Safety Science 57 (2013) 264–275

Contents lists available at SciVerse ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Review

The effect of traffic and road characteristics on road safety: A review and future research direction

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ARTICLE INFO

Article history:
Received 4 October 2012
Received in revised form 18 February 2013
Accepted 21 February 2013

ABSTRACT

Understanding factors affecting road accidents is an important area in road safety research. This paper provides a review of the factors, with specific focus on traffic and road related factors mainly for car accidents on major roads. This paper also offers an overview of road safety theories that explain how and why these factors affect road traffic accidents. This paper offers the road safety community with a better understanding of road accidents and aids in developing suitable methods and policies for road safety improvement. Several factors most notably: speed, congestion, and road horizontal curvature were found to have mixed effects on road safety and need further examination.

Future research directions on the effect of factors are also developed most notably improving the quality of data, exploring the factors in developing counties and rural areas, and employing advanced statistical models. There is also a need to further investigate issues relating to the effect of speed and congestion on road accidents, whether curvature improves road safety, and the use of more sophisticated statistical models so as to better understand the effect of factors on road accidents.

Contents

1. Introduction

Road accidents impose serious problems on society. The costs of road traffic accidents to individuals, property and society have been significant. In the European Union, more than 40,000 people die and over one million are injured every year because of road accidents (CARE, 2008). In addition, there are considerable costs

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0925-7535/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ssci.2013.02.012

associated with road accidents, including human costs (e.g. willingness to pay to avoid pain, grief and suffering); the direct economic costs of lost output; the medical costs associated with road accident injuries; costs of damage to vehicles and property; police costs and administrative costs of accident insurance (Department for Transport, DfT, 2011). The total costs of reported road accidents were estimated to be around £15 billion in Great Britain in 2010 (DfT, 2011), and it has been estimated that economic costs of road traffic accidents for high income countries are in the region of 2% of their Gross National Product (IRTAD, 2005). As such, improving road safety is one of the primary aims of transport policy.

There has been a great deal of research effort in recent years in developing road safety theory (i.e. why an accident has occurred) and the factors affecting road safety (i.e. what caused or contributed to an accident). This paper examines the literature on both theory and factors relating to road safety. Factors affecting road safety however are numerous. In recent decades, there appear to have been increasing research interest into the effects of traffic and road characteristics on road safety. As such, this paper will focus on the factors related to this area of research. The aim is to obtain a better understanding of road accidents and thus aid in developing suitable methods and policies for safety improvement.

The paper will first look at the road safety theory followed by the review of factors affecting road safety with specific focus on traffic and road characteristics. Future research directions are then outlined and conclusions are drawn.

2. Road safety theory

Unlike more theoretically mature disciplines, road safety research can be seen to lack a solid theoretical grounding in an area where road accidents are very difficult to predict (Elvik, 2004). The reason for this is mainly due to the randomness of road accident occurrences. Road accidents themselves may be truly random and non-experimental since there is the effect of regression-to-the-mean (Fridstrøm and Ingebrigtsen, 1991). On the other hand, it is also argued that accidents are deterministic events rather than a random chance (Davis, 2004); however, since factors affecting accidents cannot be perfectly observed by analysts, the functions determining the accidents are random.

There have been several attempts in the literature to try to explain accident occurrence and injury severity. For example, Elvik (2004) detailed two important road safety theories that are related to engineering and human behavioural effects. It was stated that road safety measures could affect road safety by influencing relevant factors through engineering effect and behavioural adaptation. This suggests that engineering and human behaviour related factors are two important sources of risks. For example, road lighting improves visibility (engineering effect) but road users tend to be less alert (behavioural adaptation). Most factors can be related to either engineering or human behavioural effects. Vehicle related factors can also be explained through engineering effects. For instance compared to cars large trucks have unique characteristics, most notably high gross weight, long vehicle length, and poor stopping distance, which can be associated with different levels of risk (Chang and Mannering, 1999). Similarly other vehicle features such as electronic stability control can affect road safety.

Many other safety theories can be explained based on the engineering and behavioural theories. For instance, the risk compensation theory which is closely related to behavioural theory states that drivers would adapt their behaviour to a perceived lower risk situation (e.g. increasing speed or reducing attention), especially when the lower risk is brought about by an accident countermeasure (Wilde, 1998; Assum et al., 1999).

Physiological theory may be related to both engineering and behavioural theory to some extent. For instance it was suggested that drivers are more likely to fall asleep or feel bored on straight, monotonous, dual carriageway roads with little traffic (Sagberg, 1999). In this case, drivers changed their behaviour on certain types of road (e.g. straight and monotonous roads); and on the other hand road engineers could alter the road environment in order to reduce driver boredom. However, in some cases fatigue or boredom are linked more to the characteristics of the person themselves rather than engineering or behavioural adaption. For instance, it was found that individuals with a higher level of anxiety may be more likely to feel fatigue (Jiang et al., 2003). In addition, some groups of people (e.g. older people) are inherently more vulnerable than others, thus more likely to be involved in an accident or to be more seriously injured if an accident occurred (Bédard et al., 2002).

Economic and public health theory also has a role to play. Economic theory describes the relationship between economic development and changes in road safety. Kopits and Cropper (2005) observed an inverse U-shaped relationship between per capita GDP and road fatalities per 10,000 persons. This suggests the fatality rate would firstly increase and then decrease with respect of economic development. This is in line with the fact that the fatality rate generally decreased in developed counties but increased in developing counties between 1975 and 1998 (Kopits and Cropper, 2005). The initial increase in the fatality rate may be due to the rapid growth in traffic accompanying economic development; and following that more safety regulations or engineering work may be applied which reduces the fatality rate. The economic development also reflects various factors such as the level of deprivation, education and public health which may affect road safety. Low income countries may have weak medical and emergency services which result in more fatalities. This leads to the public health theory which states that an improvement in medical services and technology could improve road safety. This is supported by studies such as those by Noland (2003a) and Noland and Quddus (2004). Noland (2003a) found that improved medical technology reduces traffic fatalities over time. Noland and Quddus (2004) investigated the effect of improvements in medical care on road accidents in Great Britain, finding that the improvement in medical service significantly reduces road fatalities.

In addition to the theories mentioned above, Elvik (2006) proposed several basic mechanisms of accident causation and proposed general regularities that can explain the relationship between accidents and related factors, which are expressed by several "laws":

- *the universal law of learning*: states that the accident rate tends to decline as the number of kilometres travelled increases;
- *the law of rare events*: implies that "rare events" such as environmental hazards would have more effect on accident rates than "regular events";
- *the law of complexity*: states that the more complex the traffic situation road users encounter, the higher the probability that accidents would happen;
- *the law of cognitive capacity*: implies that accidents are more likely to happen as cognitive capacity approaches its limits.

Although these proposed laws need further empirical evidence in order to confirm, they are useful in explaining fundamental questions such as why and how a factor affects road safety.

Road safety theories are useful in that they help explain empirical findings from road safety studies. Many factors affecting road safety have been identified and evaluated in the literature. The following section of this paper will look at these factors, with a focus on traffic and road characteristics.

3. An overview of factors affecting road accidents

There is a broad range of factors affecting road accidents. These factors are usually related to traffic and road characteristics, drivers and other road users, vehicles, and environment. Traffic characteristics (such as traffic flow and speed) and road characteristics (such as road geometry and the quality of infrastructure) might affect road accidents, which are discussed below. As for road users, their behaviour, such as seat belt usage, alcohol consumption, age, passengers' impact on drivers (for instance, talking to drivers while driving) might affect road safety (O'Donnell and Connor, 1996; Washington et al., 1999). Also different road users could expect different accident severity outcomes, for example, the female could be more vulnerable to accidents compared to the male considering their different physical conditions (Bédard et al., 2002). With regard to vehicle related factors, many vehicle designs play an important role in safety, such as airbags, electronic stability control, anti-lock braking systems and low centre of gravity design so as to avoid rollover. Other factors such as lighting and weather conditions can affect road safety through both the road user and roadway system (Shankar et al., 1995; Golob and Recker, 2003).

There has been a long history of analysing accidents by exploring various contributing factors, and there is a body of research literature related to road accidents from a broad range of aspects using various approaches. Smeed (1949) estimated the number of road fatalities by considering the number of licensed motor vehicles and population based on data from several countries, and concluded that the formula using the two covariates could give good estimates in many countries. This is an example of early work which attempts to estimate the number of accidents by using risk or exposure factors.

Thereafter there has been a large body of research in road safety, which investigates road accidents and its contributing factors from a wide range of aspects and approaches, namely economic, engineering and policy. As road accidents are a major form of external cost, many economists have been involved in road safety research (Peirson et al., 1998; Dickerson et al., 2000; Graham and Glaister, 2003). Improved infrastructure design and engineering work is also believed to play an important role in road safety (Navin et al., 2000; Pérez, 2006). Laws and legislation are also used to improve road safety, for instance, Bjørnskau and Elvik (1992) discussed the impact of laws and legislation on accidents by employing a game-theoretic model. In addition, many researchers have attempted to investigate road safety by establishing statistical relationships between accidents and related factors (Lord and Mannering, 2010; Savolainen et al., 2011).

In the following sections, previous work on the factors related to traffic and road characteristics including speed, density, flow, congestion, road geometry, and infrastructure are reviewed. A summary of the empirical studies, the data and key findings mentioned in the following two sections is presented in Table A1 in the Appendix.

4. Traffic characteristics

Accidents occur when traffic moves, thus it is natural to investigate traffic characteristics to understand their impact on accidents. Traffic characteristics can often be classified as speed, density, flow, and congestion. These traffic characteristics affect road safety through both engineering and behavioural effects.

It is worth mentioning that speed, density, flow and congestion are inextricably linked, so an understanding of one of them could provide useful knowledge on the other three. In addition, in previous studies while explaining phenomenon such as higher accident rates during night-time (Martin, 2002), all four factors are involved so it is necessary to determine which is the key factor affecting accidents. The relationship between speed, density and flow can be expressed as follows:

$$q = k\bar{v}$$

where q is flow (vehicles per unit time); k is density (vehicles per length of road); and $\bar{v}$ is mean speed (distance per unit time). As for traffic congestion it arises when traffic flow or density increases on the road with limited capacity until at some stage delay occurs, which would in turn, decrease speed.

One can expect that speed would decrease as density increases. The speed-density and speed-flow relationships can be illustrated as in Fig. 1.

Fig. 1a shows that when density increases, speed initially remains the same and then decreases. This is because during the initial period as density increases, there is not enough traffic on the road to cause congestion so vehicles are able to travel at their maximum speed. When density increases at the point when congestion occurs, the speed would then decrease. Fig. 1b shows that, as traffic enters the road the speed decreases (in the upper portion of the

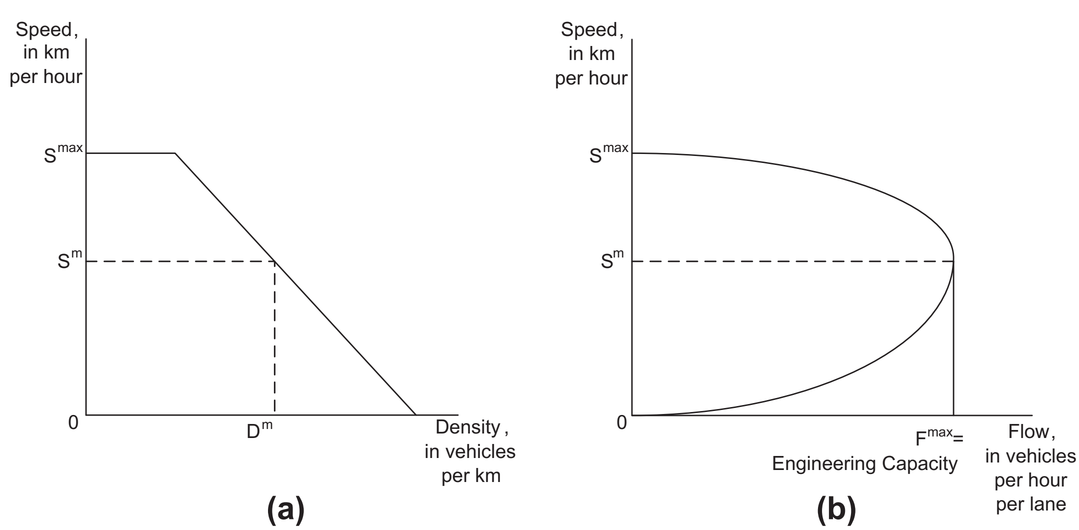

Fig. 1. Speed-density and speed-flow curves (source: Hau, 1992).

curve), and when the speed decreases to S^m, traffic flow reaches its maximum, which is referred to as the "Engineering Capacity" F^{max} (Hau, 1992). This means that during this period, as $q = k\bar{v}$, the density k increases more quickly than speed v decreases so the flow q increases, until F^{max}. If the traffic continues entering the road, the road becomes more congested and since, during this period, speed decreases more quickly than density increases, the flow decreases and the speed-flow curve turns back on itself towards zero. The upper portion of this curve (i.e. speed higher than S^m) is referred to as the "*normal flow*" situation; and the lower portion of this curve (i.e. speed lower than S^m) is referred to as the "*forced flow*" situation (Button, 2010).

As mentioned above an understanding of one of the traffic characteristics is helpful to understand the other three factors. For example, if speed and number of accidents were positively correlated (i.e. higher speed is associated with more accidents) then according to Fig. 1a an inverse relationship between accidents and density may be expected. The following sections will review previous studies on the effects of speed, density, flow and congestion on road accidents.

4.1. Speed

Speed is an important factor affecting road accidents both in terms of accident occurrence and severity (Elvik et al., 2004). It seems reasonably safe to assume that increased speed would mean that the accidents that have occurred would be more severe, if other factors (e.g., environment and vehicle design) remain the same. This can be shown by both Newtonian physics and empirical data (e.g. O'Donnell and Connor, 1996; Shankar and Mannering, 1996; Kockelman and Kweon, 2002; Hauer, 2009). It is however less straightforward for the relationship between speed and the possibility of accidents occurring, which subsequently brings into the question the relationship between speed and the frequency of accidents (or accident rate).

There have been studies that aim to explore the relationship between speed and number of accidents, most of which suggest that increased speed is associated with more accidents or higher accident rates (Nilsson, 2004; Aarts and van Schagen, 2006; Elvik et al., 2004; Taylor et al., 2002). The effect of change in speed on road safety has been extensively investigated by Nilsson (2004), who employed before-after studies in Sweden using the Power Model. It was found that changes in the number of accidents (or accident rate) can be associated with the changes in speed according to a power function. Positive associations between changes in speed and accidents were found, though the magnitude depends on types of accidents (e.g. fatal and injury). Similarly, Elvik et al. (2004) undertook an extensive evaluation on the effect of speed on accidents again using the Power Model. They concluded that there is a causal relationship between changes in speed and changes in road accidents, i.e., the number of accidents will go down if speed goes down and vice versa. Taylor et al. (2002) employed a cross-sectional analysis on 174 road segments from rural roads in England, and found a positive relationship between accident frequency and average speed. This appeared to confirm the findings of Elvik et al. (2004); however it seems that there may be a weakness in Taylor et al.'s study. Taylor et al. (2002) classified the sample into four different road groups based on a set of characteristics such as accident rate, mean speed, Annual Average Daily Traffic (AADT), junction density, bend density, access density and hilliness. Four dummy variables were created and included in the models to represent the road groups, and the variables used to classify road groups were also included in the model. This means that data such as average speed and AADT were used twice in the models. In addition, the Poisson regression model may be misspecified and a more sophisticated model such as a negative binomial (NB) model or a spatial econometric model may be more appropriate in order to model the accident frequency data. Another recent empirical study by Wang et al. (2009a) who looked at area-wide level speed and road casualties also found that increased average speed within a ward is positively associated with total fatalities and serious injuries.

The positive relationship between speed and accidents that is advocated by the studies above are, however, questioned by empirical evidence. For example, a study undertaken by Baruya (1998) employing a series of cross-sectional analyses found that average speed is negatively associated with accident frequency. The author compared this result with previous studies which also found similar results, and concluded that this "interesting" result (i.e. the negative association) is due to other factors (e.g., geometric characteristics) rather than speed. Further study is required however to see whether this is the case, and it is possible that such an inverse relationship between speed and accidents may indeed exist, as the model results indicated. One limitation of Baruya (1998)'s study is that a simple Poisson model was used to investigate the relationship between the number of accidents and various contributing factors, while a better model specification such as a NB model could be employed to better fit the accident data. Based on data from the Netherlands, Sweden and England, Taylor et al. (2000) found that there is an inverse relationship between accident frequency and average speed on European rural roads. Similar to Baruya (1998), Taylor et al. (2000) attributed this phenomenon to the inadequate design standard features represented in the model. The model employed in their study is also a simple Poisson regression model, which again may be misspecified as discussed above. A study by Kockelman and Ma (2007) examined the freeway speed and speed variation preceding accidents in California while controlling for other factors such as weather and lighting conditions. Their findings suggest that there was no evidence that speed conditions influence accident occurrence. Again the authors avoided explaining this phenomenon but attributed the result to data aggregation and accident-time reporting errors. Clearly more empirical evidence is required to ascertain the relationship between speed and accident frequency.

From the aspect of road safety theories, higher speed increases the drivers' overall stopping distance which in turn may increase the probability of accident occurrence. On the other hand, drivers at higher speed may be more cautious, and also accident risk on motorways (where speeds are higher) is lower due to various reasons such as higher construction standards and better traffic information provided.

In addition, it has been speculated that it is the dispersion of vehicle speeds (i.e. speed variance rather than speed itself) that affects the accident frequency (e.g. Lave, 1985). Lave (1985) found that the fatality rate was strongly associated with speed variance rather than average speed, thus it was argued that speed variance caused safety problems instead of speed itself. A later study by Davis (2002) however argued that such a claim of "variance kills" may be subject to ecological fallacy. Therefore there remains the question of the role of speed variance in road safety.

There has also been research exploring the relationship between speed and accidents in which other variables have been used instead of mean speed such as the speed limit (e.g., Johansson, 1996; Aljanahi et al., 1999; Ossiander and Cummings, 2002). Speed limit captures the characteristics of both speed and speed variance. These studies are often based on either a disaggregate road-level speed or a highly aggregate county level speed. For example, Johansson (1996) looked at the reduced speed limits' impact on accidents on motorways based on the data in several Swedish counties from 1982 to 1991 and found that the reduced speed limit can decrease the number of accidents involving minor injuries and vehicle damage. Shefer and Rietveld (1997) proposed a hypothesis that the rate of road fatalities is strongly related to traffic density, speed and congestion, which is supported by empirical evidence such that the fatality rate is lower during the morning period compared to other times of the day. Their findings are not conclusive since it has not been possible to identify which factors (speed, density, or congestion) play a more important role in reducing fatalities during the morning peak period. This is due to the fact that these three factors are inter-related. Other factors, such as poor night time visibility also needs to be controlled for. Their study is partially confirmed by Ossiander and Cummings (2002) who examined the change of the freeway speed limit in Washington State using time series data and found that an increased speed limit was associated with a higher fatality rate. The spatial differences in road speeds among various spatial units however may affect road accidents. This was not evaluated by Ossiander and Cummings (2002). Aljanahi et al. (1999) found that the number of accidents would reduce if the speed limit were to be lowered on dual-carriageways in the UK. In some cases, the relationship between mean speed and the accident rate is significant. Generally accidents are more serious at higher speeds. They also suggest that speed variance plays an important role. However their study did not differentiate accidents by severity levels so it is unclear how speed would affect fatal, serious and slight injury accidents separately.

Generally speed has been found to have mixed effects on road safety in the literature. While some studies found increased speed reduce safety, other studies found the opposite. It was also argued that speed itself may not be a safety problem but speed variation is. Clearly more research is required to assure the relationship between speed and safety.

4.2. Traffic density

The relationship between traffic density and accidents has been investigated less in the literature due to the dearth of relevant data. There have however been a few studies using other variables to represent density, for example Volume over Capacity (V/C) ratio (Shefer, 1994; Ivan et al., 2000). Zhou and Sisiopiku (1997) examined the hourly accident rates (per million vehicle kilometres) and the V/C ratio on a US interstate highway, finding that the relationship follows a U-shaped pattern and accidents involving injury and fatalities tended to decrease while the V/C ratio increases.

Ivan et al. (2000) investigated single and multi-vehicle highway accident rates and their relationship with traffic density while controlling for land use, time of day and lighting conditions on two-lane highways. For single-vehicle accidents, they found a negative-exponential relationship with the density (volume/capacity ratio), meaning that the accident rate is the highest at low V/C ratio. Lord et al. (2005) conducted a freeway segment based analysis on the relationship between accident, density and the V/C ratio. In their study density is measured as vehicles per km per lane. It is found that both density and V/C ratio have an overall inverse relationship with the number of accidents (per year per km). Accident-density and accident-V/C relationships were also examined according to different accident categories such as total, single-vehicle, and multi-vehicle accidents. It is found that there is an inverse U-shaped relationship for total and single-vehicle accidents but a positive relationship for multi-vehicle accidents.

Generally mixed relationships were found between density and safety in the literature, depending on the measurements of density and types of accidents. Clearly this is an area that has been studied less and as such further research is required.

4.3. Traffic flow

Many researchers have examined the relationship between traffic flow and accidents. This includes early seminal works undertaken by Belmont and Forbes (1953), Gwynn (1967), Ceder and Livneh (1982), Ceder (1982); and Turner and Thomas (1986). Belmont and Forbes (1953) developed a theory relating traffic volume and accident occurrences and found that the accident rate increases linearly with the hourly traffic flow for two-lane road sections during daylight. Gwynn (1967) later found that a U-shaped relationship exists between hourly traffic flow and accident rates on four-lane sections. The findings of Belmont and Forbes (1953) and Gwynn (1967) seem inconsistent, which may be due to the fact that different ranges of traffic flows and road designs were considered in the analyses. Ceder and Livneh (1982) focused on single and multi-vehicle accident rates and their associations with the hourly traffic flow by using power functions. They found that for different types of accidents, the relationships between accident rates and hourly traffic flow are different. For example, hourly traffic flow was found to be inversely related with accident rates for single-vehicle accidents in all cases; while in some cases hourly traffic flow was found to be positively related with accident rates for multi-vehicle accidents. Ceder (1982) further analysed the relationship between the accident rate and hourly flow under different flow conditions and found that the relationship between the total accident rate and hourly flow follows a U-shaped curve under free flow conditions while for the case of "congested" flow data the accident rate increases more sharply. This study implies the importance of investigating the impact of traffic flow on accident rates under different traffic flow conditions. It should be noted that in their study traffic flow is viewed as congested (i.e. the "congested flow") when the percentage of multi-vehicle accidents is high. This measurement for congestion may not be appropriate as it does not reflect the nature of congestion (i.e. delay). The study undertaken by Turner and Thomas (1986) also investigated the relationship between motorway accidents and traffic flow in which several linear regression models were fitted. They observed that during the early morning when traffic is light there are a high number and percentage of fatal and serious injury accidents.

Peirson et al. (1998) examined the accident risk by additional road use and how road users respond to it. In order to estimate the external cost caused by road accidents, the authors proposed that it is necessary to investigate the relationship between road accidents and traffic flow and proposed that the number of accidents increases in proportion to the increase in traffic flow. Dickerson et al. (2000) investigated the accident external costs and also examined the relationship between road traffic accidents and traffic flow in London and found that a strong negative accident externality was associated with high traffic flows. Lord et al. (2005) explored accident-flow relationships by using predictive models for rural and urban freeway segments. They also found a positive relationship, but the accidents increase at a decreasing rate as flow increases.

Later studies investigated hourly traffic flow and accident rates. For example, Martin (2002) investigated the relationship between accidents and traffic flow on French motorways, and found that accident rates are highest in light traffic compared to heavy traffic, especially on three-lane motorways. There is no significant difference between daytime and night-time accidents. However, if accident severity was considered, hourly accidents were much worse in a night-time and light-traffic situation. Therefore, the author concluded that light traffic (low traffic flow) is a safety problem both in terms of accident rate and severity. As many things could affect road safety during night time however such as lighting, this is an area requiring further study.

Apart from a post-processing statistical analysis, there is also real-time analyse. For instance, Golob et al. (2004) demonstrated a strong relationship between traffic flow conditions and accidents with the objective of providing real-time assessment of the level of safety. Similar work undertaken by Golob and Recker (2003) demonstrated how accidents are related to traffic flow conditions just prior to the occurrence of each accident. It was shown that accident severity generally tracks the inverse of traffic volume.

Overall it can be seen in the literature that the total number of accidents increases as traffic flow increases. In terms of accident rate, it seems to have a U-shaped relationship with hourly traffic flow.

4.4. Traffic congestion

The impact of traffic congestion seems to have been studied less in the literature, especially in terms of appropriate empirical and quantitative evidence. There is a dearth of literature on the effect of congestion on accident severity given an accident occurs, although Quddus et al. (2010) found that there is little impact of congestion on accident severity. As for accident frequency, Shefer (1994) proposed the hypothesis that there is an inverse relationship between congestion and accidents, in which the author used volume over capacity ratio (V/C), i.e. density as a proxy to measure the level of congestion. Shefer and Rietveld (1997) provided empirical evidence by comparing fatality rates throughout the day and found that during peak hours the fatality rate is obviously lower than at other times of the day. Due to the unavailability of data they examined the proposed model by using a simulated dataset rather than real-world data to describe the relationship between road fatalities and traffic congestion. The major limitation of their studies is that their hypothesis was not tested or examined with real-world data using an appropriate statistical analysis.

Later studies use empirical analysis on the effects of congestion on road accidents including those by Hanbali and Fornal (1997), Baruya (1998), Noland and Quddus (2005) and Kononov et al. (2008). Hanbali and Fornal (1997) found that the implementation of adaptive traffic signal systems on intersections reduced both traffic congestion and accidents. It was argued that improvements in facility capacity (i.e. decreased traffic congestion) could reduce the "stop-and-go" driving related collisions. A before–after analysis of the implementation of the adaptive traffic signal systems was conducted and confirmed this hypothesis while controlling for exposure factors. Their study however did not differentiate between the severities of accidents thus the relationship between traffic congestion and severe injury accidents was unknown. In addition, since their study was based on data from intersections, the relationship between traffic congestion and road accidents on road segments needs to be analysed. By using a linear accident model on 63 road segments of A and B roads in the UK, Baruya (1998) found that the "degree of congestion" has a negative effect on accident frequency. The study however did not differentiate accidents by their severity. Given that the proportion of slight injury accidents are usually very high, the result may suggest that congestion has an inverse relationship with slight injury accidents, but it is unclear how congestion affects fatal/serious injury accidents. One limitation of Baruya's study is the use of the simple Poisson model, where more sophisticated models such as a NB model or a spatial econometric model could be employed to better fit the data.

Noland and Quddus (2005) investigated congestion and safety in London using an area-wide spatial analysis approach. Congestion levels were measured using several proxy variables, including an indicator variable for Inner and Outer London (spatially), proximate employment and employment density. Their results were indeterminate and the proxy variables for congestion were generally statistically insignificant in their models, suggesting that there is little effect of traffic congestion on road safety. This may be due to the weakness of the proxies used for congestion, which is a major limitation of their study. The authors suggested that because congestion can be highly localised and time-of-day specific, a more precise congestion measurement should be used to better understand the effects of congestion on safety.

A recent study by Kononov et al. (2008) investigated the relationship between traffic congestion and road accident rates on urban freeways using the data from California, Colorado and Texas in the US. They found that total as well as fatal and injury accident rates increase with the increase in traffic congestion. Again, traffic congestion was measured using a proxy in their study, namely the AADT (i.e. higher AADT means higher congestion). It was found that the accident rate increases faster when AADT reaches some "critical point" (e.g., 90,000 AADT on 6-lane freeways), which suggests that an increase in traffic congestion can deteriorate road safety.

A major limitation of the studies above is the use of proxies for congestion, which may not appropriately reflect the actual amount of traffic delay. Recent exceptions are those studies by Wang et al. (2009b, 2013). Wang et al. (2009b) performed a road-segment level spatial analysis on the M25 motorway around London, finding that there is little effect of traffic congestion on road accidents. In their study traffic congestion was directly measured by using a congestion index (ratio of traffic delay by free flow travel time). Since their study was limited only on M25 for one year, the later study by Wang et al. (2013) extends their study area by including M25 and its surrounding high speed roads for multiple years. Wang et al. (2013) found that increased traffic congestion is associated with more fatal and serious injury accidents and traffic congestion has little impact on slight injury accidents. This may be due to the higher speed variance among vehicles within and between lanes and worse driving behaviour in the presence of congestion.

It can be seen from the literature that traffic congestion has been found to have mixed effects on road safety. Earlier studies and conventional wisdom appear to suggest that there is an inverse relationship between traffic congestion and road accidents as speed would be lower in congested situations. Recent studies however reveal that congestion could increase accidents. This may be due to the fact that different measurements for congestion were used in different studies. Further research could focus on testing the effects of different congestion measurements using advanced accident prediction models.

5. Road characteristics

Based on the engineering theory, one could expect that roads themselves play an important role in road safety, and improved geometry design and infrastructure could in turn help to improve road safety. Indeed, safety is an important goal in highway design (Lamm et al., 1999), for instance designing an intended operating speed according to developmental context of a roadway.

Findings from several researchers support this hypothesis. Shankar et al. (1995) explored the effects of various roadway geometrics (e.g. horizontal and vertical alignments) on road accident frequency. Shankar et al. (1996) found that the increased number of horizontal curves per kilometre on rural freeways increase the possibility of an accident resulting in 'possible injury' relative to 'property damage only'. A further study undertaken by Milton and Mannering (1998) observed the annual accident frequency on sections of principal arterials in Washington State. By using a NB model, they found that short sections are less likely to experience accidents than longer sections; narrow lanes (less than 3.5 m) and sharp horizontal curves tend to decrease accident frequency in

Eastern Washington. They also found a positive relationship between accident frequency and the tangent length before a horizontal curve. These findings confirm that road infrastructure designs do affect road safety. However, the authors did not consider spatial correlation – i.e. an accident on one road segment may be correlated to the one on the adjacent segment as they are sharing similar traffic, infrastructure or environment conditions.

Similar research was conducted by Noland and Oh (2004) and Haynes et al. (2007, 2008), who investigated the relevant factors at an aggregate area level. Noland and Oh (2004) analysed the county-level highway data from the State of Illinois in the US. Their results revealed that an increase in the number of lanes and lane widths was associated with increased fatalities; and an increase in the outside shoulder width was found to be associated with reduced accidents. Similarly, Kononov et al. (2008) found that an increased number of lanes increases the number of accidents, possibly because of the increased potential lane-change-related conflict opportunities.

Haynes et al. (2007) studied road curvature and its association with traffic accidents at the district level (a census tract) in England and Wales. Their study developed a number of measures for road curvature and found that at the district level, road curvature is a protective factor meaning that more curved roads in an area result in less road accidents, which partially confirms the results by Milton and Mannering (1998). Similar research based on New Zealand data (Haynes et al., 2008) concluded that road curvature has an inverse relationship with fatal accidents in urban settings. Curvature was generally found to be a protective factor. This finding is generally in line with their previous study based on England and Wales data (Haynes et al., 2007), although the results are not completely consistent. This may be because these two countries have different land and demographic characteristics and the spatial units used are also different (district vs. territorial local authority). A similar study by Wang et al. (2009a) also found that road curvature is negatively associated with road accidents using ward-level data in England, which is in-line with the findings by Haynes et al. (2007).

From the above it can be seen that some studies found that road curvature is protective (i.e. reduce accidents). This is counter-intuitive and also contradicts some of the existing studies. For example Abdel-Aty and Radwan (2000) found that the degree of curve increases the number of accidents on a road segment. This may be because different curvature measurements were used, such as minimum radius, number of horizontal curves per mile, mean horizontal deflection angle, degree of horizontal curve per 100 m arc, bend density (Shankar et al., 1995; Noland and Oh, 2004; Abdel-Aty and Radwan, 2000; Haynes et al., 2007). In addition, these studies were conducted at different scales, which may also be subject to the modifiable areal unit problem (MAUP, Openshaw, 1984). Curvature may be risky considering its engineering effect; however, from the behavioural aspect, drivers may drive more slowly and cautiously on curved roads. On the other hand, on straight roads as mentioned above, drivers are more likely to fall asleep or feel bored (physiological theory). Therefore the overall safety effect of road curvature (compared to straight roads) is likely to be mixed. Clearly additional research is required to further analyse the effect of road curvature on road safety.

Road infrastructure improvements (e.g., road upgrading and pavement) and roundabout design are also found to be beneficial for safety. Navin et al. (2000) suggested that not only better vehicle design, but improvements in road safety engineering can also reduce the severity of whiplash injuries when accidents occur, and this could be done by enhanced signal visibility or through complex intersection geometric upgrades. Similarly, Pérez (2006) found that highway upgrading has a significant positive effect on road safety. Hels and Orozova-Bekkevold (2007) discussed roundabout design features on cyclist accident rates. Accident rates were modelled by various geometric features, age and traffic volume. They found some interesting results, for example, the older the roundabouts the higher the probability of accidents. De Brabander and Vereeck (2007) investigated accidents at roundabouts and suggested that traffic lights can be more effective in protecting vulnerable road users than roundabouts by comparing safety situations between signalised intersections and non-signalised roundabouts at intersections. Thus signalisation is an important factor. Abdel-Aty and Wang (2006) investigated signalised state road intersections in Florida and found that the design of intersections has an impact on accidents. For example, intersections having 3-legs, with exclusive right-turn lanes on both roadways are associated with lower accident frequencies.

It is worth noting that, as argued by Noland (2003b) and Noland and Oh (2004), it appears unclear as to the role of infrastructure improvement in road accident reduction (i.e. whether infrastructure improvement can effectively reduce accidents). This is because there may be "system-wide effects" or "black-spot migration", i.e. improvement in infrastructure at one location may lead to increased risk on other parts of the road network. Therefore more research is needed on both the road segment level and area-wide (e.g., ward and county) level so as to verify the relationship between road infrastructure/geometry and road accidents.

The effects of various factors related to road characteristics have been reviewed in this section, including road geometry (road curvature, number of lanes) and infrastructure (road upgrading, signalisation). It has been found that increased number of lanes would increase accidents; and improved road infrastructure would reduce accidents. Among the various factors, road horizontal curvature has notably been found to have a mixed effect on road safety. While some studies found it to be negatively associated with road safety, other studies especially those undertaken recently found curvature are protective. This may be because, similar to traffic congestion, different measurements for curvature were used and these studies were conducted at different spatial scales.

6. Future research direction

Research effort has been devoted in reviewing the effects of various factors on road safety in the literature, especially those factors related to traffic and road characteristics. There are a number of areas however that require further research.

First, there is still debate in that some of the factors are found to have a mixed effect on road safety. For example, as discussed previously, certain studies found a positive relationship between speed and accident frequency; whereas some found the opposite. It could well be the case that speed itself has little, if anything, to do with accident frequency, but that other properties related to speed, such as speed variance play a role in accident occurrence. It is clear from the body of existing literature that the effect of speed on road accidents needs to be examined further. Similarly traffic congestion and road horizontal curvature have also been found to have mixed effects in the literature.

One of the reasons for this could relate to the issue of data quality. In terms of speed, for instance, high resolution speed data, such as individual vehicle-level high frequency speed data (i.e. sec-by-sec), should be used for a better understanding of how speed or speed variance (both within and between lanes among vehicles) affect safety. To overcome such data issues, one can use matched sampling of crash and non-crash cases which may offer insight into accident occurrence (Pande and Abdel-Aty, 2009). In addition, recent advancement in data acquisition technologies (e.g. radars, video image processing and kinematic sensors) enables researchers to collect detailed naturalistic driving event data (Jovanis et al., 2011), and future research can benefit greatly from such rich data. Traditionally researchers have often relied on aggregate data (such as accident frequency) or the data for individual accidents after accidents occurred. There was however little information on the sequence of actions preceding an accident. Therefore such naturalistic driving data may provide a better understanding as to the cause of accidents (Jovanis et al., 2011). In addition, data on "near crash" events can also be recorded and collected, which would be useful in accident prevention research as a proactive approach.

Another data related issue relates to the use of appropriate measurements. A notable example is the effect of road horizontal curvature. As discussed above, more evidence is required as to whether curvature improves road safety. The problem with curvature is that, it is not straightforward to measure. The curvature measurements include the number of sharp horizontal curves, sharp curve indicator (1 if curve radius is less than 868 m, 0 otherwise), bend density, detour ratio, straightness index, cumulative angle, and mean angle (see Milton and Mannering, 1998; Miaou et al., 2003; Haynes et al., 2007). As suggested by Haynes et al. (2007), using one single measurement alone may not be sufficient as each measurement has its limitations – in other words, "a single measure of road curvature does not capture all the properties that might be of interest". This could also be the case for other factors such as traffic congestion – as discussed above many proxy variables were used while direct measurement of traffic congestion was rarely used in previous studies. Future research should seek to improve the measurements for various factors and examine their effects on safety using different measurements. This would provide insight into how factors affect safety in different conditions.

Second, the majority of the studies cited in this paper are based on research undertaken in developed countries. Many of these effects are transferable to developing countries, for example, we expect increased speed variance decrease road safety in both developed and developing countries. We do acknowledge however that traffic management and road configurations differ between developed and developing countries. Thus the effects of some factors may be different in developing countries (Altwaijri et al., 2011). Actually even among those developed countries, some factors were found to have mixed effects as discussed above. Low-income and middle-income countries have only 48% of the world's registered vehicles but have 90% of road deaths in the world (WHO, 2011). Given the disproportionate number of road deaths in low- and middle-income countries there is a need for a significant research effort in developing countries. A challenge for area of research is the lack of data since many developing countries do not have a good road accident database. One solution to this is to utilise more sophisticated inferential statistical techniques.

Similar to the developed-and-developing-country difficulty, there may be different effects of factors and implications between urban and rural areas. Also many of the studies examined in this paper are based on high speed roads (e.g. highways) and there is a need to investigate the safety effects of these factors in rural areas where minor roads dominate.

Third, more sophisticated statistical models can be employed to better understand the effects of factors on road accidents. Statistical models such as the NB model has traditionally been used and recommended in the Highway Safety Manual (AASHTO, 2010, where the models are referred to as safety performance functions). There has recently been significant development in applying advanced statistical models in road safety research (Lord and Mannering, 2010; Savolainen et al., 2011). It is believed that advanced statistical models could ease the issues related to omitted variable bias and unobserved effects, such as spatial models that account for spatial correlation, random parameter models and multilevel models (Lord and Mannering, 2010).

In terms of statistical methodology when examining the effect of various factors on safety, more sophisticated accident models are useful in obtaining the 'correct' effects, especially when the data quality is poor. In previous studies, results were found to be "unexpected" or inconsistent with other studies, which may be due to the misspecification of their statistical models used (such as the application of a simple Poisson or NB model). More advanced models have the potential to correct this. For instance, instead of a fixed-parameter model which were used in previous studies, a random-parameter model could be used. It is believed that the use of more advanced statistical models can improve the model performance and could offer a better understanding of the factors while controlling for unobserved effects. Indeed, if all factors can be measured and included (a difficult task given that there are unknown factors that have not been identified or there is data limitation), there may be no need to use a complex model, since all factors have been controlled for. In other words, the problem of imperfect information is a major motivation in developing and using complex models.

In addition to statistical modelling specifications, other methodological issues can result in biased or misleading estimations of effects of factors. For example, Hauer (2010) found that before-after studies are considerably more consistent among different studies compared to cross-sectional regressions, while it is difficult to tell if a regression model truly captures the real effects. Before–after studies have been widely used in evaluating safety effects, notably by employing empirical Bayes methods (e.g. Hauer, 1986; Persaud et al., 1997; Persaud and Lyon, 2007), in which accident prediction models (i.e. NB models) are calibrated to correctly estimate the "expected" accident frequency in the after period had the safety measures not been applied. Recent studies have shown that full Bayesian models in which accidents in different periods were modelled in an integrated approach are more flexible and superior to conventional empirical Bayes methods in before–after safety analysis (Lord and Miranda-Moreno, 2008; Park et al., 2009; Persaud et al., 2010). It thus seems that a full longitudinal modelling approach is important in better understanding the factors affecting road safety.

Another issue related to the regression model is that it suffers from the modifiable areal unit problem (MAUP) which refers to situations that when the boundary of zones used in a spatial analysis changes, the statistical inference and interpretation derived from the zones also differs (Openshaw, 1984; Wang et al., 2012). Therefore the apparent 'inconsistent' effects of factors (in terms of both direction and magnitude of such effects), such as speed and curvature, may be due to such methodological issues. Similarly 'inconsistent' effects could be due to different study contexts and designs. One may use the method of meta-analysis to review and combine results from different studies. Meta-analysis refers to the "analysis of analysis", or "a statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings" Glass (1976). Meta-analysis has been successfully used in road safety research, such as in evaluating the bicycle helmet efficacy (Attewell et al., 2001), and driver improvement intervention (Masten and Peck, 2004). However caution is required as this approach may be subject to problems such as publication bias which refers to the tendency not to publish a study if its findings are unwanted, difficult to explain, or statistically insignificant (Høye and Elvik, 2010; Elvik, 2011).

Finally, transport systems are not as economically efficient, as environmentally benign, nor as safe as they should be, and one key cause of this is due to the 'human element'. Consequently, one key strand of transport research over several decades has been to try and automate the transport system (e.g. a vehicle with the function of autonomous driving and an infrastructure-based approach for collision avoidance at junctions) and as far as possible so as to minimise the damage (in terms of safety, exhaust emissions and climate change) caused by humans making (often sub-optimal) decisions. Since technologies (such as radar, liDAR, video cameras, laser scanner) for such autonomous systems are becoming more reliable, the safety community will need to address the issues (e.g. interaction among vehicles with and without the capability of autonomous driving) related to the context of this new driving environment.

7. Summary and conclusions

Improving road safety is one of the important objectives for transport policy makers. In order to improve road safety effectively it is necessary to understand what and how factors affect road safety. This paper has offered a review of current literature on road safety theory and the effect of various factors, with a focus on the factors related to traffic characteristics (traffic speed, density, flow and congestion) and road characteristics (road geometry and infrastructure) mainly for car accidents on major roads (such as freeways). It has been found that many of these factors have been investigated from a range of perspectives (e.g. engineering, behavioural and economic) using various methods; and some of the factors have mixed effects on road safety.

For future research, some factors need to be examined further, such as speed, congestion and road curvature, since findings from the literature is inconclusive. Future research could focus on accident analysis using detailed and improved quality data such as naturalistic driving data; and direct and multiple measurements for safety related factors. Moreover, it is yet to fully investigate these factors in developing countries and rural areas as research in these areas is under-represented, especially for developing countries which experience very serious safety issues.

It is also argued that with rapid development of technologies and techniques to capture better data, factors may also need to be re-investigated using appropriate statistical techniques so as to better understand the effect of them on road safety. More sophisticated inferential statistical techniques need to be em-

Table A1
Summary of empirical studies on the effects of traffic and road characteristics on road safety.

Study	Data/research context	Summary of key finding(s) discussed in Sections 4 and 5
Abdel-Aty and Radwan (2000)	Highway accident data for 1992–1994 on State Road 50 in Central Florida, US	The degree of curvature increases the number of accidents on a road segment
Abdel-Aty and Wang (2006)	Accidents that occurred at the signalised state road intersections for 1999–2000 in the state of Florida, US	Intersections with 3-legs, with exclusive right-turn lanes on both roadways are associated with lower accident frequencies
Aljanahi et al. (1999)	Accident data for 1988–1992 on dual-carriageway roads in two counties in the UK	The number of accidents would reduce if the speed limit were to be lowered. Accidents are generally more serious at higher speeds
Baruya (1998)	Accident data for the years 1992–1996 on rural single-carriageway roads in England. The UK model was also compared with European data (from the Netherlands, Sweden and Portugal)	Average speed is negatively associated with accident frequency; the "degree of congestion" has a negative effect on accident frequency
Ceder (1982)	Daylight fatal and injury accidents on 4-lane interurban road sections for the period 1967–1975 in Israel	The relationship between the total accident rate and hourly flow follows a U-shaped curve under free flow conditions while for the case of "congested" flow data the accident rate increases more sharply
Ceder and Livneh (1982)	Fatal and injury accidents on 4-lane interurban road sections for the period 1967–1975 in Israel	Hourly traffic flow was found to be inversely related with accident rates for single-vehicle accidents in all cases; while in some cases hourly traffic flow was found to be positively related with accident rates for multi-vehicle accidents
De Brabander and Vereeck (2007)	Registered injury accidents that occurred between 1991 and 2001 in Flanders	Traffic lights can be more effective in protecting vulnerable road users than roundabouts by comparing safety situations between signalised intersections and non-signalised roundabouts at intersections
Dickerson et al. (2000)	Road accidents in London, UK	A strong negative accident externality was associated with high traffic flows
Golob and Recker (2003)	Accident data for 1998 Californian highways in the US	Accident severity generally tracks the inverse of traffic volume
Golob et al. (2004)	Accident data for 1998 Californian highways in the US	Strong relationships between traffic flow conditions and the likelihood of traffic accidents
Gwynn (1967)	Hourly accident data between 1959 and 1963 on a four-lane highway in New Jersey in the US	A U-shaped relationship exists between hourly traffic flow and accident rates
Hanbali and Fornal (1997)	Empirical study on intersection accidents in 1993 in the city of Milwaukee, US	Improvements in facility capacity (i.e. decreased traffic congestion) could reduce the "stop-and-go" driving related collisions
Haynes et al. (2007)	District-level accident data for the period 1995–1999 in England and Wales	More curved roads in an area result in less road accidents
Haynes et al. (2008)	Fatal road accidents occurring between 1996 and 2005 in 73 territorial local authorities across New Zealand	Road curvature has an inverse relationship with fatal accidents in urban settings. Curvature was generally found to be a protective factor
Hels and Orozova-Bekkevold (2007)	Cyclist accidents occurred at roundabouts between 1999 and 2003 in Denmark	The older the roundabout the higher the probability of accidents
Ivan et al. (2000)	Accidents on two-lane highway in Connecticut in the US	For single-vehicle accidents, there is a negative-exponential relationship with the segment V/C ratio. For multi-vehicle accidents the segment V/C is insignificant
Johansson (1996)	Monthly car accidents on motorways, January 1982 to December 1991, in the Swedish counties Stockholm, Kristianstad, Malmiihus, Halland, Gothenburg and Bohus and Alvsborg	Reduced speed limit decreases the number of accidents involving minor injuries and vehicle damage

Table A1 (*continued*)

Study	Data/research context	Summary of key finding(s) discussed in Sections 4 and 5
Kockelman and Kweon (2002)	A sample of 0.85% of all police reported accidents in the US, obtained from 1998 National Automotive Sampling System GES	Males and younger drivers in newer vehicles at lower speeds sustain less severe Injuries. Pickups and sport utility vehicles are less safe than passenger cars under single-vehicle crash conditions
Kockelman and Ma (2007)	Accidents that occurred in January 1998 on six Orange County, California freeways: Interstates 5 and 405, and State Routes 22, 55, 57, and 91	No evidence that speed conditions influence accident occurrence
Kononov et al. (2008)	Five years of accident data for multilane urban freeways in California, Colorado, and Texas in the US	Total as well as fatal and injury accident rates increase with the increase in traffic congestion; an increased number of lanes increases the number of accidents
Lave (1985)	Road fatalities during 1981 and 1982 on US high-speed roads (rural interstates, arterials, and collectors; and urban freeways, interstates, and arterials; Alaska and Hawaii were excluded)	Fatality rate was strongly associated with speed variance rather than average speed
Lord et al. (2005)	Accident data from 1994 to 1998 for rural and urban highways in the US	Both road density and V/C ratio have an overall inverse relationship with the number of accidents (per year per km). There is an inverse U-shaped relationship for total and single-vehicle accidents but a positive relationship for multi-vehicle accidents. There is a positive accident-traffic flow relationship, but the accidents increase at a decreasing rate as flow increases
Martin (2002)	Road accidents on interurban motorways in France between 1997 and 1998	Accident rates are highest in light traffic compared to heavy traffic, especially on three-lane motorways. There is no significant difference between daytime and night-time accidents. However, if accident severity was considered, hourly accidents were much worse in a night-time and light-traffic situation
Milton and Mannering (1998)	Accident data for highways in the state of Washington during 1992–1993	Short sections are less likely to experience accidents than longer sections; narrow lanes (less than 3.5 m) and sharp horizontal curves tend to decrease accident frequency in Eastern Washington; there is a positive relationship between accident frequency and the tangent length before a horizontal curve
Nilsson (2004)	Road accident data from Sweden	Changes in the number of accidents (or accident rate) can be associated with the changes in speed according to a power function. Positive associations between changes in speed and accidents were found, though the magnitude depends on types of accidents (e.g. fatal and injury)
Noland (2003b)	Road casualties in all 50 states in the US over a 14 year period (1984–1997)	Infrastructure improvements (e.g. newer lane miles, additional lanes) have been ineffective in reducing road fatalities and injuries
Noland and Oh (2004)	County-level highway accident data during 1987–1990 in the state of Illinois	An increase in the number of lanes and lane widths was associated with increased fatalities; and an increase in the outside shoulder width was found to be associated with reduced accidents
Noland and Quddus (2005)	Road traffic casualties during the period 1999–2001 in London, England	There is little effect of traffic congestion on road safety
O'Donnell and Connor (1996)	Road accidents involving motor vehicle occupants in 1991 in New South Wales, Australia	Increases in vehicle speed and the age of the victim would slightly increase the probabilities of serious injury and death. Higher blood alcohol level increases the possibility of a severe accident
Ossiander and Cummings (2002)	Accidents over the period 1974–1994 on rural and urban interstate freeways in Washington State, US	Increased speed limit was associated with a higher fatality rate
Peirson et al. (1998)	Accident and traffic data for London in 1991	It is proposed that the number of accidents increases in proportion to the increase in traffic flow
Pérez (2006)	Study on rural highways during the period 1986–1993	Highway upgrading has a significant positive effect on road safety
Quddus et al. (2010)	Accidents on the M25 motorway in England during the period 2003–2006	There is little impact of traffic congestion on accident severity; increased traffic flow decreases the level of accident severity
Shankar and Mannering (1996)	Single-vehicle motorcycle accidents (i.e., accidents involving one motorcycle) during the period 1989 and 1994 in the state of Washington, US	Speeding or vehicle speed at time of accident increases the likelihood of fatality, evident injury, and disabling injury. Helmet usage tends to increase the possibility of fatality when riders collide with fixed objects
Shankar et al. (1995)	Interstate rural freeway (I-90) in the Seattle area during the period 1988–1993	Number of horizontal curves and maximum grade are found to have a positive relationship with accident frequency
Shankar et al. (1996)	Interstate rural freeway (I-90) in Seattle area during the period 1988–1993	The increased number of horizontal curves per kilometre increase the possibility of an accident resulting in 'possible injury' relative to 'property damage only'
Taylor et al. (2002)	Accidents during the period 1992–1998 on rural single-carriageway roads in England	A positive relationship between accident frequency and average speed was found
Turner and Thomas (1986)	Motorway accidents in England	During the early morning when traffic is light there are a high number and percentage of fatal and serious injury accidents
Wang et al. (2009a)	Accidents for the period 2000–2002 in English wards	Increased average speed within a ward is positively associated with total fatalities and serious injuries; and road curvature is found to be negatively associated with road accidents
Wang et al. (2009b)	Accidents for the period 2004–2006 on the M25 motorway in England	Traffic congestion has little or no impact on the frequency of road accidents on the M25 motorway
Wang et al. (2013)	Accident data for the years 2003–2007 on the M25 motorway and surrounding motorways and A roads that connect to the M25 in England	Increased traffic congestion is associated with more fatal and serious accidents; traffic congestion however has little impact on slight injury accidents.
Zhou and Sisiopiku (1997)	Accident data from 1993 to 1994 for the interstate highway I-94 in Detroit, Michigan, US	The relationship between the hourly accident rates (per million vehicle kilometres) and the V/C ratio follows a U-shaped pattern and accidents involving injury and fatalities tended to decrease while the V/C ratio increases

ployed where there is the problem of data quality such as in developing countries. Other research directions have also been discussed, such as investigating safety issues in automated driving conditions.

The factors affecting road safety are numerous. In addition to traffic and road characteristics, other factors also need to be examined and reviewed, such as road users' behaviour, demographic factors, land use, and the environment.

Appendix A.

See Table A1.

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