015	Roshandel et al, 2015
Studies (estimates)	7 (9)	6(6)
Studies included if	Effects are OR/ log(OR); 5-min time intervals; traffic flow at same location with respect to crash site (up- or downstream)	Not ramps only
Traffic data, time intervals	Loop detector data with 5 minute intervals.	Loop detector and trajectory data, several intervals.
Loop detector placement	Upstream (9)	Upstream (4), not distinguished (2)
Meta-analysis	Bayesian with fixed effects, random effects, and meta-regression (freeway as explanatory).	Inverse variance meta-analysis with random effects for “all”, unclear if fixed or random effects are used for upstream and not distinguished-estimates.
Effect on risk per detector placement		
all	-	↗*
upstream	↗	↘
not distinguished	-	↗*

Note: * The increments are minor, OR 1.001. The table outlines the numbers of studies and estimates on traffic volume. The total number of studies and estimates included is larger in both instances, as several traffic characteristics are investigated.

3.3.2 Original studies

Table 4 describes the sampling frames, analyses and main results of the original studies coded for the traffic volume risk factor.

Table 4. Overview of methodology and main results for original studies coded for traffic volume.

Author(s)	Area, sample.	Traffic flow	Design, analysis	Outcome	Crashes	Control variables	Result	Explanation
Abdel-Aty & Radwan, 2000, USA	Principal arterial, motorway in Central Florida. 3 years of crash data (1992-1994). 566 segments.	AADT per lane	Observational, negative binomial	Crash frequency	All	section length; degree of horizontal curve; shoulder width; median width; lane width/number of lanes; urban	↗	AADT increases risk, more so than other parameters investigated.
Qin et al., 2004, USA	Two-lane rural highways, 29800 segments. 4 years of data, each year analysed separately (similar results for all years).	AADT both directions	Observational, zero-inflated-poisson	Crash frequency	SV	segment length; shoulder width; lane width; speed limit	↗	Single vehicle crashes increase, but become less likely at increasing AADT.
					MV-intersecting		↗	Become less likely at increasing AADT
					MV-opposite direction		↗↗	Increase proportionally with AADT
					MV-oncoming		↗↗	Increase more than proportional to AADT
Caliendo et al., 2007, Italy	Four-lane Italian motorway, 46,6 km. 5 years of crash data (1999-2003).	AADT/1000	Observational, negative binomial	Crash frequency	All; tangent	section length; surface status; presence of junctions; year	↗	Higher AADT related to increased crash frequency, less than proportional to volume increase.
					All – curve		↗	
					Severe; fatal - tangent		↗	
					Severe; fatal - curve		↗	
Yu & Abdel-Aty, 2013, USA	Mountainous freeway (15 miles) Colorado. Aggregate (5 years)	AADT	Observational. Bayesian bivariate poisson-lognormal model	Crash frequency	MV	Degree of curvature; curve length ratio (to section length); number of lanes; segment length; median width	↗↗	Higher AADT increases probability of MV crash occurrence
				Crash frequency	SV		-	No impact on the probability of SV crash occurrence
	Mountainous freeway (15	Volume at 5-	Case-control,	Crash risk	MV		-	MV: volume ns.

	miles), Colorado. Disaggregate (1 year). 109 MV and 150 SV, 4 times as many (matched) controls.	minute intervals at detectors up- and downstream	Bayesian logistic regression, seasonal random parameters					
			Case-control, Bayesian logistic regression, seasonal random parameters	Crash risk	SV	SD of occupancy; average speed; season	↗	SV: higher sum volume downstream is associated with increased risk (other detectors presumably ns)
Lord et al., 2005, Canada	Rural motorway (40 km). 5 years (1994-1998).	Hourly traffic volume estimates based on loop detector data, per direction	Observational, generalized negative binomial	Crash frequency (per time, section and direction)	All	-	↗	Crashes increase at a decreasing rate.
					Severe + fatal		↗	Crashes increase at a decreasing rate
					SV		↗	Crashes increase at a decreasing rate
					MV		↗↗	Increase in nearly linear manner with flow
	Urban motorway (5 km). 5 years (1994-1998).				All		↗	Crashes increase at a decreasing rate
					MV		↗↗	Increase in nearly linear manner with flow

Lord et al (2005) also finds that traffic volume alone might not properly characterize crashes on freeways. They develop a different set of models that also include density, and find that for both all and single crashes, crash frequencies initially increase, and then decrease as density increases. However, MV-crashes increase with increasing density, and the functional form is different for urban and rural areas.

3.4 TRAFFIC VOLUME IN DIFFERENT SETTINGS

This section is concerned with AADT estimates from studies with a main focus on different risk factors. These studies have been coded by other SafetyCube partners and are, as mentioned in the methodology section, not identified by the literature search for AADT, but from searches on other risk factors. These AADT results have been categorized as follows: a) studies on work zones, b) studies on ramps, merging and diverging areas, and c) other studies. The results and information provided in this section is based on the coding work of partners responsible for coding of the respective studies.

It should be noted that the study designs from which these results originate (mostly cross-sectional, and at times with time-series models or before-after design) identify associations between AADT and crash occurrence or crash severity. However, the information provided below does not in and by itself reveal whether this relationship is causal or not, i.e. whether traffic volume causes increased crash frequency/severity, or if this association is due to some other mechanism.

3.4.1 Traffic volume in work zones

Five studies on the effect of work zones on road safety provided estimates for the role of traffic volume. These results are presented in Table 5. The three studies investigating AADT in relation to work zones find that road safety deteriorates with increasing AADT, both for injury crashes and property damage only crashes. The studies of Chen and Tarko (2011; 2013) are based on the same dataset, and find that the crash frequency increases with the total number of vehicles passing through the work zone over the entire construction period, but at a decreasing rate. The authors note that "it may also mean that longer work zones with higher traffic volume exhibit lower crash rates (per unit length or unit volume) than shorter or less busy work zones".

Table 5. Effects of traffic volume on road safety in work zones.

Author(s), year, country	Sampling frame	Outcome, analysis	Traffic volume	Crash severity	Effect on outcome	Control variables
Chen & Tarko, 2013, USA	Indiana, 2009, 72 Work zones, several road types, n 547 observations	Crash frequency, fixed parameters negative binomial model with random effects, and with random parameters	Total ADT (accumulated over entire construction period	All	↘	Work zone length, left shoulder width; right-of-way- width; urban land development fraction; park lane fraction; detour sign; lane shift; lane split; restricted to one lane per direction; multilane with/without system interchange; low/high construction intensity; summer; winter per area
Chen & Tarko, 2011, USA		Crash frequency, random effect negative binomial model	Total ADT (accumulated over entire construction period	All	↘	Work zone length; fractions in urban area/road with full access control/road with parking lane prior to construction/collector road; avg left shoulder width; right of way width; lane shift; lane split; winter; summer; concrete pavement in poor condition; work intensity; police enforcement
Khattak et al., 2002, USA	California, 1992-1993, work zones and non-work zones n 144	Crash rate, negative binomial model	Ln(AADT)	PDO, injury	↗	Work zone presence; work zone duration; work zone length; urban indicator; injury indicator
	California, work zones, 1992-1993, n 36 work zones	Crash rate, negative binomial model	Ln(AADT)	PDO	↗	work zone duration; work zone length; urban indicator
				Injury	↗	

Ozturk et al, 2013, USA	New Jersery 2004-2010. N=950	Crash frequency, negative binomial model	Ln(AADT)	PDO	↗	work zone length, night, speed, n operating lanes, n closed lanes, speed limit, road class, n ramps, n intersection, duration of work zone
				Injury	↗	
Yang et al., 2013, USA	New jersey state, 7 years, (2004-2010), 60 work zones.	Crash frequency, full Bayesian negative binomial models	Ln(AADT)	PDO	↗	light condition;speed limit;road system;dropped lanes;aadt;number of lanes; direction; season; hours
				Injury	↗	as above + work zone length

3.4.2 Ramps, merging and diverging areas

Nine studies coded primarily for the risk related to ramps, merging or diverging areas provide estimates for the effect of traffic volume on road safety in these areas. The sampling frames of these studies are presented in Table 6, and the results are summarized in Table 7.

Table 6. Sampling frames and analyses of studies on ramps, merging and diverging areas.

Author(s), year, country	Sampling frame	Crash type/severity	Analysis	Control variables
Bared J., Giering G., Warren D., 1999, USA	Sample of interstate highways in Washington State. Data from 1993-1995, n 1452, all severities. Mainline and ramp flows separately.	Mainline	Negative binomial	ramp length; AADT on ramp; AADT on the mainline; ramp type; rural area
		Ramp		
Chen et al., 2009, USA	Freeway diverge areas, Florida, 2004-2006, n=7872. Separate estimates for one- and two-lane exit ramps.	Ramp (exit)	Negative binomial	deceleration lane length; AADT in the mainline/ramp; shoulder width; speed limit
		Mainline		
Chen et al., 2011, USA	Freeway diverge areas, n=60, 4 years, observational, Florida.	Mainline	Negative binomial	deceleration lane length; ramp length; AADT on ramp/mainline segment; ramp type
		Ramp		
Chen et al., 2014, USA	Motorcycle crashes, 2005-2010, Florida state, n 573.	Ramp	Negative binomial	ramp length, directional exit, loop exit, outer connection exit, ramp speed limit
Garnowski, Manner, 2011, Germany	Germany, Dusseldorf, 197 ramps and n 3048.	Ramp	Negative binomial, random parameters	truck percentage; deflection angle; curve gets steeper; length deceleration lane; lane width; position steepest curve
Mergia et al., 2013. USA	Ohio, 2006-2009, merging and diverging areas, motorway.	Diverging areas	Generalized ordinal logit	Adverse weather; adverse road condition; age;gender;collision type; n mainline lanes; n ramp lanes; alcohol related; speed related; lane-ramp configuration type [not all are used for all severity comparisons]
		Merging areas		
Wang et al., 2009, USA	2003-2006, crashes on selected ramps in state of Florida. N=10946.	Freeway diverge areas; exit ramp segments	Ordered probit	deceleration lane length; AADT on the mainline; ramp length; ramp length; curve/no; grade/no; shoulder width; speed on the mainline; number of lanes on the mainline; surface; landtype; peak hour; alcohol; heavy vehicle/not; time; crash type; barrier
Wang et al., 2011, USA	diverge areas, truck-crashes. N= 4630. 2005-2008.	Mainline	Ordered probit	shoulder width; median width; deceleration lane length; number of lanes; ramp type; AADT of trucks in the mainline/exiting AADT
		Exiting		
Wu et al., 2014, China	Motorway ramp crashes over 4 years.	Mainline	Generalised Linear Model for four year average	bad weather, temporal correlation
		Ramp		
		Mainline	Generalised	bad weather, temporal correlation

		Ramp	Linear Model for annual data	

Generally, the studies indicate that increased AADT in ramp areas, on ramps and in the mainline nearby the ramp is related to increased crash occurrence. A higher AADT in merging and diverging areas also appear to affect crash severity adversely. The evidence for different road users is limited, and should thus be considered with caution. Nonetheless, the results indicate that this is also the case for motorcycle crashes, while the severity of truck crashes is worsened by a higher truck AADT in the mainline and unaffected by the exiting AADT.

Table 7. Effects of AADT on road safety from studies on ramps, merging and diverging areas.

Author(s), year, country	AADT modelled as	Where	Outcome	Effect on outcome
Bared, Giering, & Warren, 1999, USA	AADT	Mainline	Crash count	-
	AADT	Ramp	Crash count	↗
Chen et al., 2009, USA	AADT	Ramp (exit)	Crash count one-lane ramp	↗
			Crash count two-lane ramp	↗
		Mainline	Crash count one-lane ramp	↗
			Crash count two-lane ramp	↗
Chen et al., 2011, USA	Ln(AADT in thousand)	Mainline	Crash count (per year)	↗
		Ramp	Crash count (per year)	↗
Chen et al., 2014, USA	AADT (in thousands)	Ramp	Crash count, motorcycle crashes	↗
Garnowski & Manner, 2011, Germany	Ln(AADT passenger cars)	Ramp	Crash count	↗
Mergia et al., 2013, USA	AADT	Diverging areas	Crash severity (fatal vs non-fatal)	↗
		Merging areas		↗
Wang et al., 2009, USA	AADT	Freeway diverge areas; exit ramp segments	Crash severity	↗
Wang et al. 2011, USA	AADT (in thousand)	Exiting	Crash severity, truck crashes	-
	AADT trucks (in thousand)	Mainline	Crash severity, truck crashes	↗
Wu et al., 2014, China	ln(AADT)	Mainline	Crash count on ramp, 4 year average	-
		Ramp		-
		Mainline	Crash count on ramp, annual	↗
		Ramp		↗

Note: for crash frequency outcomes, ↗ indicates and increase in crashes, corresponding to a worsening of road safety. Similarly, the upward arrow reflects a higher probability of more severe crashes. – indicates a non-significant effect.

The 4 studies examining the importance of AADT on road safety without focusing on specific road users all find that crash frequency increases with increasing ramp AADT. One of these studies finds this only on an annual level analysis and not for 4 years of data aggregated (Wu et al., 2014), while another finds this tendency for both one- and two-lane exit ramps. 3 of the 4 studies find a higher mainline AADT to be associated with increased crash frequency, while one finds it not to be statistically significant.

3.4.3 Other studies

Five remaining studies with other main focus areas have also been coded. They are summarized in Table 8.

Table 8. Overview of sampling frames and main results of other studies.

Author(s), year, country	Sampling frame, [main focus of study]	Traffic volume	Outcome	Analysis	Effect on outcome	Control variables
Choi et al., 2011, Korea	Case-control, 2002-2003, rural national roads. [Highway terrain types]	AADT	Crash severity (PDO, minor, serious, fatal)	Ordinal logistic regression	↗	Travel speed; shoulder width; median and terrain type
Milton et al., 2008, USA	Highway, state of Washington, observational longitudinal, 1990-1994 [Injury severity distributions.]	AADT general	Crash severity (PDO, possible injury; injury)	Mixed logit	↘	Average annual snowfall; AADT truck; Number of interchanges per mile
		AADT trucks			↘	Pavement friction; Percentage of trucks
Chen et al., 2014, USA	Segment of Colorado motorway. 1 year. [Predicting hourly crash rates]	Hourly volume	Crash rate daytime	Random effects tobit models	↗	Low speed limit; speed gap; % trucks; visibility; November; weekend; n enter ramps, n lanes, segment length; curvature, shoulder width; long remaining service life of rutting; wet road surface; snow;
			Crash rate night-time		↗	
Rahman et al., 2011, Canada	Alberta, single bus collisions on highways, n 109, 2000-2007, [Bus crashes]	Ln(AADT)	Crash severity (injury, PDO)	Binary logistic regression	↗	Type of collision; gender; season; weather; light condition
Montella & Ibramini, 2015, Italy	Motorway section Naples area, 2007-2011 [Highway design]	Ln(AADT)	Crash frequency	Generalised linear model, negative binomial error structure	↗	Dispersion, constant, design consistencies, yearly effects
Wang et al., 2013, UK	Major roads and motorways, London area, 2007-2013 [Congestion]	Ln(AADT)	Crash frequency, KSI crashes	Bayesian spatial model	↗	Congestion (delay); maximum gradient; number of lanes; speed limit; motorway; year; spatial correlation
			Crash frequency, minor injury crashes	Bayesian spatial model	↗	
Daniel & Maina, 2011, USA	Urban and rural, freeways and arterials, New Jersey, 1 year [Capacity]	AADT	Crash frequency	Negative binomial	↗	V/c-ratio; section length; % trucks: speed limit; number of lanes; lane width; shoulder width; ramp density.

Crash rates are found to be higher both at daytime and night time when the hourly volume is higher (Chen et al., 2014). The effect of traffic volume on crash severity varies between studies: Choi et al.

(2011) finds a higher AADT to be associated with more severe crashes, while Milton et al (2008) find the opposite. Rahman et al. (2011) find single bus crashes more likely to be injury than PDO when AADT is high.

Daniel & Maina (2011) find crashes to increase less than proportional to traffic volume

The study of Montella & Ibramini (2015) finds a higher AADT to be negative for road safety under a wide range of conditions, and find that, in both curves and tangents, a higher AADT is related to an increased crash rate for the following types of crashes: single-vehicle run-off-the-road, other single vehicle, multi vehicle, daytime crashes, night-time crashes, non-rainy weather crashes, rainy weather crashes, dry pavement crashes, wet pavement crashes, property damage only, slight injury, and severe injury (including fatal), as well as all crashes considered jointly.

ADDITIONAL REFERENCES

Elvik, R. (2015). Some implications of an event-based definition of exposure to the risk of road accident. Accident Analysis and Prevention, 76, 15-24.

Golob, T., Recker, W., & Pavlis, Y. (2008). Probabilistic models of freeway safety performance using traffic flow data as predictors. Safety Science, 46, 1306-1333.

Mensah, A., & Hauer, E. (1998). Two problems of averaging arising in the estimation of the relationship between accidents and traffic flow. Transportation Research Record: Journal of the Transportation Research Board, (1635), 37-43.

Theofilatos, A., & Yannis, G. (2014). A review of the effect of traffic and weather characteristics on road safety. Accident Analysis and Prevention, 72, 244-256.

Wang, C., Quddus, M., & Ison, S. (2013). The effect of traffic and road characteristics on road safety: A review and future research direction. Safety Science, 57, 264-275.