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Review of Speed and road crashes relationship in low-and -middle-income countries. Do the power and exponential model hold?

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Abstract

Low-and-middle income countries (LMICs) continue to suffer the negative consequences of crashes with speed recognised as the main causative factor. The relationship between speed and crash outcome is complex and has been subject to debate. Over the years, how speed affects the outcome of a crash has been investigated amongst researchers and argued to depend on the type of traffic environment which has led to the re-analysis and development of models for different road environments. However, the literature neglects the effects of mixed traffic on speed and crashes, and this has raised questions on the applicability of the conventional power and exponential models. This study reviews the literature on speed and crashes in mixed traffic, for LMICs, and verifies the applicability of the power models to the context. Study results indicate that speed studies in LMICs are rudimentary and while studies support the positive relationship between speed, speed variance, and crashes, the strength of the relationship is unknown. Literature provides no conclusive evidence on the applicability of the power and exponential models to LMICs roads, and this remains controversial. More research efforts in LMICs should focus on the effects of speed, impact speed and speed variance on crashes both at the aggregated and individual road user levels.

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Keywords: Speed; Road safety; Low-income countries; Middle-income countries; Mixed traffic; Heterogenous traffic; Power model; Exponential model

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1. Introduction

Speed and crash studies are at rudimentary stages in low-and -middle-income countries (Damsere-Derry et al., 2008), thus making speed review research in the context imperative.

Speed and crash relationship have been well established in literature using high-income countries' (HIC) data. Areas of the established relationship include: linking the crash liability of individual vehicles to their driving speeds (Elvik et al., 2019a; Vadeby & Forsman, 2017), linking average traffic speed to crash rates of given roads (Aarts & van Schagen, 2006), linking impact speeds and fatalities (Jurewicz et al., 2016; Rosén & Sander, 2009) and linking changes in speeds to different injury severities (Elvik, 2013; Elvik et al., 2004; Nilsson, 2004).

Included in the literature also are: the highly cited power model which Nilsson initially developed (Nilsson, 1982) and later validated in his doctoral thesis (Nilsson Goran, 2004); systematic reviews (Aarts & van Schagen, 2006); and meta-analyses (Cameron & Elvik, 2010; Elvik, 2009, 2013, 2014; Elvik et al., 2004, 2019b) which have well explored and provided estimates of the speed and crash relationship. However, researchers (Cameron & Elvik, 2010) have contested early models, such as the Nilsson power model, of its applicability on different road environments. This is because the development of earlier models was limited to specific road environments or did not differentiate their applicability to different road environments, such as rural or urban roads. Besides, due to the dependence of speed on factors such as land use practices, speed distribution and traffic flow conditions which vary between speed environments, the relationships between speed and crashes are bound to differ; hence speed models need to control for the road environment type. Given these gaps, researchers (Cameron & Elvik, 2010; Elvik, 2013, 2014; Elvik et al., 2019b) have developed aggregated models considering analyses for different road types such as urban, rural, residential or freeway roads.

Nonetheless, other issues concerning the traffic environment and composition such as traffic heterogeneity (or mixed traffic) have not received greater attention over the years. Only a few studies have acknowledged and controlled for the effect of mixed traffic on the relationship between speed and crashes, and this consideration has remained understudied. The reasons for the observed gaps are apparent. Firstly, most speed studies are carried out in a homogenous setting typical to HICs making the issues of traffic heterogeneity non-relevant or not evident. Secondly, the few studies that have identified the effects of mixed traffic on speed tend to be methodologically flawed (i.e., not controlling for several biases or confounding factors that affect crashes or not using appropriate model forms), or the issues are less observed or addressed (i.e., not highlighting the traffic heterogeneity intensity or composition).

Since mixed traffic is a common feature of Low- and middle-income countries (LMICs), this review aims to discuss studies that have addressed speed and crashes in LMICs to provide any theoretical evidence, identify gaps and propose areas of future research. The review will also identify any evidence on the applicability of the power and exponential model to LMICs context. It will also briefly discuss the road safety issues in LMICs to provide a comprehensive view of the overall problem.

2. Methods and materials

A literature search was conducted from May to August 2022. This involved identifying studies that have addressed the speed and crash relationship, narrowing down the studies to those carried out in LMICs or those that indicate the presence of mixed traffic and lastly identifying studies that have discussed road safety issues in LMICs. Different search strategies were used including using electronic databases through search engines and contacting institutions for grey literature.

2.1. Research Questions

The following research questions guided the analyses of our literature.

- What are the road safety problems in LMICs?
- What is the existing relationship between speed and crashes in a mixed traffic environment common to LMICs?
- Do the power and exponential model hold for LMIC's data?

2.2. Search Strategy

A pre-defined methodology according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines was employed to carry out the literature search. PRISMA is an evidence-based framework that provides a transparent, systematic, and unambiguous process for literature searches within healthcare and safety interventions (Hussain et al., 2019; Moher et al., 2009). The strategies used to gather papers and publications were as follows:

Use of Search Engines: Different search engines were used to identify articles, including Scopus (www.scopus.com), Google Scholar (scholar.google.com), Google (www.google.com), Science Direct, and Research Gates. The predefined methodology (which was iterative) included fixing some limitations /exclusions to the paper search. For example, in SCOPUS, the limitation was: • published: year > 1990 • Document Type: “Article” or “Review” or “Conference paper” • Source Type “Journals” • Subject area: “Engineering” • Language: “English” or “French”, where “TITLE-ABS-KEY” refers to the search query. The search included the combination of several keywords including road safety, speed, fatalities, speed models, heterogenous, developing countries, and speed attitude. Table 2.1 below provides the results for different combinations of keywords using logical search operators in Scopus.

Table2.1: Search Items and Queries for processing papers in Scopus

Type	Keywords combination	Hits
1	“Speed”	657,724
2	“Speed modelling” OR “speed calibration” OR “speed models”	1,804
3	("road safety" OR "road crashes" OR "crash risk" OR "fatalities" OR "crash casualties" OR "casualties" OR "injuries" OR "accidents" OR "incident" OR "collision" OR " severity" OR "crash" OR "road users" OR "pedestrian" OR "vehicle occupants")	411,728
4	(“speed variations” or “Speed changes” or “speed reduction” or “speed increase”)	8,721
5	“Speed limit” or “Mean Speed” or “85th Percentile speed” or” travel speed”	9,626
6	("heterogenous traffic" OR "heterogeneity" OR "mixed traffic" OR "homogenous") AND "roads" AND ("low-income countries" OR "LIC" OR "developing country" OR "developing countries" OR "emerging countries" OR "low- and middle-income countries" OR "LMICs")	1072
7	(“urban roads” OR “rural roads” OR “motorways” OR “expressways” OR “residential areas”)	28,008
10	1 OR 2 OR 4 OR 5 and 3	65920
11	1 AND 2 AND 4 AND 3	72
…….	11 OR 14 OR 15 OR 16 OR 17 OR 21 OR 23	745
…….		
24		
25	24 OR 20	1004

Note: Hits refers to the number of papers obtained after each keyword combination. Type refers to the different keyword combinations.

Papers from Research Institutes: Research institutes were contacted including the Global Road Safety Facility (GRSF) of the World Bank and iRAP who mostly carry out and lead research activities and projects on speed, especially for LMICs. They were asked for any grey literature and literature database on speed. Some databases were collected and combined with the database obtained from the literature search.

Reference List: The reference list of relevant papers was screened to identify other important studies tha t could have been missed.

2.3. Screening and Analysis of papers

The papers from each electronic database and the research institutes were screened by reading the titles and abstracts, and full-text reading was considered for papers linked to the areas of interest, i.e., speed & crashes and road safety in LMICs. The full texts were downloaded and stored in the Mendeley reference manager desktop application for easy documentation. The papers were read in detail and separated into different folders representing different thematic areas of speed. The reference lists of all full-text papers were screened to identify relevant studies. The overall steps used for the literature search are summarized in a PRISMA chart in Figure 2.1.

Articles considered for full-text reading were those that explained road safety issues in developing countries (LMICs), those that explained the speed-crash relationship in any LMICs or discussed the effects of traffic mix on speed & crashes irrespective of the country, and those that described the power and exponential models. The reference list of meta-analyses that led to the development of the power and exponential models and their updated estimates were screened to identify the sources of data.

In analyzing the papers, special emphasis was laid on key factors, including the inclusion of heterogeneity or mixed traffic in studies, the magnitude of the effect of speed on crashes, and the comparisons of the results with the power and exponential model. Potential sources of bias in the papers were identified, but no paper was excluded due to limitations in the number of papers. In total, 1252 papers were processed.

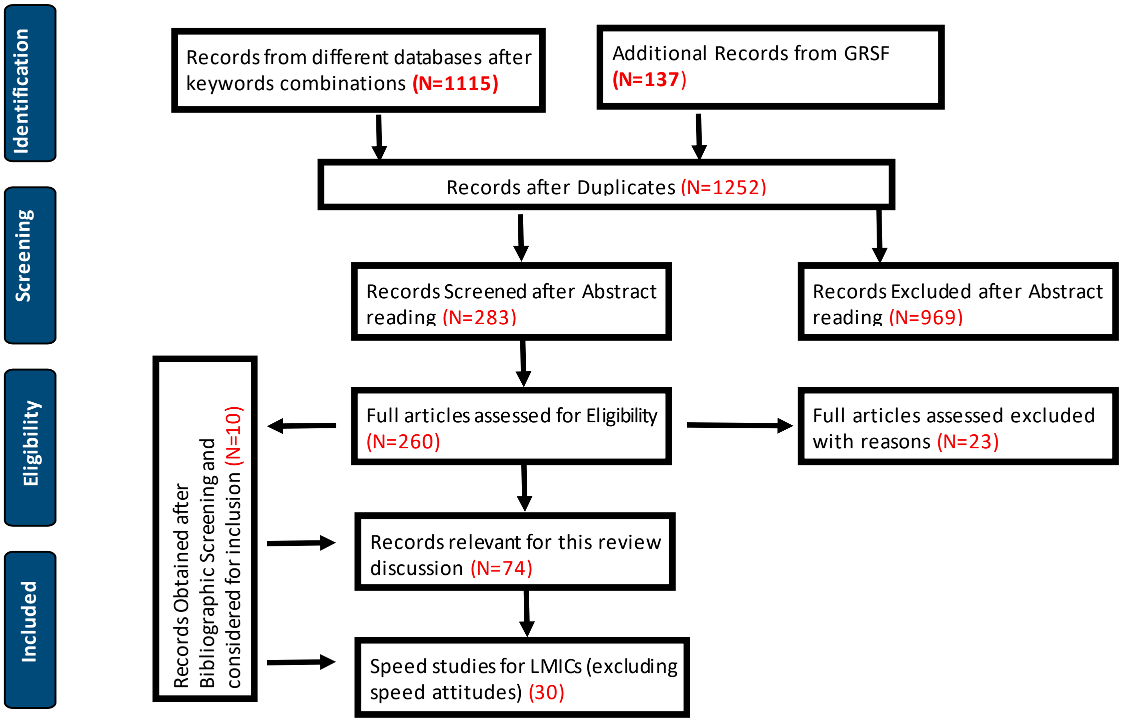

Figure 2.1: Methodology for Literature Review

3. Results

Seventy-four relevant studies were identified for this review; 24 focused on an overview of road safety issues in LMICs, 30 were related to speed and crashes in LMICs, 10 summarized the power and exponential model, and 10 were complementary studies. The analysis of these papers is discussed under different thematic areas which are interrelated to this study's central discussion and investigation. The areas of focus include the road safety context in LMIC, the power and exponential model, and the speed-crash relationship in LMIC context.

3.1. Road Safety in low-and-middle-income countries. An overview.

The epidemic of road traffic death in LMICs has observed no substantial reduction globally and is deteriorating with crashes posing as “weapons of mass destruction”. Since 1999, while a progressive reduction in road traffic death has been observed in HICs, the trend for LMICs is escalating, accounting for 85, 90 and 93% of global deaths according to WHO (2004), WHO (2009) and WHO (2018) respectively. Despite LMIC occupying just 60% of the world's vehicles, they are responsible for 93% of the 1.35 million people dying each year on the world's roads (WHO, 2018). Unfortunately, with the rapid motorization and growth in the number of vehicles in LMICs, non-motorized vehicles have failed to disappear and are on an increase, thereby further exacerbating road safety issues (Soames Job & Wambulwa, 2020).

The highest traffic rates in most LMICs are experienced in Africa and Southeast Asia, with death rates of 26.6 and 20.7 per 100,000 population, respectively (WHO, 2018). For example, on African roads, over 650 road deaths occur per day, and unless measures are taken, road crashes in Africa are projected to increase by 68% over the next decade.

The high burden of road traffic injuries in developing countries is related to several factors, including growth in vehicle numbers, poor enforcement of traffic safety regulations, the inadequacy of public health infrastructure, and poor access to health services (Nantulya & Reich, 2002). In addition, it is perceived that automobility cultures, the issue of corruption, and road safety cultural characteristics for developing countries have a direct link to crash occurrences which are brought about by the unsafe behaviour of road users or their inobservance of traffic safety policies (Wells & Beynon, 2011).

Road crashes come with a high economic loss, and a greater impact is felt by the poor in developing countries with fewer financial resources to rely on, which ultimately leads to reduced financial security and food consumption (Aeron-Thomas et al., 2004). The economic burden is exacerbated as high deaths and injuries are registered for the youthful and most active population, who are often breadwinners (Aeron-Thomas et al., 2004; Hashempour et al., 2019). LMICs continue to pay the price of road crashes as the cost is so high and consumes about 6.5% of GDP for all LMICs (World Bank, 2019), resources which would otherwise be used to improve living standards. This high socioeconomic loss due to road crashes could be a contributory factor to Africans and other LMICs inhabitants in Asia and South America living on less than $5.50 per day.

In LMICs, the majority of traffic fatalities and injury severities tend to occur mostly on rural roads than in urban areas, as in the case of Ghana (Afukaar et al., 2003). These observed differences could be attributed to features in rural areas such as increased distance and time exposure, inadequate speed calming measures, rural-urban exodus, excessive and inappropriate speeding on rural roads, the proximity of hospitals, and inadequate or insufficient ambulance services. Therefore, LMICs must examine rural road safety as rural dwellers are at much greater risk of crash death than urban residents (Soames Job & Wambulwa, 2020). Notwithstanding, road safety in both rural and urban environments continues to deteriorate in LMICs, given the rapid motorization and the associated increase in traffic exposure. Sufficient research and development (R&D) is needed to understand and resolve the fundamental problems (Heydari et al., 2019; Huang et al., 2010). However, the lack of adequate and appropriate road safety data in LMIC (Khanal & Sarka, 2014) remains a critical bottleneck in carrying out any in-depth road safety research. Other road safety issues observed in LMICs are related to passenger transport which mainly depends on old "second-hand" vehicles driven on poorly maintained roads (Afukaar et al., 2003).

The World Bank (2017) studies on traffic injuries show that if LMICs achieve a reduction in traffic mortality and morbidity and can sustain it over 24 years, it would lead to substantial long-term growth in their economy with about 7 to 22 per cent growth in GDP per capita. According to Fazlur & Farah Naz, (2019), most LMICs were unsuccessful in meeting the UN target of halving the number of Road Traffic Injuries (RTIs) set between 2011-2020. This was linked to the complexity of problems in preventing RTIs in LMICs, including the failure to perceive the problem, setting appropriate policies, limited resources, and the complexity and little knowledge of safety interventions.

There is little evidence on the cost-effectiveness of interventions to prevent road traffic injuries (RTIs) in LMICs, especially for vulnerable road users (Banstola & Mytton, 2017), and those interventions (such as speed, helmet or seatbelt enforcement) that are proven effective in HICs do not necessarily translate to LMICs (Banstola & Mytton, 2017; Esperato et al., 2012; Hyder et al., 2013). However, interventions in HIC that are feasible in LMICs will need to be evaluated considering factors such as costs, sustainability, and barriers that tend to be country-specific (Forjuoh, 2003). Research has proven that as the GDP per capita in lower-income countries grows, the number of traffic fatalities instead rises and does not decline as in the case of HICs (Bishai et al., 2006). This suggests that care must be taken when choosing or tailoring interventions to lower-income countries, as the causes and consequences of road trauma vary across economies and countries (Hofman et al., 2005; Peden & Khayesi, 2018). Overall, road safety intervention in LMICs is a neglected research area (Blackhall, 2007; Huang et al., 2010) that needs to be explored.

The plethora of reasons that suggest differences in road safety between HIC and LMICs includes: limited financial resources, political situations, cultural beliefs, low literacy rates, competing health problems, and an entirely different traffic mix coupled with an uncontrolled rate of urbanization (Forjuoh, 2003). Additionally, the capacity of LMICs to manage road safety is hampered by a lack of adequate crash data due to underreporting issues. Despite the road safety differences observed between LMIC and HIC, merging LIC (low-Income country) and MIC (Middle-Income Country), i.e., as LMIC is problematic.

LICs and MICs differ from each other in terms of road safety performance. While some MICs have experienced a decrease in road traffic deaths, no LIC have experienced any decrease since 2013 (WHO, 2018). Moreover, LICs have lesser resources than MICs to address road safety. Underreporting in LIC is up to 84%, while that in MIC is at 51% (WHO, 2018). Additionally, LICs, MICs, and countries with similar income levels should NOT be treated as one group (Soames Job & Wambulwa, 2020). However, since no sufficient evidence of road safety even exists when treating LMICs as one group, it is a starting point, though with careful attention. This review study considers all countries belonging to the group LMICs.

Speed is one of the most important risk factors, and moderating speed can substantially improve traffic safety. Safety countermeasures that alter speed and flow should be carefully considered when implementing interventions in LMICs (Staton et al., 2016). To improve road safety in LMIC and lessen the burden of RTIs, research on speed will be quintessential to understanding how speed and speed interventions affect crashes in the LMIC context so that appropriate policies can be set. Speed models which have been developed using HIC data will have to be tested for their applicability in the LMIC context. This review focuses on addressing these issues and placing speed-crash research within the context of LMICs.

3.2. The power and exponential models. A summary.

Past studies have established the relationship between speed and crashes to be described by a power function (Elvik, 2009; Elvik et al., 2004; Nilsson, 1982; Nilsson Goran, 2004; Aarts & van Schagen, (2006)) and by an exponential function (Elvik, 2013, 2014; Elvik et al., 2019b; Kloeden et al., 2001). The power model developed and validated by Nilsson (2004), the updated estimates of the power model by Elvik et al., (2004), and the exponential model developed by Elvik (2013, 2014) are highly cited in road safety reports and journals and used by policymakers to estimate the effects of speeds on crashes when new countermeasures are planned and investigated. The discussion in this section aims to briefly summarize these models and later investigate their potential application in the LMICs context.

The power model explaining the relationship between crash rates and speeds was first described by Nilsson (1982), who fitted the model using Sweden's crash and speed/speed limit data. The indices of the model were 4, 3, and 2 for the fatal crash rate, fatal and serious injury crash rate, and all injury crash rates, respectively. Nilsson (2004), in his PhD thesis, tested and validated the power model in both Before and After Studies (BAS) and in Cross-sectional Studies (CSS) and concluded that the power model was valid with regard to injury crashes, fatal crashes, and the number of injured but not for the number of fatalities, where the effects are underestimated. Nilsson (2004) described the speed safety relationship to be formed on two key hypotheses: crash risk and crash consequences. The hypotheses were on the basis that the effects of speed on injury crashes and the probability that an injury resulted in fatal crashes can be regarded as due to a change in kinetic energy.

For these hypotheses, Nilsson commended that the power model is a model between speed and the number of injury crashes, number of injured, number of fatal crashes, and number of fatalities. Nilsson empirically developed and refined estimates of his previous power model (Nilsson 1982) and summarised them on six crash categories in a cumulative form. The general equations for the power models are:

$$y_1 = y_0 \left(\frac{v_i}{v_0}\right)^{\alpha} \tag{1}$$

$$z_1 = \left(\frac{v_i}{v_0}\right)^{\alpha} y_0 + \left(\frac{v_i}{v_0}\right)^{\beta} (z_0 - y_0) \quad (2)$$

Where y denotes crashes, z is the number of crash casualties, v is the speed, and subscripts 1 and 0 are changes before and after. α, β are power coefficients depending on the injury severity of the crashes; for example, $\alpha = 4$ for fatal crashes, $\alpha = 3$ for fatal and serious injury crashes, and $\alpha = 2$ for all injury crashes. Similarly, $\beta = 8$ for fatalities, $\beta = 6$ for fatalities and severely injured, and $\beta = 4$ for all injured.

The power model summarises that the number of fatal crashes, fatal and serious injury crashes, and all injury crashes are respectively proportional to the fourth, third, and second power of the relative change in the mean speed of traffic, while their respective victims' numbers: fatalities, fatalities and serious casualties, total casualties are related to additional speed components raised to the eight, sixth and fourth power respectively. For example, for Fatal crashes, the index of 4 would mean a decrease in speed from 100 to 90km/h will reduce fatal crashes by 36%.

However, Elvik et al., (2004) argued that while the powers for injury crashes developed by Nilsson (2004) are based on the equation of Kinetic energy, the powers for fatal crashes and serious injury crashes have no theoretical foundations since they were based on best fitting values to data from Sweden.

Evaluating Nilsson's power model studies shows that the data from which the model was developed and validated came entirely from HIC data sources and none from LMIC. Hence, it may be debatable the applicability or transferability of the model to the LMIC context (a detailed explanation is provided in section 4).

Elvik et al., (2004) performed a meta-analysis to evaluate if the power model initially proposed by Nilsson (2004) adequately describes the relationship between speed and crashes. After an in-depth literature search and screening, the authors identified 98 relevant studies that contained 460 estimates of the effects of speed changes on safety which was used to perform meta-analysis. The 460 estimates were combined using different meta-analysis techniques with the greatest weights given to the most reliable estimates, i.e., to studies well controlled for biases. The authors carried out a conventional meta-analysis and a meta-regression analysis for 6 models on cumulative and mutually exclusive categories of injury. Additionally, they compared the power indices for the results of cumulative categories of injuries to that obtained by Nilsson (2004). This comparison was made because Nilsson had derived the power model indices based on a cumulative injury category. The results are summarised in Table 3.1.

Table 3.1: Comparison between Estimates of Elvik and Nilsson Power Model

Category	Elvik (2004)	Nilsson (2004)
Fatal crashes	3.65	4
Fatal and serious injury crashes	3.29	3
All injury crashes	2.67	2

Noting insignificant differences between the power indices, Elvik et al. concluded that the power model derived by Nilsson is supported. For the mutually exclusive categories of injuries, a direct comparison was not made because the equations postulated by Nilsson were rather additive (see equation (2)).

The data derived and used in Elvik et al., (2004) meta-analyses were from studies carried out in over 20 countries mostly from the US, Sweden, Denmark, and Great Britain. After carefully evaluating the reference list used by Elvik et al., (2004) in the meta-analysis, it is observed that none of the studies included in the meta-analysis came from LMICs, hence raising doubts about their applicability LMIC context.

Elvik (2009) re-analysed and updated the 2004 estimates of the power model now based on 115 studies containing 526 estimates of the speed and crash relationship. Before Elvik's new analyses, other authors (Hauer and Bonneson 2006) had re-analysed the 2004 data and noted some drawbacks. Specifically, it was noted that the effect of a given relative change in speed depended on the initial level of speed, and this was not accounted for in the power model. Based on the review of the re-analyses made by other authors, Elvik, (2009) highlighted some issues/differences that were not evident in the original power model. These included:

- The effects of a given percentage change in speed vary according to the type of environment and tend to be lower in urban areas than in rural areas and freeways.
- The effects of a given percentage change in speed appear to be greater for fatal crashes and injury crashes (for rural and freeways) than predicted by the estimates of power developed in the original analysis.

- The effects of a given percentage change in speed for urban areas do not appear to be larger for serious injuries than for slight injuries.

Inspired by these differences Elvik, (2009) reanalysed the 2004 data with additional 66 estimates, using mutually exclusive categories of injuries. Elvik developed two versions of the power model to capture the effects of initial speed, one for urban and residential roads and the other for rural and freeways. Additionally, Elvik adjusted downwards the values of the exponents referring to all injury crashes and all injured road users to allow consistency. The analysis results showed that the power estimates differed according to the type of traffic environment, and the power estimates for rural traffic environments were higher than those for urban traffic environments. Cameron & Elvik, (2010) also reanalysed Elvik's 2004 data to verify the applicability of Nilsson's power model but separated the analysis to urban arterial roads, residential streets, rural highways, and freeways. The outcome was similar to that of Elvik (2009), as higher powers were obtained for freeways and rural highways than for residential streets and urban arterials.

Elvik, (2009) also evaluated the changes in the estimates of the powers over time and he observed a decline in these values, hence concluding that "the effects on crashes of given changes in speed reduces over time, especially for fatal crashes". He equally explained that due to improvements in technology, such as helmets, seat belts, and airbags, crashes that were fatal 30-40 years ago are often survivable today. In addition, Elvik (2009) concluded that the results of the power model could be generalised across countries. However, these conclusions made by Elvik, (2009) about the reduction in speed effect over time and the generalisation of the power model across countries may not be totally true, especially for LMIC, as the number of crashes/fatalities has even doubled and continued to increase over the years for these countries (WHO, 2018). Elvik's conclusion may also be limited due to the absence of studies from LMICs in the 526 estimates used to derive new estimates of the power model. Hence the application of the power model to LMIC is questionable and remains to be tested.

Both Cameron & Elvik (2010) and Elvik (2009) recognised the importance of traffic environment but unfortunately could not identify the importance of traffic composition, i.e., the effects of traffic heterogeneity (mixed) or homogeneity to speed. However, failing to appreciate this could be attributed to the lack of robust research on mixed traffic context, which their meta-analysis could have included.

Inspired by the fact that the power model does not take into consideration the effects of initial speed, Elvik, (2013) reparametrised the power model by fitting exponential functions to data points using the updated Elvik, (2009) data that contained 526 estimates. The fitted exponential model was compared to the power model, and Elvik, (2013) noted that both the power model and exponential model fitted data extremely well, even though the functions are naturally distinct. Notwithstanding, the exponential function fitted slightly better than the power function, and Elvik concluded that it is more supported as compared to the power function for modelling the relationship between speed and the number of crashes.

Elvik et al., (2019) reanalysed the power and exponential models for studies published after 2000 to see if the relationship between speed and safety remained strong. To estimate the effects, they performed a meta-analysis using studies retrieved after 2000 containing 31 estimates for injury crashes and 18 estimates for fatalities (including data from one LMIC, Turkey). Based on the analysis results, they concluded that: both models still describe the speed crash relationship with great precision, and the relationship between speed and safety remains strong for studies published after 2000. The form of the exponential model as defined by Elvik, (2014) and Elvik et al., (2019) is:

$$\boldsymbol{Y_1 = Y_0 e^{(\beta(v_1 - v_0))}} \tag{3}$$

Where Y denotes crashes, v speed, and subscripts 1 and 0 are changes before and after. β is the coefficient of estimation.

3.3. Speed in Low- and Middle-Income Countries

The greatest impact and consequences of speed reduction on fatalities and serious injuries are expected to be felt more in developing countries that have fewer economic resources to rely on. Hence interventions on key risk factors such as reduction in speed are a way forward for LMIC.

With respect to safety interventions such as speed management, the issue of the differences in traffic mix (motorised and non-motorised vehicles combination) between HICs (high rate of traffic homogeneity) and LICs (high rate of traffic heterogeneity) has raised questions on the transferability of traffic engineering solutions from HIC to LIC, who due to their limited resources for research or other pressing/priority issues look for HIC traffic solutions (Fazio et al., 1999). Significant R&D is needed to explore the solutions that work for the high mixed traffic typical to LMICS. Homogeneity & heterogeneity of traffic flow are important road safety parameters, with the former known to increase road safety(Leblud, 2017).

Heterogeneity by definition is referred to any traffic mix not comprising at least 85 per cent of automobiles or at least 90 per cent of automobiles, trucks and buses of on-street traffic during a peak period (Fazio et al., 1999; Fazio & Tiwari, 1995). Hence the average peak period traffic compositions (excluding pedestrians) define its heterogeneity (Fazio & Tiwari, 1995). According to Siregar et al., (2020), heterogeneous traffic is that which is composed of different vehicle types with non-uniform characteristics sharing the same lane and may result in distinct vehicle speed characteristics in terms of mean speed and speed deviation.

In this sub-chapter, speed-crash studies in LMICs are assessed to determine the theoretical evidence of the relationship between speed and crashes, to identify any potential gaps in the literature and to verify any evidence of the power and exponential models. However, the power and exponential models are developed on aggregated levels based on robust BAS and may only be validated based on these studies: hence CSS may not be used to evaluate or validate these models since most often they are not derived from any interventions influencing speed. Nonetheless, CSS studies in LMICs are still evaluated in this review for the power and exponential model, with the aim understanding the strength of the speed-crash relation. Studies in LMICs that do not mention any elements of heterogeneity are discussed separately. Moreover, due to the advancement in road safety culture in some MICs, the current traffic conditions tend to distort from the dense mix of traffic common in other LMICs.

3.3.1. Studies on speed-crash with evidence of traffic heterogeneity.

Van der Horst et al., (2016) and Vet et al., (2016) studied the effectiveness of an integrated speed management program on selected Bangladesh rural roads that had observed significant road safety issues. The integrated speed management at the selected locations consisted of infrastructure measures (speed humps, lateral rumble strips, pedestrian crossing, signs and lining, and a bus bay on either side of roads), education intervention (training of school children, drivers, and pedestrians) and community involvement intervention. The study was a Before and After Analysis (BAA) in which the authors recorded in real time the number of crashes occurring at locations before and after the treatment, hence controlling the possibilities of crash underreporting. Local record keepers collected the crash data at sites, and conflict observations were recorded using a 'DOCTOR method' with video recordings.

Different categories of road users at the study location were considered and included: buses, trucks, passenger cars/microbuses, compressed natural gas vehicles (CNGs), motorbikes, rickshaws/bicyclists, light motorised vehicles, and pedestrians (adults-children). The pedestrians, CNG, and buses had the highest share of the traffic. In the before period (19 months) at all locations, there were 175 crashes, 377 injuries, and 19 fatalities, with pedestrians accounting for 63% of fatalities, followed by motorbikes (16%). Following the implementation of the countermeasures, i.e., in the after period, the number of fatalities, seriously injured, and injuries reduced by 67%, 66% and 73%, respectively. In addition, the implemented measures led to a net speed reduction of 13.3km/h. The authors compared this speed reduction to the expected fatalities of applying Nilsson's power model. The power model indicated a 59% reduction in fatalities; hence the authors suggested some evidence of the applicability of the power model in LMIC context.

However, despite the success of this speed management strategy in reducing crashes, it is not clear which specific countermeasure (education or specific components of infrastructure measures) could have contributed to the reduction in crashes. Moreover, Hirst et al., (2005) argued that "in establishing the relationship between the impact of schemes on crashes and speeds, it is important to separately estimate those crash changes attributable to speed changes". Hence, it may be inconclusive that the power model is better for predicting the crash reductions for the speed management program, as the education and awareness measures could have contributed to a decrease in crashes.

Cetin et al., (2018) investigated the impact of speed limit change from 90km/h to 110km/h on 114km dual carriageways in Turkey. The study controlled for underreporting of crashes and assumed that the crashes during the investigation period occurred due to the speed limit change since there were no changes in geometry or improvement of the study sites, and no major changes were observed for the AADT (Annual Average Daily Traffic). However, the authors did not control for any increase in pedestrian volumes or bicyclists within the period of the speed limit change. When the average speed in the before and after periods were compared, it was observed that the average speed rose by 3.2% (101.97 km/h to 105.25 km/h) for passenger cars and 5.8% (86.99 km/h to 92 km/h) for buses. Due to the speed limit change, the observed number of fatalities and injuries increased by 43% and 36%, respectively. If the speed and crash observation for this study were to be converted to power estimates of the power model, these estimates would be 11.35 and 9.76 respectively for the number of fatal and injury crashes respectively; which is very much out of the range predicted by Elvik's and Nilsson's power models. However, the estimates show that the effect of mean speed changes on crashes for this study is stronger than that predicted by the power model, though this could have resulted from biases.

Siregar et al., (2020) applied a structural equation model (SEM) to assess the traffic heterogeneity and crashes as captured in speed, speed deviation, and traffic volume for inter-urban roads in Indonesia. Several regression analyses were carried out, modelling simultaneously the effects of speed (including speeds for all individual vehicle types), traffic volume, road geometry (bendiness, hilliness, bend density, and hill density), and road surface condition (represented by International Roughness Index (IRI)) collectively as independent variables and with crash rate and fatality rate as dependent variables. The SEM was performed in two levels; level 1 included only speed variables, and level 2 was composed of level 1 variables in addition to geometry and volume parameters. The results for level 2 models are summarized below as linear equations.

$$S = -0.329\ Vol - 0.559\ Geom \quad (4)$$

$$SD = -0.422\ Vol - 0.672\ Geom \quad (5)$$

$$FR = 0.473\ S - 0.421 SD \quad (6)$$

$$AR = 0.396\ S - 0.491 SD \quad (7)$$

Where S is the speed, SD is the standard deviation speed (defined as speed variation of vehicle categories), FR is the fatality rate, AR is the accident rate, vol is the volume, and Geom is the geometry parameters.

The above mathematical results indicate a positive speed-crash relation and a negative speed variation-crash relationship. However, the study showed that speed was not significant in predicting crash rates but was significant in predicting fatality rates; the reverse was true for speed deviation. If holding other factors fixed, a 1 km/h increase in speeds increases fatality rates by 0.473, which is very weak and far from the power model results. On the other hand, an increase in 1km/h speed deviation decreases crash rates by 0.491. If equations 4 to 7 above are resolved for traffic volume, opposite results in crash rates and fatality rates are observed, which is not theoretically plausible as a change in volume cannot lead to a positive change in fatality rate and an adverse change in crash rate AR at the same time.

The study methodology and results have several limitations to be conclusive. The results show a linear relationship between fatalities, speed, and speed deviation as single variables. However, researchers (Elvik, 2009, 2011; Elvik et al., 2004; Taylor et al., 2002) have refuted studies which use a linear model form to represent the speed and crash relationship as such models have no theoretical significance. The exponential and power functional forms are the most acceptable for modelling speed-crash relationships (Elvik, 2009; Elvik et al., 2004). For instance, the linear relationship in the study will indicate that a change in fatality rate due to speed change is independent of initial speeds, which is not valid. Further, the study is likely to have omitted variable bias (the effects of the number of lanes, length of segments, pedestrian, and bicyclist volume), bias due to inappropriate choice of the dependent variable (use of crash rates as dependent variable) and bias due to incorrect functional form (Elvik, 2011). In addition, the SEM employed by the authors does not allow any proof of causality between variables and can only be used for confirmatory purposes (Gargoum & El-Basyouny, 2016). Moreover, the authors did not indicate the speed range to which the equations can be applied, hence inconclusive for any speed environment.

In the subsequent year, Siregar et al., (2021) carried out a speed study on inter-urban roads in Indonesia, aiming to develop a power model to investigate the relationship between speed change and traffic safety in the heterogenous setting of Indonesia. The authors highlighted the importance of studying safety by considering traffic heterogeneity as studies need to emphasize on the different vehicle category-based speeds, which have often been omitted in scientific literature. The authors developed new powers of the power model through some speed change combinations (for both mean speed and mean speeds of individual vehicle types) for different injury types (in cumulative form as the initial Nilsson 2004 study) by applying the general equation:

$$f(x)=\beta x^{m} \quad (8)$$

The independent variable x (the speed ratio before and after the study period (2013 to 2016)) was modelled with the dependent variable f(x) (the crash ratios for each crash category according to the Nilsson power model) for the mean traffic speeds and the mean speeds of each vehicle type, to estimate the indices (m) of the power model. After calibrating the models, the results indicated that the mean traffic speed was significant in predicting changes for all crash categories, while the individual vehicle mean speed was significant only for specific crash categories. For instance, while the number of fatal and serious injuries was most sensitive to changes in the speeds of pickups and passenger cars, the number of fatalities (victims) was more sensitive to the changes in the speed of trucks only. This indicated the complex effects of traffic heterogeneity on safety outcomes. Largely, the observations suggest the importance of a given vehicle's speed in mixed traffic as a primary contributor to certain crash types or as a reference speed. Studies carried out by Zhao et al., (2019) in China highlight the importance of the speed of other vehicles in traffic, especially when drivers want to keep the desired speed; hence it is always important to identify which road user speed is critical for any mixed traffic.

This study by Siregar et al., (2021) was essential as it set the basics for establishing the relationship between speed and safety in a heterogeneous environment and also demonstrated the effects of individual vehicle speed contribution to crashes. However, due to the study's methodological issues and significant limitations, the results of the power estimates are not presented for this review. The study did not control for biases and confounding factors (like flows) that could have contributed to the crashes observed. Moreover, the study did not indicate the absolute speed changes between the study periods or highlight any engineering measures or policies that could have led to the speed change between the reference periods. Additionally, the mean speed applied in the study varied from 54.4 km/h to 58km/h and the estimates can only be concluded for this limited range. A collection of these limitations will imply that the study's results only provide partially supported evidence of the effects of speed on a heterogenous traffic environment.

In the subsequent year, Siregar et al., (2022) applied (and compared) machine learning techniques (random forest, gradient boosting machines, bagging regression trees) to investigate the effect of traffic heterogeneity and road geometry features on fatal crashes. The analysis permitted variables affecting all crashes and fatal crashes in mixed traffic to be placed in order of importance. The geometry variables such as length and curvature were rather at the top followed by the average speed of angkot vehicles, the average daily traffic (ADT) for pickups and trucks, and then the standard deviation speeds of motorcycles, buses, and angkots. Unfortunately, the authors did not include the average traffic speed as one of the explanatory variables. As per the results, the classification suggests the complexity of factors responsible for crashes in a mixed traffic composition and shows how the speed or speed deviation or the flows of a particular road user might be a determining factor in crash occurrence. However, the position of the ranking showing exposure factors more likely to be at the top than speed factors are debatable and would necessitate further research or a solid theoretical explanation which the authors did not provide. This study did not provide any assessment to investigate the effects of speed and other parameters for different injury categories, nor did the authors provide any quantitative estimates of the effects of speed on crashes, hence highlighting gaps for future research.

3.3.2. Studies on Speed and Crashes with limited evidence of heterogeneity (these studies did not explain the traffic composition)

Wang et al., (2018) investigated the effect of speed, speed variation, and crash relationship on 234 one-way segments of 16 urban arterials in Shanghai, China. They introduced a new approach using taxi-based high-frequency GPS data that captures the effects of the spatio-temporal distribution of speeds, hence eliminating potential biases. They employed the data set; mean speed, speed variation, road geometry, and crash data (99% being PDO -property damage only crashes) to develop a hierarchical Poisson log-normal model with random effects (which accounts for correlation amongst segments) to show the relationship between speed and crashes. The speed variation coefficient used in the study considered both the variation in speed amongst vehicles and the speed changes for each vehicle. The authors controlled for unobserved heterogeneity by grouping the arterials into homogenous groups using a Chi-squared automatic detection decision tree, with each segment as the response variable and the reciprocal of the average length of an arterial as the independent variable. After fitting the model, the results showed that a 1% increase in mean speed and speed variation was associated with a 0.7% and 0.74% increase in total crashes, respectively. Their results compared to Elvik's 2009 power model for PDO crashes in urban areas were very consistent and suggested the applicability of the power model. In addition, the study result supported that speed variation was strongly linked to higher crash frequency. A key aspect to note in this study is that most crashes were PDO which is often not the usual for LMICs. Moreover, the study did not mention the traffic composition though it controlled for the speed variation between vehicles. Further, having 99% of PDO crashes would suggest few VRU (vulnerable road user) crashes and would likely mean these VRUs are highly segregated from traffic. Due to these observations, and the limitation of the study to PDO crashes, which is usually more likely underreported, the study shows only limited evidence on the applicability of the power model in a mixed-traffic environment

In earlier studies, Wang et al (2015) investigated the effects of average speed on crash frequencies for both peak and non-peak hours, though with some limitations as the authors failed to control for speed variation and flows of VRU. Nonetheless, the study results showed that average speed was only significantly related to crashes during peak periods and not during off-peak periods. In particular, an increase in 10km/h speed during peak periods increased crash frequency by 3%. Using the results presented by the authors, it was possible to calculate the crash elasticity, which showed that a 1% increase in mean speed increased crash frequency by only 0.08%. This relationship is very weak and slightly out of the range predicted by the power model. This weak evidence could result from the authors not controlling for the biases identified. In addition, it is possible that the majority of crashes were PDO related, as observed in a later study (Wang et al., 2018). The differences in results between Wang et al., 2015 and 2018 would suggest the importance of controlling for speed variation in speed-crash modelling, as was done by Wang et al., (2018). However, both studies did not indicate the type of traffic composition, providing no conclusive evidence of the power model for mixed traffic.

Besides investigating the speed and crash relationship, Xu et al., (2019)) applied a hierarchical Poisson model to investigate the effects of speed variance on PDO crashes for 190 expressway segments in China. They derived two speed variance measures called the standard deviation of the cross-sectional speed mean (SDCSM) and the cross-section speed standard deviation (MCSSD) to capture the spatial and temporal speed variances. The model results showed that a unit rise in the standard deviation of the cross-sectional mean speed and the cross-section speed standard deviation was associated with an 8.80% and 3.7% increase in PDO crash occurrence, respectively. However, this study was limited to PDO crashes, and there are likely possibilities of bias as the authors failed to consider mean speed as an independent variable in the models.

Ang et al., (2020) conducted before and after studies to investigate the effect of speed limit reduction from 90km/h to 70km/h on main highways in São Paulo, Brazil. The study included over 202 different roads with a total length of 570km. To estimate the effect of speed limit change on road crashes, the authors used a dynamic event study which makes use of the exogenous variation in the timing of speed limit reduction. They argued that a semi-dynamic model was flexible to capture the effects that change in the periods from initial treatments, hence controlling for unobserved heterogeneity bias. After calibrating their models, they found that the speed limit reduction reduced 21.7% of road crashes on the treated road segments. Hence, providing some evidence of the effectiveness of speed limit reduction in a developing country context. However, the authors did not mention how the mean speeds changed with the speed limit changes during the study period, so directly comparing the results with the power model is difficult.

Following the speed limits increase by 10-20km/h on different roads in Hong Kong (between 1999-2002), Wong et al., (2005) studied the speed limit relaxation effects in terms of changes in FSS (fatal, serious, and slight injuries) and FS (fatal and serious injuries) by comparing treated and untreated group. They noted that when the speed limit increased by 20km/h (from 50 to 70km/h), the FSS increased by 15% and FS by 1%. When the increase was 10km/h (70 to 80km/h), the FSS increased by 18% and FS by 36%. Though both results indicate adverse safety effects when the speed limit is increased, it is interesting to note that the effects observed for an increase in 10km/h are higher than that at 20km/h. In as much as these results could be due to study bias, they could suggest the importance of an initial and final speed as more crashes are (of course) expected to occur at higher speeds (80km/h) than at relatively lower speeds (70km/h), so the increase from 70 to 80km/h (10km/h) could probably produce more adverse effects than the increase from 50 to 70km/h (20km/h). The changes in mean speed were not indicated in the study, and as such a direct comparison with the power model is not feasible. However, from the results of the estimates, it is noted that the effect produced for FS when the speed limit increased by 20km/h is too small and lower than the effect for FSS, which is inconsistent with the power model since the power model estimates decrease monotonically as injury severity decreases and the effects of FS should be greater than the effect of FSS. Nonetheless, the results for the speed limit increase by 10km/h were more consistent with the trend of the power model.

There is also evidence of the detrimental effects of speed limit increases in other developing country contexts, such as in Ankara, Turkey. Ture & Tuydes (2020) studied the effect of speed limit increase (from 50km/h to 82km/h) in Ankara urban arterials using a GIS-based evaluation and employing a nearest-neighbour hierarchical clustering. They observed that the number of crash clusters increased after the period of speed limit increase. However, the authors did not conduct any objective study to determine the direct influence of the speed limit change on average speed and crashes.

Table 3.1 provides a summary of the studies that have investigated the effects of speed and crashes in low and middle-income countries (also referred to as developing countries for this study).

Table 3.1. Summary of speed-crash studies for LMICs

Study	country	Network type	Main theme	crash outcome	comment on methodology
Ang et al., (2020)	Brazil	Rural roads	Speed limit change (90 to 70 km/h)	27.1% reduction in all crashes	Sound methodology though the authors did not measure the mean speed. BAS
Cetin et al. (2018)	Turkey	Rural roads	Speed limit change (90 to 110 km/h)	Mean speed increased by 3.2% (passenger cars), and 5.8% (for the bus) which led to a 43% increase in the number of fatalities and a 36% increase in the number of Injuries	Assumptions were logical, but it was not very objective for some confounders that affect crashes. BAS
Vet et al., (2016)	Bangladesh	Rural roads	Integrated Speed management	Mean speed was reduced by 13km/h and led to 67%, 66%, and 73% changes in fatalities, seriously injured and injured respectively.	The methodology was sound but did not control for the effects of other interventions. BAS
Siregar et al., (2020)	Indonesia	Inter-urban	Speed-crashes in heterogeneous traffic	For a 1km/h increase in mean speed, fatality rates increase by 0.473	The study was biased for model form and omitted variable. CSS
Siregar et al., (2021)	Indonesia	Inter-urban	Speed-crashes in heterogeneous traffic	Power estimates for mean speed are 1.4 for fatal crashes,1.01 for fatal and serious crashes, and 0.78 for all injured road users	The study was biased for omitted variables and confounders that affect crashes. CSS
Siregar et al., (2022)	Indonesia	Inter-urban	Effects of heterogeneous traffic on fatal crashes	The speed of angkot and standard deviation speeds of motorcycle, bus, and angkot were the main causative factors in fatal crashes	Sound Methodology.CSS
Ture & Tuydes, (2020)	Turkey	Urban roads	speed limit change (50 to 82 km/h)	More crash clusters	Sound Methodology, the focus was on crash clusters. BAS
Wang et al., (2018)	China	Urban roads	Speed crash modelling	1% increase in mean speed and speed variation increased total crashes by 0.7% and 0.74% respectively	Mostly PDO crashes, and the study did not control for volumes of VRU.CSS
Wang et al., (2015)	China	Urban roads	Speed crash modelling	10km/h increase in speed during peak periods increases crash frequency by 3%	Did not control for speed variation and volumes of VRU.CSS

Wong et al., (2005)	China	Rural roads	Speed limit increase by 10 and 20km/h	FSI increased by 1% & 36% for 20km/h (50 to 70) & 10km/h (70 to 80) increases in speed limit respectively	Mean speed changes were not measured. CSS
Xu et al., (2019)	China	Urban roads	Speed crash modelling	A 1% rise in speed standard deviation increases PDO crashes by 8.8%	Mostly PDO crashes and the study did not control for volumes of VRU. CSS

NB:BAS=Before and After study: CSS=Cross-sectional study.

3.3.3. Studies on other speed context /countermeasures for developing countries

Afukaar (2003) was one of the first to study/address speed issues in developing countries, particularly in Africa. He examined the challenges and opportunities for speed control vs traffic safety relationship in developing countries, with Ghana as a case study. He highlighted that excessive speeds are very common in industrialised and developing countries where drivers usually travel far above the posted speed limit, concluding that posted speed limits alone do not guarantee compliance. Studies on speed attitudes and drivers' behaviours (Bachani et al., 2013; Mahasirikul et al., 2021; Zhao et al., 2019) carried out in different developing countries confirm the presence of excessive speeds and inappropriate speeds in mixed traffic, where road users travel at the same time and space with varying high speeds. Afukaar (2003) highlighted that the adoption of speed countermeasures proven effective in HICs would not always produce the same results for developing countries, and caution needs to be taken. Afukaar cited that the problems in developing countries were related to the failure of law enforcement, insufficient resources for traffic police, bribery and corruption, weak transport policies, and low public awareness. Moreover, speed control measures and compliance most often tend to be cultural and with the existing cultural differences amongst countries (some of which can include: drivers' attitude, type of vehicles driven (old or new), maintenance rates of vehicle, overloading, drivers' choice and perceptions, land use types/practices), the application of measures effective in developed countries will not always work in the context. In addition, drivers' choice of speed depends on a variety of factors that are different between countries. These factors could be classified as legal, social, person-related, and situational factors (Judy & Barry, 2006).

Afukaar (2003) highlighted that the use of physical speeding control such as rumble strips and speed humps (that segregates high and low-speed users), which are usually less costly, can be appropriate for developing countries. In an earlier study in Ghana, Afukaar et al., (2001) showed that implementing rumble strips effectively reduced crashes by about 35% and fatalities by about 55%. In a later study, Afukaar (2008) supported the effectiveness of speed humps in reducing speed and its associated safety benefits. Besides using physical speed calming measures, Afukaar (2003) highlighted that fitting speed control\warning devices in vehicles is an opportunity to control speeding in developing countries.

Damsere-Derry et al., (2008) assessed the speed of vehicles for different roadways categories in Ghana to establish the mean speed and its dispersion on the studied roadways and determine the level of speed compliance. They measured the travel speeds of 28,489 vehicles for three highway categories (national, international, and regional roads (for both rural and urban roads environment)) using a radar gun. It was observed that all vehicles were driving at speeds far greater than the 50km/h Posted Speed Limit (PSL) for urban areas and also greater than the 80km/h recommended speed limit for a rural area. In addition, they noted that private cars exceeded the PSL most and by up to +40km/h in urban areas, while trucks drove at relatively lower speeds. Given that urban areas are usually more populated with high VRU flows, these high speeds observed suggest the criticality of the levels of safety since vehicles -pedestrian collisions at such high speeds would lead to high chances of fatality; hence would justify speeding as a contributory factor to high fatality rates in Ghana urban areas.

Regarding speed dispersion, the authors observe high values in all road environments, with the greatest values in rural roads. These high values reflect a high combination of vehicles travelling at different speeds (too high and too low speeds), which is detrimental to safety. The conclusion that can be drawn from the study by Damsere-Derry et al., (2008) is that both inappropriate speed (trucks travelling at relatively lower speeds impeding free flow; high-speed dispersion) and excessive speed (travelling at speeds far greater than recommended speeds) are issues for developing countries. Therefore, speed is considered a major contributory factor to crashes in developing countries.

Carrillo-Gonzalez et al., (2021) carried out a traffic simulation study in Mexico to understand the dynamics of traffic in developing cities by evaluating the impact of vehicles (buses, taxis, passenger cars) and traffic infrastructure on average speed. The study results were threefold: (a) buses' arrival frequency and curbside bus stops affected the passenger cars' average travel speed, (b) Taxis' arrival frequency, stopping frequency, and speed tendency was found to influence the passenger cars' response and (c) The number of speed bumps, the arrival frequency of passenger cars, and their speed conditions (homogeneous and heterogeneous) affected the passenger cars' response. These study results reveal the complexity of traffic dynamics in a heterogenous traffic environment and how the speed of a road user depends on its interaction with the speed of other road users. More research in this domain is needed to unveil the hidden dynamics in mixed traffic, which will help provide appropriate policy measures.

Hydén & Svensson, (2009) conducted a twin study to identify pedestrian safety issues and feasible traffic calming solutions in India. After carrying out a field investigation, they noted that: pedestrians are highly exposed and very vulnerable to too high speeds (85^{th} % speed > 50km/h), and pedestrians are not offered comfortable or safe crossing options. As a result, it would often lead to pedestrian jay crossings and haphazard crossings at dangerous locations. Regarding the traffic calming measures, speed humps and rumble strips were observed to be effective in reducing speeds, with most vehicles driving at speeds less than 30km/h in the areas of the measures. In addition, the authors observed that speed humps were more effective in reducing car speeds than motorcycle speeds. Longer rumble strips were observed to be more effective than shorter ones. Overall, the authors concluded that simple and low-cost traffic calming measures, which also make approaches for pedestrians comfortable and safe should be promoted for large-scale use in developing countries.

Traffic calming measures and their effectiveness have also been investigated in other developing country contexts (different traffic mix). Nadesan-Reddy & Knigh (2013) investigated how traffic calming affects pedestrian injuries and motorcycle collisions in South Africa. They carried out a BAA through an interrupted time series for roads in school zones following the implementation of road humps. The study results indicated that traffic calming (using hump) was effective as it reduced the number of serious pedestrian-vehicle collisions by 22%-23% and fatality collisions by 50-68% in the study areas. As with other related studies on traffic calming measures, the authors did not report controlling for any confounding biases, especially regression to mean bias (RTM), which is common for BAS.

4. Discussion: summary of findings and future directions

This review on road safety and speed studies within the context of developing countries revealed some important findings and provided answers to the questions which were not too evident. Overall, studies in the literature are limited and have not fully uncovered the relationship between speed and crashes in a mixed-traffic environment. The discussions of findings are separated under different research question areas to provide more explicit evidence on the outcome of this review. Nonetheless, the topics discussed are interrelated, and the evidence from one leads to the other with the overall aim of addressing the speed and crash relationship in LMICs.

4.1. Road safety a problem for LMICs

Findings show that LMICs continue to suffer the negative consequences of road traffic deaths and injuries with the highest impact on the poor, and if no effective measures are taken, this epidemic is expected to double. Rapid motorisation combined with the non-disappearance of non-motorised vehicles has been identified in the literature to be a contributory factor to the high toll of crashes in LMICs. This can be attributed to the fact that growth in vehicles increases crash exposure and hence the likelihood of a crash. Moreover, road safety culture in LMICS remains detrimental; vehicles purchased & used are most likely to be "second-hand", less likely maintained, and most often overloaded; street vendors most often occupy sidewalks for pedestrian movement; and drivers are less likely to give way for pedestrians crossing. The identification and resolution of these factors through research or policies are critical to making any improvement in road safety in LMICs. The high burden of traffic crashes in LMICs has also been attributed to poor enforcement of traffic safety regulations, the inadequacy of public health infrastructure, and poor access to health services.

These complexities of problems in LMICs are further aggravated by the failure to actually perceive the problem and set appropriate policies and coupled with the little knowledge of safety interventions, LMICs have resorted to

HICs for solutions. Evidence in the literature suggests that due to differences in road safety culture between HICs and LMICs, especially in terms of traffic mix, land use practices, and literacy rates, interventions proven effective in HICs do not necessarily translate to LMIC's context. Hence in cases where interventions must be implemented especially on a large scale, there is a need to research and test the adequacy and effectiveness of these interventions at least on a smaller scale before implementation. However, due to limited financial resources, this is usually not the case. In addition, a lack of adequate data usually hampers the capacity of LMICs to manage road safety.

Speed is being recognised as a key contributor to the tragedy of traffic deaths in LMICs. The literature identifies that both excessive and inappropriate speeds are typical for LIMC drivers, and this is associated with the increase in the risk, frequency, and outcome of crashes occurring. However, how speed affects the outcome of a crash is clear-cut, and undebatable and can be explained by the laws of physics, but how much it affects the likelihood of a crash is debatable and remain controversial.

Speed characteristics, its nature, and distribution in LMICs and its differences from that of HICs have highlighted the growing need for testing safety interventions or research carried out in HICs. As compared to the homogenous traffic in HICs, the traffic in LMICs is mixed (heterogenous) and usually contains different categories of vehicles. Sometimes within the same categories, the vehicles vary by size and have different operating and manoeuvrability characteristics, making the whole phenomenon complex (Dhamaniya & Chandra, 2013). Research in LMICs needs to focus on this direction to understand how the traffic mix and its dynamics affect safety and safety interventions.

4.2. Speed and crash relationship in LMICs

The speed and crash relationship in the LMICs context is complex and enigmatic. The complexity of speed in LMICs is defined by its mixed traffic**.** The mixed traffic in LMICs has vehicles which are most likely “second hand”, with different static and dynamic characteristics driving at varying speeds in the same space and time. This complex phenomenon makes it difficult to understand how speed and its interrelation with the traffic environment affect crashes. There is supported evidence from studies that the speeds of particular road users in mixed traffic are more important than those of others and are a determining factor in the occurrence of some crash types and levels of injury severities. Hence research must focus not only on the aggregated mixed traffic scenario but try to unveil the hidden relationship between speeds and crashes of each individual road user in traffic.

Due to the characteristic difference observed between traffic in LMICs and HICs, the impact, success, and consequences of speed management strategies are expected to vary between the two. Though considerable research on speed has been undergone for HIC, only a few studies have addressed the issue of speed and crashes for LMIC. While studies for LIMC have confirmed the positive relationship between speed and crashes, they are mostly flawed, and the results are daunting for the established strength of the speed-crash relationship.

Studies carried out in other developing country context, as in the case of Wang et al., (2018); Wang et al., (2015), does not appropriately account for the issues of mixed traffic either because the traffic composition in the study area is closer to being homogenous or due to under-appreciation of the issues of heterogeneity. However, the study details provided by the researchers would instead suggest the former to be true. The differences in results observed between studies suggest the importance of determining the degree of traffic mix and its characteristics as a first step to any speed and crash modelling exercise. Hence studies in developing countries that fail to appreciate or control for traffic heterogeneity are either invalid or valid if there is sufficient evidence to prove homogeneity (in which case deviates from the usual traffic considered for LMICs). Notwithstanding, cities in some MICs or upper-MICs like Shanghai treated in this study that are adopting technology, implementing new policies, and moving towards more homogenous traffic and better road safety culture should not be treated in the same group as those with fully mixed traffic.

In general, studies provide evidence of the positive relationship between crashes and mean speed, but there is no substantial evidence of the strength of the speed-crash relationship in mixed traffic because studies have failed to account for different biases sufficiently. However, speed is being recognised as an impactor contributory factor to crashes in LMICs and the pedestrian often not offered comfortable or safe crossing options are most likely affected.

Evidence from studies highlights speed variance and individual road users' speed as important factors responsible for crash occurrence in mixed traffic. The differences in speeds between vehicles in mixed traffic scenarios with a combination of too fast and too slow drivers and too big and too small vehicles will undoubtfully affect safety due to the increased chances of collision and high severity of a collision if it occurs.

Literature highlights substantial evidence of the effectiveness of low-cost measures to speed management initiatives in LMICs; examples include rumble strips and speed humps. On the other hand, there is limited evidence of the effectiveness of speed limit reduction for LMICs. However, studies suggest that such a measure would not be effective, especially if not complemented with other measures like enforcement or infrastructure modification.

Given the evidence provided, speed- crash studies in LMICs are still rudimentary, and there is an urgent need to research and understand how speeds affect crashes in a mixed and complex traffic environment and for which road users are highly impacted and likely to be responsible for the crashes. Before examining the relationship between speed or speed variance and crashes in LMICs roads, research should first focus on understanding the complex and interwoven relationship between speed and: road geometry features; traffic volumes of each road user; driver speed choice and attitudes; land use practices; and weather conditions. No study has examined the consequences of impacts speed and survivability of each road user in LMICs context, and future directions should also be made in this aspect.

4.3. The power and exponential model in LMICs. Evidence or Not?

From the assessment of the literature on speed, including studies in LMICs and an evaluation of the power and exponential model, there is no conclusive evidence that these models can be applied to the LMIC context; hence caution should be taken when generalising or using these models for LMICs.

An evaluation of Nilsson's and Elvik's power models and Elvik's exponential model gives limited evidence of their applicability in LMICs. Firstly, Nilsson (1982) developed and Nilsson (2004) validated the power model using HIC data, and no data source from LMIC was used either in the development or validation of the model. Secondly, Elvik et al., (2004) carried out a meta-analysis to estimate the power model on 98 relevant speed studies, Elvik (2009) updated the power model on 115 speed studies, Elvik (2013) reparametrize the power model by fitting exponential functions using Elvik, (2009) studies, Elvik et al., (2019) reanalyzed the power and exponential models at individual and aggregated levels for studies published after 2000, but unfortunately, apart from one study in Turkey (which is an upper MIC) that was included in the 2019 study, none of the studies used to calibrate the meta-analyses contained data from any LIC or MIC. However, part of the problem is the absent of robust research on LMICs that meets the criteria for inclusion in the calibration of the power and the exponential models.

Given the evidence that these models didn't include data from LMIC, it is possible to argue that the models cannot be applied in LMICs. This is because due to the characteristic difference between HIC roads and LMIC roads in terms of traffic mix, land use practices and road safety culture, which unanimously affects the extent of speed and its distribution, models that are developed in one context do not necessarily apply in the other context and needs to be validated.

Based on Elvik (2009) analyses, he observed a decline in the estimates of the power model over time, especially for fatal crashes and concluded that the effects on crashes of given changes in speed reduce over time, and the power model could be generalised for all countries. However, this is not totally true for LMICs, especially for LIC as the number of crashes has even doubled, and no LIC has observed any decline in traffic fatalities since 2013 (WHO, 2018). Therefore, this observation suggests that the applicability of the power model in the LMIC context is questionable and needs to be sufficiently tested.

Few studies that have assessed the speed and crash relationship in a developing country context and those that have discussed aspects of speed and crashes in a mixed traffic scenario have failed to fully prove, demonstrate or provide sufficient evidence on the applicability of the power and exponential models to this context. Either because these studies are methodologically flawed (i.e., cannot validate the models), contradict the power and exponential model, or have not controlled for traffic heterogeneity.

Evidence from speed studies in LMICs suggests that the speeds of some individual road users in mixed traffic determine the occurrence of different types of crashes and severities. However, the power and exponential models are developed based on aggregated data which is usually based on the mean speed, and there is still limited evidence in the literature on how these models can be applied at the individual vehicle levels; as such, it is inclusive that these models can be applied to road users in mixed traffic in LMICs.

Given the above evidence, the power and exponential models remain to be tested and validated. To test these models, an extensive set of data from different LMICs would need to be collected, controlled for underreporting and speed-crashes models developed while controlling for traffic heterogeneity and other confounding bias such as road features (Gargoum & El-Basyouny, 2016; Taylor et al., 2002; Victoria, Gitelman, Etti, Doveh, Shlomo, 2017), traffic exposure (Gargoum & El-Basyouny, 2016; Taylor et al., 2002; Victoria, Gitelman, Etti, Doveh, Shlomo, 2017), weather (Imprialou et al., 2016; Tanishita & van Wee, 2017), collinearity amongst variables (Elvik, 2011; Tanishita & van Wee, 2017; Taylor et al., 2000), temporal and spatial correlation (Lord & Mannering, 2010) and controlling for various bias peculiar to the type of study method/data type (Aarts & Van Schagen, 2006; Carter et al., 2012; Elvik, 2011)

5. Conclusion

The main conclusions of the review in this paper can be summarized as follows:

- LMICs continue to suffer the negative consequences of traffic deaths and injuries, and while rapid motorization is observed, non-motorized vehicles have failed to disappear, further aggravating safety problems.
- Road safety differs between HICs and LMICs, and interventions proven effective in one context must be tested in another.
- The relationship between speed and crash likelihood is complex in mixed traffic common to LMICs.
- The relationship between speed, speed variance, and crashes is positive in mixed traffic.
- The speeds of some road users in mixed traffic are more important than others and are a determining factor for particular crashes and injury severities.
- There is substantial evidence of the effectiveness of low-cost measures to speed management initiatives in LMICs, such as rumble strips and speed humps.
- There is no conclusive evidence that the power and exponential models developed based on HIC's data can be applied to LMIC's context. Part of the problem is due to lack of robust research in LMICs.
- The relationship between speed and survivability limit of road users in mixed traffic is not known.
- Speed studies in the LMICs context are rudimentary and the strength of the speed-crash relationship is not known.

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