SPEED MANAGEMENT RESEARCH:

A Summary Comparison of Literature Between High-Income and Low and Middle-Income Countries

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Acronyms

AADT	Annual Average Daily Traffic
ADT	Annual Daily Traffic
AMF	Accident Modification Factor
ANOVA	Analysis Of Variance
API	Application Programming Interface
BAS	Before and After Studies
BIGRS	Bloomberg Philanthropies Initiative for Global Road Safety
CSS	Cross Sectional Studies
ESRA	E-Survey of Road Users' Attitudes
FCD	Floating Car Data
GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographic Information System
GLM	Generalized Linear Models
GPS	Global Positioning System
GRSF	Global Road Safety Facility
HIC	High Income Countries
ISA	Intelligent Speed Adaptation
KPI	Key Performance Indicators
LIC	Low Income Countries
LMICs	Low- and Middle-Income Countries
MIC	Middle Income Countries
NMT	Non-Motorized Transport
NMV	Non-Motorized Vehicles
OBD	On Board Diagnostic
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSL	Posted Speed Limit
SSA	Sub-Saharan Africa
TPB	Theory of Planned Behavior
VMT	Vehicle Miles Travelled
VRU	Vulnerable Road Users
VSL	Variable speed Limits
WHO	World Health Organization

Executive Summary

Low- and middle-income countries (LMICs) have been experiencing growth in vehicle travel and mobility but have not yet realized road safety gains experienced by high-income countries (HICs). Excessive and inappropriate speed is known to be a major cause of road crashes, injuries and deaths. Thus, speed management is considered a key initiative for improving road safety outcomes worldwide and has been applied successfully in most HICs. Proven interventions do not necessarily have the same impacts in LMICs, or may not be feasible to apply, due significant differences in traffic mix, road user behavior, road design and vehicle standards.

This document summarizes current available knowledge about speed, its effects on safety, mobility and emissions, along with potential safety effectiveness of speed management initiatives in the LMIC context. Knowledge gaps for LMICs are clearly referenced for further consideration.

Relationship between speed and safety outcomes. All road users are at increased risk of crashes, injuries and death when travelling at higher speeds. Vulnerable road users experience very high risk of death at vehicle impact speeds as low as 30 km/h. Empirical models relate change in mean traffic speed to changes in fatal and serious injuries and could be used to estimate effectiveness of many speed management initiatives. LMIC-specific models are not available especially for the vulnerable road users such as powered two- and three-wheelers (a knowledge gap). In the interim, the HIC models are likely to provide a general conservative estimate. Global Road Safety Facility (GRSF) provided a practitioner tool to assist in estimating safety benefits via its Speed Management Hub.

Speed and emissions relationship. There is ample evidence that high speeds and stop-start urban traffic result in increased emission and pollution. Reviewed studies point to reductions in emissions and pollutants when speeds are reduced from high to moderate. There is emerging evidence that reducing urban speeds via traffic calming and introduction of 30 km/h speed limits would also reduce emissions via smoother traffic flow and modal changes away from driving. There was a general lack of knowledge and emission rate models applicable to the diverse traffic scenarios found in LMICs.

Speed variance and crashes. Higher traffic speed variation is associated with increased crash and injury risk. The nature of this relationship with mean speed is not simple and poorly understood outside of LMIC high-speed road networks. Safety effects of speed differences between different driver / vehicle types need to be understood (e.g. two-wheelers and trucks).

Traffic mix and speeds of different road users. Research recognized that LMIC traffic has more diverse vehicle and road user types than found in most HICs. This results in greater variance around mean traffic speeds, speeds of different vehicle types and in complex interactions between them. There is a need to better understand how these affect crash injury risk for different road users, and effectiveness of speed management initiatives in LMICs.

Speed limits and travel time (mobility). Speed limit reductions have been used as a low-cost measure to reduce crashes and injuries. Research demonstrates that drivers have a bias to overestimate time lost when speed limits are reduced, leading to frequent opposition. In urban areas, actual travel time impacts were negligible due to delays at intersections and other traffic disruptions. Rural trip times were minimally longer at reduced speed limits, with practical impacts dependent on the overall trip length. Variable speed limits used on motorways were found to reduce travel times through predictive application of temporary reductions in speed limits. LMIC There was little LMIC research on the effects of speed limits on travel time.

Cultural differences affecting attitudes to speed. Cultural differences may influence attitudes toward speed selection and speeding with factors including personal, social, situational, legal and travel time (economic) pressures. Reviewed studies found speeding was more acceptable or likely in LMICs due to attitudes and behavioral norms. Still, speed attitudes are significantly different amongst LMICs and need to be understood in individual country context. There was a need to provide a standardized framework for understanding the complex factors affecting speeding in each country.

Speed data collection methods. The review highlighted the need to select fit-for-purpose traffic speed Key Performance Indicators (KPIs) before undertaking any speed data surveys. Leading speed data collection methods were summarized and compared, including conventional roadside and recent floating-car data (FCD) sampling approaches. The lack of guidance on selection of speed KPIs and methods was noted in the LMIC context of more mixed traffic.

The knowledge summary provides a useful reference for practitioners wishing to inform themselves about traffic speeds, their selection and impacts on safety outcomes, mobility and emissions. The LMIC knowledge gaps will be useful in considering future research and data priorities.

1. Introduction and Background

The World Bank's Global Road Safety Facility (GRSF) has been partnering with Bloomberg Philanthropies to help improve road safety in developing countries since 2009. As part of the BIGRS 2020-2025 program, this includes providing an active leadership role in speed management related activities, including the production of global guidance, technical assistance, and research on this topic, all developed under GRSF's Speed Management Hub[1].

Since 1999, a progressive reduction in road traffic death has been observed in high-income countries (HICs), yet the proportion of road traffic deaths in low- and middle-income countries (LMICs) has been increasing, accounting for 85%, 90% and 93% of global deaths according to WHO (2004, 2009 and 2018) respectively. This is despite LMICs having just 60% of the world's vehicles (WHO, 2018). With rapid motorization and growth in the number of vehicles in LMICs, road safety issues may be further exacerbated in these countries (Job & Wambulwa, 2020).

Excessive and inappropriate speed is known to be a major cause of crashes, contributing to between 30% and 50% of road fatalities. Thus, moderating traffic and driver speeds, or speed management, is considered a key initiative for improving road safety outcomes worldwide and has been applied successfully in most HICs.

The vast majority of the research on speeds and safety occurred in HICs. Interventions proven effective in HICs do not necessarily have the same impact in LMICs or may not be feasible to apply. There are large differences in road user mix (e.g., proportion of motorcycles), road use (e.g., roadside trading), levels of compliance and enforcement, vehicle safety and road design standards, and different cultural norms. There is little LMIC-specific evidence relating the impacts of traffic speed on safety and to effectiveness of speed management interventions in preventing road traffic injuries. These are only some of the gaps in knowledge that need to be addressed.

It was thus imperative to review a broad range of knowledge about speed, its effects on safety, and potential effectiveness of speed management in the LMIC context. This needed to include behavioral and vehicle factors relating to speed and speeding across different cultural contexts, speed effects on travel time and mobility, on emissions and on pollution.

This literature review aimed to summarize current understanding and knowledge gaps across a selected set of speed related topics in the context of LMICs. The findings will assist World Bank client countries to improve their capability in managing speeds for improved safety, mobility and emissions.

This summary of research is structured to provide an easy reference in key areas relating to speed, speeding, safety outcomes and other key transport performance measures:

- Relationship between speed and safety outcomes
- Speed variance and crashes
- Traffic mix and speeds of different road users
- Speed limits and travel time (mobility)
- Cultural differences affecting attitudes to speed
- Speed data collection methods.

This selective literature review identified the latest available knowledge along with LMIC-specific knowledge gaps across the above subject areas. The review was based on published journal articles and reports, commissioned reports by research institutes, and on relevant technical information resources such as websites.

A pre-defined methodology according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-

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[1] https://www.roadsafetyfacility.org/speed-management-hub

Analyses) guidelines was employed to carry out the literature search. These guidelines provide an evidence-based framework which is transparent, systematic, and unambiguous, and suited to healthcare and safety fields (Hussain et al., 2019). The strategies used to gather papers and publications were as follows:

- Use of search engines and databases such as Google Scholar, SCOPUS, Web of Science, Google Science Direct, etc. using subject-relevant search terms and inclusion criteria.
- Papers from research institutes, e.g. grey literature based on project publications.
- Reference lists and bibliographies of relevant papers were screened to identify other important studies.

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2. Relationship between speed and safety outcomes

Speed is one of the most important risk factors responsible for traffic deaths globally and especially in LMICs. In particular, excessive and inappropriate speeds are associated with an increase in the crash risk, frequency and severity of injuries (Nilsson, 2004, Elvik et al. 2004, 2019a Elvik 2009, Vadeby & Forsman, 2017)

The kinetic energy dissipated in collisions is directly related to the square of impact speed, and hence a higher crash severity is expected to occur when speed increases even by small amounts. Established HIC research tackled the following speed-safety relationships linking:

- individual vehicle speeds to risk of injury crash occurrence (Kloeden et al., 2001, 2002, Elvik et al., 2019)
- vehicle impact speeds to risk of fatal and serious injury outcomes in crashes (Jurewicz et al., 2016; Rosén & Sander, 2009, Hussain et al., 2019).
- changes in average traffic speeds to changes in risk of crashes and injuries of different severities (Nilsson, 2004 Elvik et al., 2004; Elvik, 2013, Elvik et al., 2019)

Relationship between traffic speed variability and safety outcomes is considered separately in Section 4.

Occasionally, selected studies show negative (e.g. Tanishita & van Wee, 2017) or insignificant relationships (e.g. Kockelman & Ma, 2007; Quddus, 2013) between speed and safety. Such findings may be attributed to specific data or methodological choices limiting their broader relevance. The best quality studies used systematic reviews of research, or pooled data from a wide range of environments to generalize a speed-safety relationship.

While the vast majority of empirical studies show a positive relationship between increasing speed and risk of crashes and injuries, the strength of this relationship is not uniform and may vary by road environment and presence of confounding variables.

The findings of the review of available literature on the effects of speeds on safety outcomes have been summarized in logical groupings, as follows.

Effects of individual vehicle speeds

High speeds affect the crash likelihood in a variety of ways. At higher speeds:

- Drivers cover more distance while they react to and process information about potential risks like pedestrians crossing or change in road geometry. This leads to reduced chances of effective braking to avoid a crash.
- Braking/stopping distance is longer and often underestimated by drivers. It takes vehicles longer to dissipate the higher kinetic energy at high speed. This is also highly dependent on road surface and the vehicle (mass, tires, brakes, ABS, ESP, engine braking). Figures 2.1 and 2.2 illustrate the combined effect.
- Drivers are more likely to fail to yield to pedestrians at unsignalized crossings (Job & Brodie, 2022).
- There are possibilities for other road users, such as the elderly and children, to underestimate the time of arrival of the speeding vehicle, and hence they might fail to take necessary caution leading to collisions.
- It is easier for a vehicle to lose control or run off road, especially when negotiating a curve or driving in bad weather conditions.

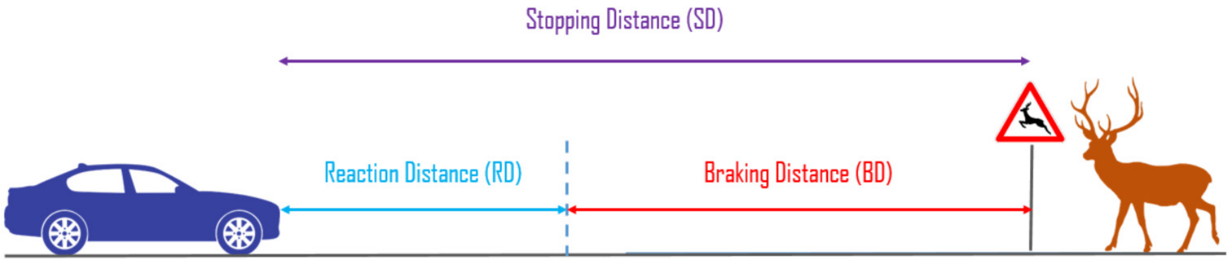


Figure 2.1. At higher speeds drivers need longer distance to react, process and brake to stop.

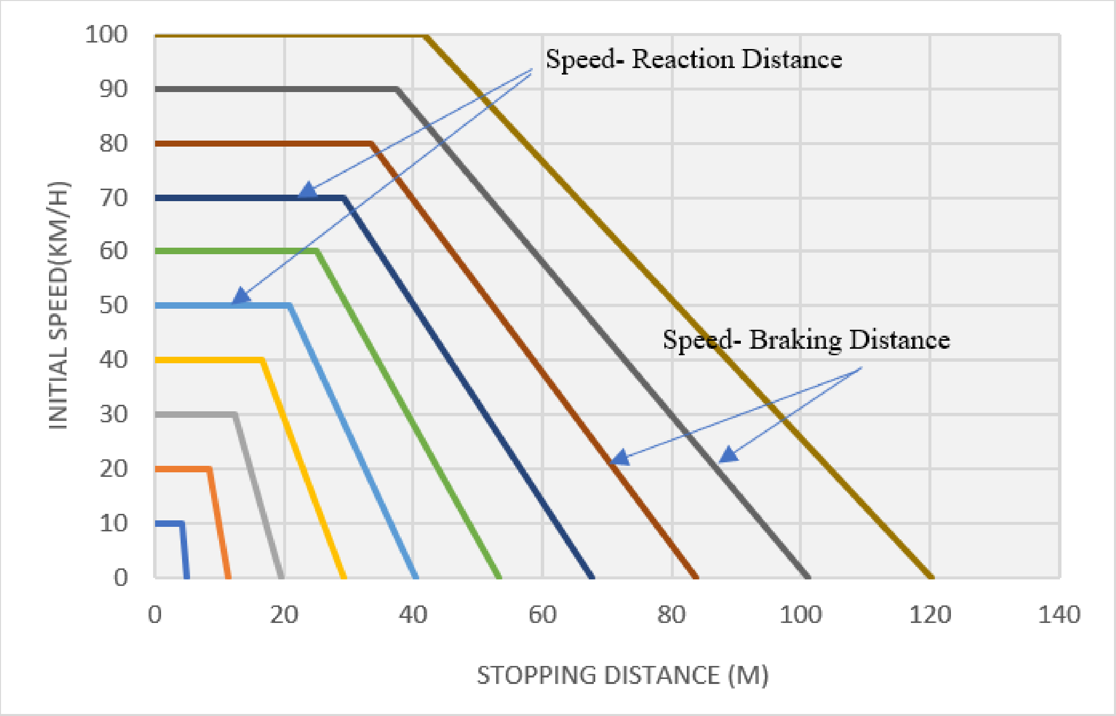


Figure 2.2. Relationship between initial speed and stopping distance.

An increase in driver's free travelling speed above the mean speed (i.e., travelling at speeds greater than the traffic average speed) is expected to increase the likelihood of being involved in a casualty crash on urban and rural roads (Kloeden et al., 2001, 2002 reanalyzed by Elvik et al. 2019).

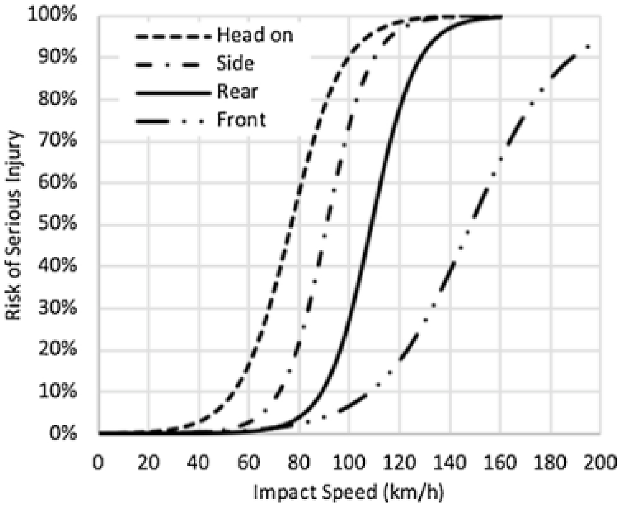
Most of this HIC research focused on crash risk for vehicle occupants. Reviewed literature did not consider motorcyclists, public transport passengers (e.g. minibuses) or cyclists. This represents a knowledge gap, especially in the context of LMICs where these modes form a significant proportion of traffic.

Effects of crash impact speeds

Since the late 1990s, impact speeds above which humans are likely to sustain fatal injuries have been widely studied in crash lab testing environments. This assisted in forming consideration of survivable speed levels for the road system. Wramborg (2005) proposed a set of theoretical relationships between vehicle impact speeds and probability of a fatal outcome. Wramborg suggested that a 10% chance of fatality may be associated with impacts speeds of 30 km/h for pedestrian, 50 km/h in side impacts crashes and 70 km/h in head-on crashes, and that survival rates decreased substantially as speeds increased above these levels. However, these impact speeds were proposed without providing further details (e.g. probability or crash scenario definitions). Despite this lack of supporting evidence, there has been a general acceptance of these speeds as a set of Safe System benchmarks for safe speed policy development.

Further research followed through analysis of high numbers of in-depth crash analyses stored by various safety organizations in HICs. Drawing on US research, Jurewicz et al. (2016) suggested several probability curves for fatal or very serious injuries per crash in several common vehicle-vehicle crash scenarios such as head-on, adjacent direction, opposing-turning and read end. These were probabilities for a crash event, i.e. accounting for multiple people in two vehicles. Similar research for impacts with pedestrians was reviewed and included. At a nominal 10% risk of a fatal or very serious injury in a crash, the suggested speed thresholds were about 30 km/h head-on, adjacent direction and opposing-turning crashes, 55 km/h for rear-end crashes and about 20 km/h for pedestrian crashes.

Doecke et al., (2020) studied the effects of impact speed on the risk of a fatal or very serious injury per vehicle using more recent US in-depth crash data and refining the definitions of crash scenarios (not directly comparable with Jurewicz et al., 2016 or Wramborg, 2005). Figure 2.3 presents these for the main vehicle-vehicle crash scenarios.



Source: Doecke et al., (2020).

Figure 2.3. Impact speed risk curves for vehicle occupants for head-on, front, side and rear impacts.

Doecke et al.'s 'head-on' and 'front' was the impact speed and risk to occupants of a vehicle doing the hitting. 'Side' and "rear' represented probability for occupants of the vehicle being hit, while the impact speed was for the hitting vehicle. Doecke et al. and Jurewicz et al. provide broadly similar findings although presented differently thus requiring some interpretation[2].

Hussain et al., (2019) carried out a systematic review of 55 studies and meta-analysis of 20 studies to determine the relationship between impact speed and pedestrian fatality, the most robust study of this type to date. The authors estimated that the risk of pedestrian fatality increased by 11% for each 1 km/h increase in vehicle impact speed. Specifically, the authors found that the risk of fatality reached 10% at 37 km/h. Figure 2.4 shows the main model based on the meta-analysis.

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[2] Doecke et al. 10% risk per vehicle has roughly double the speeds of Jurewicz et al. provided for a 10% risk per a two-vehicle crash event.

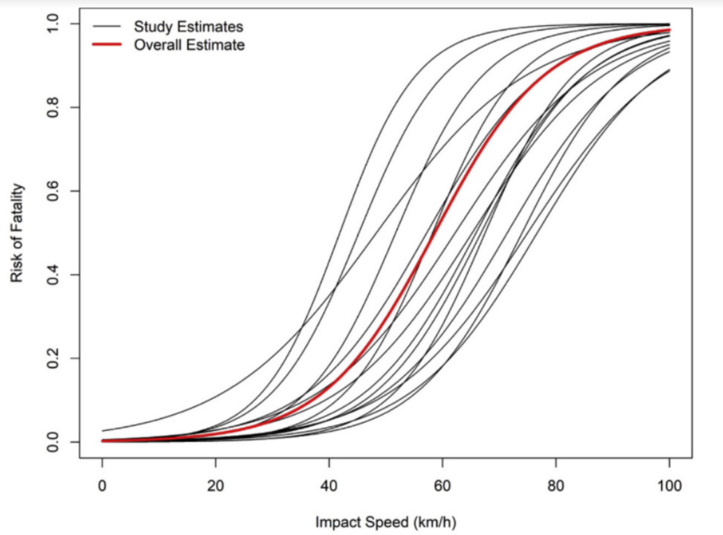

Figure 2.4. The relationship between impact speed and pedestrian fatality risk. Source: Hussain et al., (2019).

It is worth noting that the 10% risk of a fatal or very serious injury outcome in any collision is a nominal value used for comparison of studies. It is considered extreme and well above the risk found on most road networks in HICs. Doecke et al. (2020) points this out questioning what should be considered 'safe' i.e. acceptable level of risk in Safe System. They present a dilemma that anything other than zero risk is arbitrary and disputable, and an absolute zero may be impossible. The authors reinforce the need to aim to minimize death and serious injury under the Safe System approach.

A fatal or very serious injury risk value of 1% for occupants of a vehicle suggested by Doecke et al. (2020) may be a realistic aspirational target which would result in impact vehicle speed thresholds shown in Table 2.1. Hussain et al. (2019) was used to suggest the value for pedestrian-vehicle crashes, with the pedestrian being the presumed injured party (a fatal outcome was conservatively assumed equal to a very serious injury). These approximate thresholds reinforce the impact speed-related vulnerabilities well-understood since the late 1990s: pedestrians, side impacts and head-on crashes.

Table 2.1. Threshold impact speeds for 1% risk of a fatal or very serious injury outcome, per vehicle.

Crash scenario	Approximate impact speed for a 1% fatal or very serious injury risk threshold
Head-on, hitting at	30 km/h
Front, hitting at	65 km/h
Side, being hit at	50 km/h
Rear, being hit at	65 km/h
Pedestrian, being hit at	20 km/h

Sources: Doecke et al. (2020); Hussain et al., (2019).

Impact speeds into roadside hazards of different types are a clear gap in this knowledge. Critical impact speeds for different road users such as public transport passengers, motorcyclists and cyclists are also a significant gap.

In summary, the most recent robust research on the relationship between impact speed and severe casualty risk confirms that speed plays a critical role. The need to minimize impact speeds in conflicts between vehicles and in conflicts with pedestrians is clear.

Effects of traffic mean speed

Mean (average) speed changes may influence not just the number of crashes but also the number of injury victims at different severity (Elvik 2009). These relationships have been investigated in many studies over the years, especially from HIC country context. They provide the scientific evidence for many successful speed management policies and interventions.

These studies related a change in mean traffic speed to changes in fatal, injury and property damage only (PDO) crashes, and also to changes in fatalities, injuries and non-injuries by developing statistical models from multiple evaluations of past interventions. A smaller number of these studies included models for serious injury (hospitalization) crashes and injuries.

The most relevant and frequently cited studies include systematic reviews (Aarts & van Schagen, 2006) and meta-analyses of safety estimates from speed change evaluation studies (Nilsson, 2004; Cameron & Elvik, 2010; Elvik, 2009, 2013, 2014; Elvik et al., 2004, 2019).

Traffic speed and its relationship with safety depends on other factors such as land use and traffic flow characteristics. Hence, speed-safety models were developed for different road types such as urban, rural, residential or freeway (Cameron & Elvik, 2010; Elvik, 2013, 2014; Elvik et al., 2019).

This section provides information from a critical review of recently published models in their different forms (power, exponential) providing increasingly sophisticated estimation of crash/injury changes due to changes in traffic mean speed. The models were largely based on traffic conditions in Western Europe and North America, although some studies from Turkey and Israel were included in the most recent models.

The most common type of speed-safety relationship was a Power Model proposed by Nilsson (2004) and updated many times since by Elvik and other authors. This model has gained wide use due to its simplicity as shown in Equation 1 below.

$$\mathrm{Outcomes}_{\mathrm{after}} = \mathrm{Outcomes}_{\mathrm{before}} \times \left(\frac{\mathrm{v}_{\mathrm{after}}}{\mathrm{v}_{\mathrm{before}}}\right)^{\alpha} \qquad (1)$$

Where Vafter and Vbefore are mean speeds before and after some speed management intervention, and ‘Outcomes’ can represent fatal, serious injury, minor injury and non-injury crashes. Alternatively, all models can also estimate injuries (number of victims) arising from these crashes. The only aspect which changes is the estimate of power ‘α’. The model is symmetric, i.e., applies to both increase and decrease in speed. There is a general consensus that the models were developed from studies using free-flow spot speeds (i.e. based on driver choice of speed, while traffic impeded by other vehicles, including in congested conditions, is excluded).

Since 2004, Rune Elvik and other researchers have been developing these models further adding new studies and using more refined analytical techniques. An Exponential Model was developed as an alternative, as shown in Equation 2.

$$\mathrm{Outcome}_{\mathrm{after}} = \mathrm{Outcome}_{\mathrm{before}} \mathrm{e}^{(\beta(\mathrm{V}_{\mathrm{before}} - \mathrm{V}_{\mathrm{after}}))} \qquad (2)$$

where β is the coefficient dependent on the crash or injury severity. Some important additional conclusions were drawn from these model revisions. The safety effect of a given change in mean speed:

- Depended on the initial speed level, e.g. stronger effect at 100 km/h than at 50 km/h (Elvik, 2009, 2013).
- Varied according to the type of environment and tended to be lower on residential and urban roads than on rural roads and on freeways (Elvik, 2009; Cameron and Elvik, 2010).
- Reduced over time, especially for fatal crashes, however it remained strong in studies published after 2000. Authors noted greater survivability in crashes given effects of helmets, airbags, and seatbelts (Elvik, 2009; Elvik et al. 2019).
- Followed the same relationship as safety effect vs. change in individual driver speed e.g. from Kloeden et al. work. Hence the power and exponential models could be applied to individual vehicle speeds as well (Vadeby and Forsman 2017; Elvik et al. 2019).

A critical evaluation of the Power and Exponential models suggested that the Exponential Model was better and more applicable as it takes better account of the initial speed and is based on more recent studies.

The best current estimates of the speed coefficient (the value of β in the equation 2) in the Exponential Model are 0.08 for fatalities and 0.06 for injury crashes (Elvik et al. 2019). The table of exponents and coefficients is shared in Table 2.2. These models based on post-2000 studies no longer differentiate between urban and rural roads, as they account for initial mean speeds before change.

Table 2.2. Power Model exponents and Exponential Model coefficients from Elvik et al. (2019).

Outcome severity	Data points Included*	Coefficient of Exponential Model, β (standard error)	Share of explained variance (R-squared)	Exponent of Power Model, α (standard error)	Share of explained variance (R-squared)
Fatalities	All	0.086 (0.004)	0.986	6.724 (0.458)	0.969
	≤ 95 km/h	0.081 (0.008)	0.967	5.531 (0.208)	0.994
Injury crashes	All	0.060 (0.005)	0.957	4.154 (0.235)	0.978
	≤ 95 km/h	0.062 (0.008)	0.918	3.860 (0.290)	0.973

* Non-weighted models were shown, as these were preferred by the original paper authors.

The Exponential Model demonstrates that even a small change in speeds may lead to a notable change in safety. For instance, a mean speed reduction of 2 km/h is estimated to reduce fatalities by 15% and serious injuries by 11%. A more significant reduction of 10 km/h is expected to result in 55% and 45% reductions in fatalities and serious injuries respectively[3].

Conversely, a modest mean speed increase of 2 km/h may lead in fatalities increasing by 17% and serious injuries by 13%. A strong speed increase of 10 km/h could lead to fatalities increasing by 123% and serious injuries by 82%. Thus, the Exponential Model demonstrates that speed management can be a powerful tool for change in road safety.

Finally, it is worthwhile to mention cross-sectional studies into association between observed speeds and safety performance. Taylor et al., (2000) and Taylor et al., (2002) investigated the effects of driver's speed on the frequency of road crashes on different European urban and rural roads using multivariate regression modelling. The difference of this approach was inclusion of other speed characteristics in addition to mean speed, such as

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[3] The exponential Model by Elvik et al. (2019) was converted into an online Speed Impact Tool as part of GRSF's Speed Management Hub: https://www.roadsafetyfacility.org/publications/speed-impact-tool

coefficient of variation (ratio of standard deviation to mean speed) and percentage of drivers exceeding speeding threshold. A key conclusion was that reducing the speed of the fastest drivers is likely to produce the greatest individual risk reductions. However, the greatest number of crashes would be saved by targeting low-speeding drivers who are present in much greater numbers.

Also, the authors observed that it is possible to observe a negative speed crash relationship, meaning that when comparing different roads, it is sometimes seen that higher speeds are associated with improved safety. This is because the safest roads, in most cases, are the fastest (such as motorways). This is the effect of high design standards that accommodate high speeds, absence of side friction characteristics, or fewer vulnerable road users. Crashes, when they occur in these road environments, are also usually of lower severity thanks to design elements such as safety barriers and using ramps rather than at-grade intersections.

Speed-safety relationships in LMICs

As compared to the more homogenous traffic in HICs, the traffic in LMICs is often more mixed, containing different categories of vehicles and road users. Sometimes within the same categories, the vehicles vary by size, condition, operating and maneuverability characteristics, making the situation more complex (Dhamaniya & Chandra, 2013). This issue is discussed in further detail in Sections 4 and 5.

This complexity makes it difficult to understand how interactions within traffic flow affect speeds, crashes and severity of injuries, and how this would differ on different road networks. There is evidence that the speeds of particular road users in mixed traffic are more important than those of others and may be a determining factor in the occurrence of some crash types and levels of injury.

Ideally, speed-safety research findings would account for and provide findings for different road user types (or vehicles), and their interaction. This could help to determine the effectiveness of speed management interventions in a variety of mixed traffic environments found in LMICs.

Speed is recognized as a key contributor to road trauma in LMICs. The more robust literature originating from LMICs identifies that speed changes result in fatal, serious injury, injury and PDO crashes or injuries. Table 2.3 summarizes selected studies deemed sufficiently robust to cite. All of these studies reflect the positive relationship between speed and crash or injury change (i.e. speed increases, injuries increase). Some showed effects similar to those produced by Elvik et al. studies.

Table 2.3. Summary of robust LMIC studies on the effects of speed and crashes or injuries.

Study, country	Network	Main theme	Crash or injury outcomes	Comment on methodology
Ang et al., (2020), Brazil	Rural roads	Speed limit change from 90 to 70 km/h	27.1% reduction in all crashes	BAS[4]: Sound methodology though the authors did not measure the mean speed
Vet et al., (2016) Bangladesh	Rural roads	Integrated speed management interventions (included education)	Mean speed was reduced by 13 km/h and led to 67%, 66%, and 73% changes in fatalities, seriously injured and injured respectively.	BAS: The methodology was sound but did not control for the effects of other interventions

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[4] BAS – Before and After Study, indicating a comparison in the outcome measure from before and after a change was made.

Wong et al., (2005), China	Rural roads	Safety compared between roads with 50 and 70 km/h speed limits (20 km/h higher), and between 70 and 80 km/h (10 km/h higher)	Fatal and serious injuries were higher by 1% for the 20 km/h higher speed limits, and 36% higher for the 10 km/h higher speed limits.	CSS[5]: Mean speed changes were not measured. Size of safety effects were potentially confounded by different road environments.
Siregar et al., (2022), Indonesia	Inter-urban roads	Effects of heterogeneous traffic on fatal crashes	The speed of mini-buses and standard deviation in speeds of motorcycles, buses, and mini-buses were the main causative factors in fatal crashes.	CSS: Sound methodology
Ture & Tuydes, (2020), Turkey	Urban roads	Speed limit change from 50 to 82 km/h	More crash clusters	BAS: The methodology was sound; the focus was on crash clusters

Other reviewed studies were less robust and suffered from methodological limitations, such as not controlling for other known variables influencing safety outcomes. Most of these also showed a positive relationship between speed and crashes, although weakened or specific to certain conditions.

There is no clear evidence that contradicts the applicability of the Exponential Models to LMIC context. However, caution should be taken when generalizing or using these models for LMICs. From the assessment of the literature on speed from LMICs, there is very limited robust research to test these models and their applicability.

All the reviewed LMIC-based research highlighted the importance of understanding the mixed nature of traffic, more so than in HICs where traffic is relatively more homogenous. There is a need to understand the composition of traffic in any given LMIC context, and the effects this has on the overall effectiveness of speed interventions, and on the effectiveness on different road users (buses, motorcyclists, pedestrians).

Knowledge Gaps in LMICs

- For now, there is no clear evidence that contradicts the applicability of the Exponential and Power models to LMICs due to limited available research.
- There is a need to test and validate such models for LMICs through controlled before and after studies based on representative LMIC data for different road users, and controlling for underreporting, road features, traffic exposure, weather, temporal and spatial correlations, and others listed in the extensive literature.
- This gap includes the effect of speed variation on safety in highly mixed traffic, as well as for different road user types (e.g. mean speed of motorcyclists in mixed traffic vs. their FSI outcomes).
- Impact speed survivability thresholds for different road user types found in mixed traffic are not known (e.g. public transport passengers, motorcyclists, cyclists, etc.).
- Likewise, impact speed thresholds in collisions into common roadsides hazards are unknown.

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3. Speed and emissions relationship

There is great global concern about reducing the emissions of greenhouse gases (GHG) and improving air quality due to the detrimental effects of emissions on the environment (global warming) and human health. The direct link between some road safety interventions (such as speed management) and emission reduction offers opportunities for curbing this global challenge.

Carbon dioxide (CO_2) emissions account for a large proportion of GHG, which are key contributors to global warming. The transport sector alone contributes to about 24% (IEA, 2020) of the Global total CO_2 emissions and is also a major source of local air pollutants, accounting for 39% Nitrogen Oxides (NOx), 26% Black Carbon (BC), 20% Carbon Monoxide (CO) and 10% Particulate Matter (PM) emissions (EEA, 2020). These pollutants are usually short-lived but significantly affect human health. An estimated 4.2 million premature deaths globally are related to ambient air pollution, with LMICs affected disproportionately and accounting for 91% of these deaths (WHO, 2018).

Given this global challenge, many countries are adopting policies to decarbonize the transport sector and reduce air pollution. Such policies include reducing the number of vehicles and kilometers of travel by encouraging public and active transport, implementing traffic management solutions (such as lower speed limits), improving vehicle fuel efficiency (such as introducing hybrid or electric vehicles), using alternative sources of fuels and motorization management.

Amongst these measures, vehicle speed is recognized as influencing vehicle emissions. Managing speeds through different interventions, including speed limit reduction, speed cameras or traffic calming, is considered an effective carbon abatement policy (Gabriel & Ellen, 2017). Speed limit reduction is often chosen as the least-cost alternative to reduce emissions and has been widely adopted since the 70s to save fuel (Kamerud, 1983).

However, there is some debate about the impact of traffic speed changes on emissions. On the one hand, it is argued that lowering speeds could result in additional emissions due to:

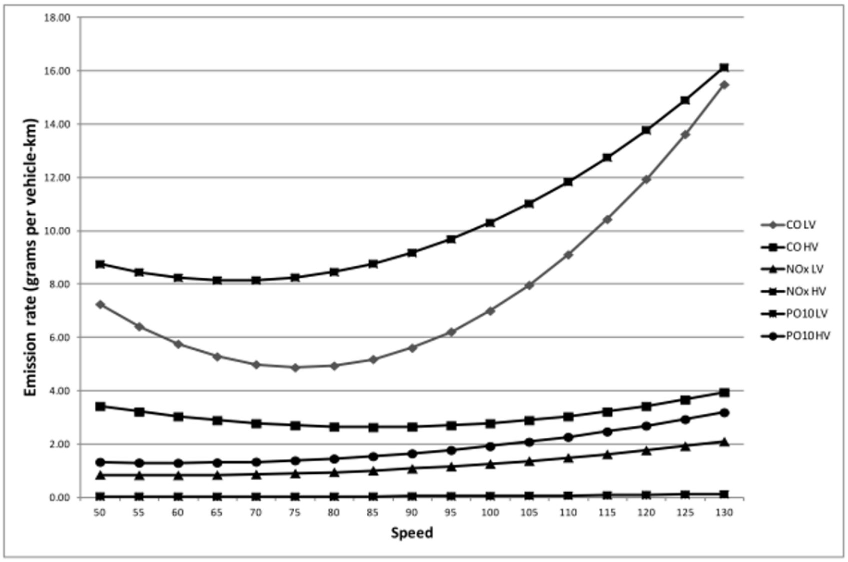
- more idling and gear changes
- more stop-and-go traffic conditions (i.e., more frequent acceleration and deceleration)
- longer time for pollutant emissions (Alahmer, 2018)
- less efficient fuel consumption.

On the other hand, increasing speeds are argued to add to emissions because of:

- rapidly increasing vehicle air resistance
- hard acceleration from low to high speeds using a lot more fuel
- generally higher engine revolutions using more fuel (Alahmer, 2018; Thomaz & Baeta, 2020).

However, these effects also depend on the speed environment, types of pollutants, fuel used, engine and vehicle types.

There are many speed – emission rate models created for standard vehicles. These are frequently used in emission modelling and simulation studies reviewed further on. Figure 3.1 presents an example of such a rate relationship for light vehicles (LV) and heavy vehicles (HV).



Source: Cameron, (2022)

Figure 3.1. Emission rates of carbon monoxide (CO), nitrogen oxides (NOx) and particulates (PO10) related to speed of light vehicles (LV) and heavy vehicles (HV).

Reviewing other models suggested there may not be one ideal range of traffic speeds for the lowest emissions. Much is dependent on the traffic mix of fuel types (e.g. petrol, diesel, LNG and electric) and vehicle types (light, heavy, powered-two-wheeler, etc.). In addition, it is likely that LMIC fleets will be older than in HICs, thus lacking emission controls assumed in models developed in HICs.

There are likely to be further differences between LMICs and HICs regarding vehicle emission rates. LMIC traffic can be more diverse, with vehicles with different dynamic characteristics operating at significantly different speeds to each other (see Section 5). This may lead to higher speed variations that increase the frequency of acceleration and deceleration with the negative consequences on emissions.

The effect of speed reduction on transport externalities such as safety, travel time, congestion or emissions usually depends on the initial speeds. Hence, it is essential to consider the effects of speed reduction on emissions from the perspective of both:

- lower-speed environments, such as urban arterials, collectors, feeders, or residential streets, typically ≤ 80 km/h and
- higher-speed environments, such as rural highways, freeways, expressways, or intercity motorways, typically > 80 km/h.

Therefore, this review separated the findings into these two groups.

Lower-speed environments (≤ 80 km/h)

Table 3.1 summarizes effects of speed reduction on emissions from 14 studies relating to:

- 20 mph / 32 km/h speed limit reduction analysis,
- mixed speed limit reduction / traffic calming measures, and
- selected traffic calming measures.

The main finding is that urban speed limit reductions to 20 mph / 32 km/h were found to have mixed potential for reducing emissions. Most studies found small to moderate reductions, others showed mixed results, and some showed emission increases. Vehicle travel demand reduction was shown to be a key factor reducing emissions, as shown by Schmaus et al., (2023). There are some additional considerations worth highlighting in this context:

- Most speed limit reduction studies were models or simulations of speed limit changes and could be prone to assumptions about emission rate models (e.g. Figure 3.1). These emission rate models assume higher fuel use at lower speeds as dictated by test-cycles reflecting current low-speed urban driving paradigm. It involves frequent braking, stopping and acceleration to higher speeds leading to higher fuel use and thus higher emissions. It is proposed that calmed urban traffic would be more uniform and avoid much of this acceleration by not offering opportunities to reach higher speeds.
- Emission changes were dependent on engine and fuel type, with diesel vehicles more likely to show emission reductions.
- Traffic calming findings were not representative due to small number of publications reviewed (not the main goal of this review).

It is noted that none of the reviewed studies were carried out in LMICs. This is a knowledge gap. The summarized findings could be used in the interim while LMIC evidence is being developed.

Table 3.1. Studies on the relationship between speed and emissions in low-speed areas

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Introduction of 30 km/h speed limits (20 mph)							
Int Panis et al., 2011	Reducing speed limits for passenger vehicles from 50 to 30 km/h	Macro- and micro-modelling: + Only minor reductions in NOx & C02 (inconsistent amongst methods) + PM may increase or decrease (results dependent on vehicle type)	↓	↓		↓↑	Local roads. Belgium and Spain
Madireddy et al., 2011	Speed limit reduction from 50 to 30 km/h	A simulation study: + Reductions in CO2 by 26.8% + Reduction in NOX by 26.7%	↓	↓			Urban residential areas in Antwerp, Belgium
Schmaus et al., 2023	Reduction of speed limits to 30 km/h	A simulation study accounting for changes in traffic demand: + CO2 reductions in 3/3 cities + NOx reductions in 2/3 cities (with one negligible increase) + PM reductions in 2/3 cities (one modest increase) Emission reductions were clearly dependent on the reduction in kilometers of travel. Emissions increased when only speed reduction was accounted for.	↓	↓		↓↑	Dresden, Magdeburg, Stuttgart, Germany

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Casanova & Fonseca, 2012	Influence of 30 km/h speed limit on emissions compared with 50 km/h.	Based on on-road emission measurements of a light vehicle with a turbo-diesel engine and oxidizer catalyst, finding that 30 km/h speed limit driving resulted in: + 27% NOx reduction + 21% CO reduction + 22% PM reduction compared with 50 km/h speed limit driving. Also showed a 15% reduction in fuel consumption.	↓		↓	↓	Madrid, Spain
Rhode et al., 2022	Hypothetical decrease in speed limits 50 to 30 km/h	A simulation study. + NO2 decreased by 40% + PM10 decreased by 10%	↓			↓	Urban network in Berlin, Germany
Williams & Robin, 2013	Comparison of sites with 30 mph and 20 mph speed limits	Evaluation based on vehicle trials: + Higher emissions of NOx (+7.9%) and CO2 (+2.1%) pollutants in petrol vehicles in 20 mph zones + Lower emissions of NOx (-8.2%) and CO2 (-0.9%) pollutants for diesel vehicles in 20 mph zones + Lower Particulate matter emissions (-8.3%) for all vehicle types in 20 mph zones.	↓↑	↓↑		↓	Urban roads in London, UK
Gressai et al., 2021	Hypothetical decrease in speed limits 50 to 30 km/h	A simulation study. + CO increased by 21% + HC increased by 22% + CO2 increased by 8% + NOx increased by 12%	↑	↑	↑		Urban network in Budapest, Hungary
Tang et al., 2019, 2020	Hypothetical decrease in speed limits 50 to 30 km/h	A simulation study. + NO2 increased by 1 to 13% (2020) + NOx increased by 3% (2019) + PMx increased by 2% (2019, 2020).	↑			↑	Urban network in Dublin, Ireland
Jones & Brunt, 2017	Hypothetical 20 mph speed zone comparison with 30 mph zones	Computational estimation study (no data collected): + NOx emission increased by 7.6% (deaths due to NOx increased by 63) +PM10 decreases by 24.9% (deaths decreased by 117) + Overall benefits in life savings + other benefits: reduction in crash, noise, and increased active travel and social inclusion.	↑			↓	Urban areas in Wales, UK

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Mixed measures							
Casanova & Fonseca, 2012	Influence driving styles on emissions in Madrid	Based on on-road emission measurements of a light vehicle with a turbo-diesel engine and oxidizer catalyst, finding that Eco driving style resulted in: + 22% NOx reduction + 11% CO reduction + 56% PM reduction Compared with Aggressive driving style. Also showed a 24% reduction in fuel consumption.	↓		↓	↓	Madrid, Spain
Owen, 2005; Cited in Cleland et al., 2020	0.5×0.5 km 20 mph zones using signage and speed humps	Study from meta-analysis (unknown): + In one zone, concentrations of NO2 decreased at all sites, including the control, by between 4% and 13%; Concentrations of benzene decreased by 10%-35% at all sites including the control. + At a second zone, NO2 concentrations increased by 1%–10% at all sites including the control. +concentrations of benzene increased at all sites, including the control (19%–36%). NB: Changes were small (p> 0.05)	↓↑				UK, NW England
Layfield et al. (2003) Cited in Cleland et al., 2020	Traffic calming measures on key streets in Leeds (road narrowing, 20 mph signs, new shared road surface)	Study from meta-analysis (unknown): + Little change for benzene and NO2 before and after; the control site and one intervention site showed slight decrease (−5% and −10%, respectively), the 3 other intervention sites showed increased (2–43%) + Relative to the control site, benzene concentration decreased slightly at intervention sites. NB: All findings were non- sig.	↓↑				Urban areas in Leeds, UK

Higher-speed environments (>80 km/h)

The effect of speed and speed limit reductions on emissions was clearer in the higher-speed range. Table 3.2 presents the summary of the 15 reviewed studies. The main finding was that most studies showed a clear reduction in emissions given a reduction in speeds limits and/or speeds for this speed environment. Only a few studies showed negligible or context-dependent results. The following may be considered in relation to these findings:

- Six of the reviewed studies pertained to speed limit reductions on motorways around Barcelona and Madrid, Spain. The findings may be influenced by Spanish conditions.
- Also, only one study involved an LMIC. Lack of LMIC-specific knowledge is gap as traffic composition and operations may differ.

- Many studies were models or simulations of real or proposed changes and could be prone to assumptions about emission rate models (e.g. Figure 3.1), and other modelling assumptions.
- Some studies hint at different strength of response depending on vehicle type (light or heavy, petrol or diesel).

Interventions aimed at reducing speeding also showed reductions in emissions.

Table 3.2. Studies on the relationship between speed and emissions in high-speed areas

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Speed limit reductions							
Gonçalves et al., 2008	Introduction of 80 km/h speed limits or Variable speed system where speeds were at 100 km/h and 120 km/h	Simulation study for variable speed limit + reduced NOx by 5.7% + reduced CO by 5.1% +reduced SO2 by 4.8% + reduced PM10 by 5.1% o	↓		↓	↓	Metropolitan motorways in Barcelona, Spain
		Simulation study for 80km/h speed limit + reduced NOx by 1% + reduced CO by 1% + reduced SO2 by 0.9% + reduced PM10 by 0.9% o	↓		↓	↓	Metropolitan motorways in Barcelona, Spain
Keller et al., 2008	Speed limit reduction from 120 to 80 km/h	Simulation and modelling: + reduced NOx by 4% + reduced peak ozone layers by 1%	↓				Swiss motorways
Baldasano et al., 2010	Introduction of 80 km/h speed limits where speeds were at 100 km/h and 120 km/h	Before / after evaluation: + reduction in emissions by 4-11% + improving air quality by 10-15% + reducing mortality rates by 0.6% + reduction by 14.81% for CO, 10.98% for nitrogen oxides, 12.47% for PM2.5 and 10.99% for PM10	↓		↓	↓	Metropolitan motorways in Barcelona, Spain

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Bel & Rosell, 2013	Introduction of 80 km/h speed limits or Variable speed system where speeds were at 100 km/h and 120 km/h	Further evaluation regressions for variable speed limit + reduced NOx by 7.7-17.1% + reduced PM10 by 14.5-17.3%	↓			↓	Metropolitan motorways in Barcelona, Spain
Cohen et al., 2014	Reducing speed limits from 110 km/h to 90 km/h	Macroscopic traffic simulation: + road sections with high decrease in mean speed experienced daily savings in emissions by 2 to 10% + one of the sections with a lower decrease in mean speed experienced an increase in emission.	↓	↓		↓	Lille motorway in France
van Benthem, 2015	Increasing* speed limit by 10 mph (16 km/h) from 55 to 65 mph	Before / after evaluation: + Increase in CO by 23% + Increase in NO2 by 15% + Increase in O3 by 11% + No sig. change in PM10 (* direction of change reversed for comparison with speed reduction studies)	↓*	↓*	↓*	↓↑	US freeways
Perez-Prada & Monzon, 2017	Speed limit reduction from 90 to 70 km/h	Simulation based study for treated roads: +16.4% reduction in NOx +14.4% reduction in CO2.	↓	↓			Inter-urban roads, Madrid, Spain
		For overall road section (treated & untreated) + 4.6% reduction in NOx + 4.1% reduction in CO2	↓	↓			Inter-urban roads, Madrid, Spain

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Schmaus et al., 2023	Introducing maximum speed limit of 120 km/h from none	Microscopic traffic flow simulation model combined with travel demand modelling and emission modelling: + reduction of 9.6% in NOx + reduction of 4.2% in CO2 + reduction of 6.6% in PM With kilometers of travel having a lower impact that for lower speed ranges evaluated.	↓	↓		↓	Intercity motorways in Germany
	As above combined with 80 km/h speed limit outside of urban areas	+ reduction of 11.1% in NOx + reduction of 5.1% in CO2 + reduction of 7.3% in PM	↓	↓		↓	Intercity motorways and rural roads in Germany
Dijkema et al., 2008	Speed limit reduction from 100 km/h to 80 km/h	Before \ after evaluation: + reduced PM10 by 7.4% + reduced PM1 by 2.8% + reduced black smoke by 15% + No. stats. sig. effect on NOx reduction + reduction in non-intervention areas observed for PM10 and black smoke.	↓↑			↓	Amsterdam: urban ring highway
Folgerø et al., 2020	Speed limit reduction from 80 to 60 km/h (effects near treated roads)	Evaluation: + No improvement in air quality + Weak evidence for increase in NOx	↓↑			↓↑	National road, Oslo, Norway

Authors	Measures	Effects	NOx	CO2	CO	PM	Location
Lopez-Aparicio et al., 2020	Environmental speed limits (80 km/h reduced to 60 in winter, then returned to 70 km/h or 80 km/h in summer)	Modelling using speed data: + low to negligible effects on PM2.5, NOx and CO2 + reduction in PM10 emissions by 6-12%	↓↑	↓↑		↓	Metropolitan area of Oslo, Norway
Int Panis et al., 2011	Reducing speed limits for trucks from 90 to 80 km/h	Macro- and micro-modelling: + C02 emissions decrease (9%) + NOx & PM increase slightly (2 & 4% respectively)	↑	↓		↑	Motorways in Belgium and Spain
Speeding interventions							
Lai et al., 2012	Intelligent Speed Adaptation (ISA) project on 70 mph roads (125 km/h)	Observed changes: + reduced C02 emissions by 5.8% on 70mph roads + insignificant effects on low-speed roads		↓			UK roads
Keuken et al., 2010	80 km/h speed limit with strict enforcement	Scenario modelling and estimations: + reduced PM10 emissions by non-significant to 8% + reduced NOx emission by 30 to 32% Note: Stronger results were observed for uncongested traffic.	↓			↓	Motorways in Rotterdam and Amsterdam, The Netherlands
Zhai et al., 2012	Analysis of speed limit enforcement regimes Toronto vs. Beijing (stronger regime with lower speeds, low speeding, smoother traffic flow).	Modelling of standardized GPS speed data, with Beijing showing comparative: + 14% reduction in CO2 + 57% reduction in CO + 14% reduction in NOx, and + 21% reduction in Particle Number	↓	↓	↓	↓	Urban roads in Toronto and Beijing.

In summary, there is evidence of decreased emissions from reducing speed limits and speeds in high-speed areas. The evidence of emission reduction at lower speed limits (urban, below 60 km/h) is weaker, but there appears to be little disbenefit from a reduction in speeds.

It is likely that emission benefits would be much stronger when combined with reductions in driving (modal shift) as suggested in the recent study by Schmaus et al., (2023). There were hints that this modal shift could provide stronger emission reductions than speed reductions in urban areas (i.e. in the lower speeds range).

Some of the research demonstrated the negative role of acceleration and deceleration, and benefits of traffic flow smoothing through interventions such as speed limit enforcement, Intelligent Speed Adaptation, variable speed limits and adoption of Eco driving style.

Some vehicle types may be more likely to produce emission reductions with lower speeds (e.g. diesel).

Knowledge Gaps in LMICs

- Almost all research was generated in HICs. There was lack of LMIC research on the emission effects of lower speeds, across the full range of road environments.
- The link between lowering speeds and modal shift leading to reduction in kilometers of car travel needs to be explored further, as it is a strong emerging factor in reducing emissions.
- It would be helpful to understand emission effects of reduced braking and acceleration due to lower and calmer speeds in heterogeneous LMIC traffic scenarios.
- There is a lack of clear standard speed – emission rate models most applicable to LMIC vehicles of different types, including fuel types (e.g. diesel, LNG, electric). Developing such models would assist in future modelling of impacts of speed management initiatives on carbon and pollutant emissions which disproportionately affect the health of LMIC populations.

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4. Speed variance and crashes

There is a general agreement that speeds of vehicles are more varied in LMICs than in HICs. This is suggested to be due to wider range of vehicles present in traffic, and due to more disrupted traffic flow. While there is clear information about the role of mean speed in road safety outcomes (see Section 2), there is also a discussion about the role of speed variance and the impact this might have on crashes.

There is no universally accepted definition of speed variance, which affects the mixed available knowledge on its effects on safety outcomes. The following types of speed variance have been observed:

- Individual driver's speed variability along a road (speed profile) due to changes in traffic conditions and performance of certain maneuvers, e.g. harsh braking, slowing for an intersection or overtaking, or due to their vehicle types or performance characteristics (e.g. effect of road grade). This type of speed variance resulting from driver choice and limitations in consistent driving speeds is common in LMIC roads carrying mixed traffic (Taylor et al., 2000, 2022).
- Traffic diversity: speed variability due to a wide range of vehicle types and sizes with varying engine power and maneuverability characteristics, e.g., speed, lateral clearance acceleration, and deceleration (Asaithambi et al., 2012; Dhamaniya & Chandra, 2013).
- Temporal, or time-of-day variance in traffic speeds, between congested peak and off-peak periods, different seasons, and due to traffic disruptions (e.g. harvests, incidents, road works).

Some of the reviewed research argued that variance was the leading risk due to speed (e.g. Solomon, 1964; Davis, 2002; Choudhary et al., 2018), while others argued that mean speed was the leading factor (e.g. Jehle et al., 2010, Quddus, 2013, and research by Nilsson, Elvik et al. or Kloeden et al. cited earlier).

Much of the early research strongly associated speed variance with crash and injury risk (e.g. Solomon, 1964; Lave, 1985; Garber & Gadirau, 1988). This seminal knowledge made its way into traffic engineering training and lore in HICs but has been questioned by later research. The main issues with this early research related to omitted variables (e.g. role of geometry, intersections, traffic flow) or use of inadequate regression methods. The later studies often showed that speed variance measures had inconsistent relationship with crash frequency.

Many later studies showed a significant or weak positive relationship with crash risk (Taylor et al, 2000; Quddus, 2013, Li et al. 2013, Choudhary et al., 2018; Park et al., 2021; C. Wang et al., 2022a). Some studies showed no clear or mixed safety relationships (Davis, 2002; Kockelman & Ma, 2007; Gittelman et al, 2017). Only one reviewed study showed a negative relationship, although not strongly significant ($\alpha = 0.1$; Gargoum & El-Basyouny, 2017).

There has been recent relevant research from LMICs, especially from China (Liande et al. 2006; Chen et al., 2007, Wang et al. 2018; Xu et al., 2019; C. Wang et al., 2022) and from Indonesia (Siregar et al. 2020, 2022). Most of these studies showed positive relationships between speed variance metrics and crash risk, although with qualifications. Most of these LMIC studies focused on high-speed roads, hence there is very limited knowledge for urban arterial and lower order roads (i.e. lower speed ranges).

Table 4.1 summarizes the results of the reviewed studies on the speed variance and crash relationship, including various definitions of speed variation used in the literature.

There is a lack of consistency in findings, and this may be due to:

- Studies using different definitions and measurement methods for speed variance (e.g. standard deviation, coefficient of variation, difference between 85th percentile and speed limit, differences in speed between vehicle types, etc.).
- Mean speed and speed variance being correlated with each other and with other traffic variables (i.e. multicollinearity).
- Using regression modelling techniques not adequate to establish causality of the speed variance effect (only association).
- Speed variance affecting some crash types more (e.g. overtaking, head-on, intersection, rear-end) than others (e.g. run-off-road, pedestrian).
- Speed variance affecting crashes of different severity differently (e.g. all crashes vs. fatal crashes).
- Studying different road types with different traffic and design characteristics, e.g. intercity motorways vs. mixed-use urban arterials.

Table 4.1. Summary of studies on speed variance and crash relationships

Author	Study site	Cases	Country	Crash measure	Definition of speed variation	Method	Results: Relationship with crash
Garber & Gadiraju, (1988)	Interstate roads, arterial roads, and major rural collector road	124 crashes, 36 road links	USA	Fatal, injury and PDO	Statistical variance of speed	Cross-sectional study	Positive Crash rates increase with increasing speed variance for all classes of roads.
Taylor et al., (2000)	Urban roads	300 link roads	UK/ Europe countries	Crash frequency	Ratio of standard deviation to mean speed	Cross-sectional study	Positive Crash frequency rises by 15% if the coefficient of variation rises by 0.025.
Kockelman & Ma, (2007)	Freeways	744 crashes	USA	Total crashes	Within-lane speed variation and across-lane speed variation	Cross-sectional study	Non-significant
Jehle et al., (2010)	Highways	Speed limits increase 55 to 65 mph	USA	Fatalities	Percentage of traffic traveling >10 mph over the speed limit	Simple before and after	Positive Decreased speed variance led to a decrease in crashes. Note: negative relation between speed and crashes observed.

Author	Study site	Cases	Country	Crash measure	Definition of speed variation	Method	Results: Relationship with crash
Li et al., (2013)	Freeways	454 crashes, 10km road	USA	Rear end, sideswipe, and all collisions	+Speed Standard deviation +Speed Standard deviation/ mean sped	Cross-sectional study	Positive.
Quddus (2013)	Highways	298 road segments	UK	Killed and serious injury	Standard deviation of hourly average speeds on a segment over a year	Cross-sectional study	Weak positive. A 1% increase in speed variation is associated with a 0.3% increase in crash rates. NB: Average speed was not significant
Gitelman et al..,(2017)	Interurban road	1,174 crash cases,179 road sections	Israel	Total crashes	Standard deviation of speed	Cross-sectional study	Non-significant
Gargoum & El-Basyouny, (2017)	Two- lane urban roads	353 two-lane urban roads	Canada	Total crashes	Standard deviation	Structural equation modelling	Non-significant negative
Choudhary et al., (2018)	Motorways	1075 crash cases, 17km road	UK	Fatal and injury crashes	Standard deviations of speed within the lane and between- lanes	Cross-sectional study	Positive Crashes increase for both increase in within-lane speed variation or between-lane speed variation
Dutta & Fontaine, (2019)	Rural and urban freeway	95.87 miles	USA	PDO, injury, multiple vehicles, single vehicle	+ Standard deviation of average hourly speeds (SD) + difference between posted speed limit and average speed (PSL-Av speed)	Cross-sectional study	Positive or negative + positive relationship with crashes for SD + negative relationship with crashes for (PSL-Av speed)

Author	Study site	Cases	Country	Crash measure	Definition of speed variation	Method	Results: Relationship with crash
Hutton et al., (2020)	Highways: urban and sub urban arterial	109 sites	USA	KABCO crash-severity Single vehicle, multi vehicle crash	Standard deviation of space mean speed	Cross-sectional study	Positive For multivehicle crashes and total crashes Not positive for single vehicle crashes.
Park et al., (2021)	Urban roads	290 miles of varied road types with speed limit range 25 – 45 mph	USA	KABC	Multiple measures: Standard Deviation, Coefficient of Variation, 85th percentile – Avg. Speed.	Structural equation modelling	Positive 1 mph increase in standard variation increased injury crashes by 15%. Injury crashes increase 5% for each 0.025 increase in Coefficient of Variation. Models could not show a crash relationship with mean speed when speed variance metrics were included.
Chen et al., (2007)	Expressway	875 crash cases, 23 sites	China	Fatal, injury and PDO	The difference in hourly average speed between large vehicles and small vehicles	Cross-sectional study	Positive or negative A speed difference of 10 to 15 km/h reflects a high crash rate. Crash rate reduces for speed difference <5km/h or for >20km/h
Wang (2018)	Urban arterials	1567 crash cases, 234 road segments	China	99% PDO	Speed variation coefficient which considers both speed differences among vehicles and speed changes of individual vehicles	Cross-sectional study	Positive A 1% increase in speed variation was associated with a 0.74% increase in total crashes

Author	Study site	Cases	Country	Crash measure	Definition of speed variation	Method	Results: Relationship with crash
Xu et al., 2019	Expressway	347 crash cases, 199 segments	China	PDO crashes	the standard deviation of the cross-sectional speed mean (SDCSM) and the cross-section speed standard deviation (MCSSD)	Cross-sectional study	Positive 1% 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
Serigar et al. (2020, 2022)	Inter urban roads	5 cities	Indonesia	Fatality rate Crash rate	Standard deviation of space mean speed	Structural equation modelling	Negative An increase in speed deviation lowers the crash rates.
C. Wang et al., (2022)	Urban Expressway	1188 crash cases, 37 km of roadway	China	All collision types, rear, side, heavy vehicle, light vehicle	Average of the speed standard deviation within lanes for a 5 min interval	Cross-sectional study	Positive for all collision types; higher speed variation within lanes increases crash risk.

On the balance of the reviewed evidence, it is very likely that:

- Higher speed variance is associated with increased crash and injury risk,
- This effect is likely to be small unless speed variance change / difference is very large.
- This effect may be due to correlation with higher speeds and has not been generalized reliably yet.
- There is some evidence that shows that when either speed or variance is low and the other high, there is always a crash increase.

Based on the limited research, it is not possible to discern if LMIC findings differ from HIC findings. The issue of differences in speeds of different road user groups is explored in further detail in the following Section 5. Knowledge summarized in both sections may be useful in understanding the variable nature of LMIC traffic and how this may affect the relationship with safety outcomes.

Knowledge Gaps in LMICs

- Due to differences in traffic mix, speed variation is likely to be higher in LMICs than in HICs (see Section 5). There is lack of research on speed variation specific to LMICs compared to HICs, especially other than for high-speed expressways or motorways.
- There is evidence that the speed variance is positively related to injury crashes. Nevertheless, the relationship

is not as strong as that of mean speed, although we cannot tell if there would be differences between HICs and LMICs in this regard.

- There is poor understanding of effects of different types of speed variance on safety, with variance at individual driver level and due to traffic mix being of particular interest to LMICs.

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5. Traffic mix and speeds of different road users

Mixed traffic is prevalent in most LMICs making it more challenging to implement sustainable traffic management strategies which work for very different vehicle categories. It is thus important to better understand speeds of different road users in different speed environments (e.g. rural and urban areas), and how this mixed traffic (heterogeneity[6]) affects measured speeds used in safety analysis. There is a significant amount of LMIC research in this area.

According to Siregar et al., (2020) heterogenous 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. The definition is simple and was considered for this study.

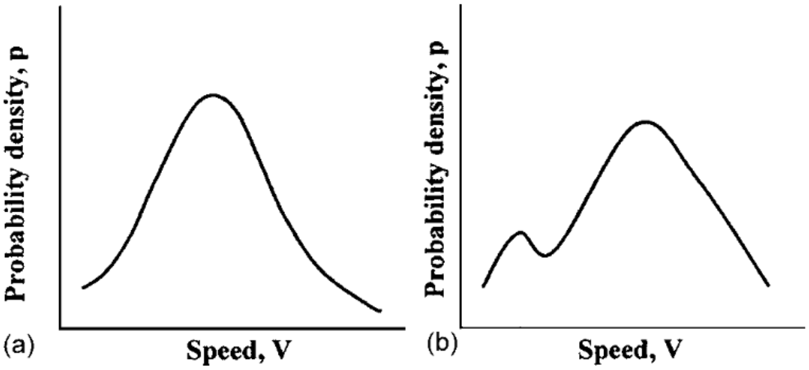
Many studies sought to measure heterogeneity of traffic. Pandey et al., (2022) reviewed a number of methods suggesting the Heterogeneity Index (HI) of a traffic stream based on defined vehicle types, their footprint (projected area) and mean speed in traffic, assessed at 5-minute intervals.

Speed standard deviation was another indicator of traffic heterogeneity, with large values seen as a sign of highly mixed traffic. A small number of studies provided a comparison between typical ranges found in HICs and in LMICs, suggesting that the latter had much higher standard deviations of speed.

The main issue noted was a breakdown in the normal distribution of highly mixed traffic. It was shown that multiple speed distributions of different vehicle types mix into bi- or multi-modal overall distribution where normal distribution statistics lose their usefulness. Figure 5.1 shows a bimodal speed distribution example.

Similar to standard deviation is the analysis of percentiles. When vehicles drive at very low speeds (lower 15th percentile) and at very high speeds (higher 85th percentile), such that the ratio of the difference in 85th and 50th percentile speed to the difference in 50th and 15th percentile speed is outside a defined range (0.86 – 1.11), the normality in speed fails and the speeds becomes heterogeneous.

Figure 5.1. Probability density curves: (a) Unimodal distribution; (b) bimodal distribution. Source: (Dey et al., 2006)



Changing traffic volumes, e.g. by time of day, impact speed variance. Roy et al. (2017) and Saha et al. (2017) investigated this effect on two-lane rural highways in India to show, that under heavy flow, slower vehicles tended to force formation of platoons and that delayed faster vehicles resulting in erratic movements. Hence normality of speed distribution broke down under high volume conditions.

The speed variance in rural areas is relatively higher than those in urban areas, creating more traffic heterogeneity and unsafe conditions compared to urban areas. There have been a handful of LMIC studies in rural areas, e.g. Hashim, (2011) in Egypt indicating highly mixed traffic with high overall speed standard deviation (10 – 19 km/h).

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[6] Heterogeneity is a concept exactly opposite to homogeneity.

However, more research is needed to clearly show the speed behavior of both motorized and non-motorized vehicles in mixed rural traffic and their contribution to operating speeds.

Passenger cars exhibit the highest mean speeds in traffic and, in some cases, have the highest speed variance**.** Evidence from most studies reviewed shows that the speeds of passenger cars are statistically different from others and are responsible for the high overall stream speeds observed in any mixed traffic (e.g. Leong et al., 2020 in Malaysia, or Siregar et al., 2021 in Indonesia). The speeds of cars tend to reach their maximums when the flow of three- and two-wheelers and buses in traffic are lowest. However, studies show that the mean speeds of cars do not represent the stream characteristics when their speeds are low.

Three-wheelers have the lowest speeds and speed variations in traffic, and these low values distort normality in traffic flow. All studies which included motorized three-wheelers noted them to impede speeds of faster vehicles, thereby creating unsafe conditions due to frequent overtaking (e.g. Thomas et al., 2012 and Balakrishnan & Sivanandan, 2015 in India, or Leong et al., 2020 in Malaysia).

Two-wheelers, especially motorcycles, in most cases exhibit the highest speed variations in traffic and significantly contribute to the overall mean traffic speed and the level of heterogeneity**.** Evidence from most studies points out that an increase in the proportion of motorcycles increases speed variance in mixed traffic, reduces in maximum speeds of other vehicles (especially cars), yet higher motorcycle speeds increase mean speed of the mixed traffic (e.g. Maurya et al., 2015 in India, or Leong et al., 2020 in Malaysia, and Siregar et al., 2021 in Indonesia).

However, this may not be generalized for all two-wheelers as there exists a high intra-vehicle class variability, with scooters and mopeds travelling more slowly and with lower speed variance.

Non-motorized vehicles (bicycles, rickshaws, and hand carts) significantly affect the speeds of motorized vehicles and hence the overall operating speeds. While a few studies have investigated the sole impact of non-motorized vehicles on speeds, evidence suggests that the presence of non-motorized vehicles has the most significant reduction in the speeds of heavy vehicles (e.g. Patkar & Dhamaniya, 2020 in India).

Heavy vehicle speeds are generally higher than those of two and three-wheelers but lower than those of passenger cars (e.g. Thomas et al., 2012 in India)**.** Their increased volumes lower the average traffic speed (e.g. Siregar et al., 2021 in Indonesia). There might be some distortion in the trends of the speeds of heavy vehicles due to the road environment or other traffic conditions due to slow acceleration characteristics. Studies highlight that heavy vehicles impede the speed of other vehicles. This observation could be linked to their sizes that makes overtaking more difficult (e.g. Damsere-Derry et al., 2008 in Ghana).

Bus effects on traffic speed variance were mixed according to available studies. There was reasonably consistent evidence for higher speed roads, where bus speeds and speed deviations may be higher than for heavy vehicles but lower than for cars (e.g. Siregar et al., 2021 in Indonesia), noting significant variations between speeds of buses of different sizes.

Both intra- and inter-vehicle class speed variations increase overall traffic heterogeneity. The literature suggests that focusing on difference between vehicle classes (inter) alone may lead to unobserved effects of the causes of traffic heterogeneity. It is also important to account for speed variations within each class (intra) because of different sizes and shapes with different maneuverability in traffic characteristics (e.g. light vs. heavy trucks as shown by Damsere-Derry et al., 2008 in Ghana, or for small vs. large buses by Siregar et al., 2021 in Indonesia). This needs to be accounted for in traffic studies of mixed traffic.

Knowledge Gaps in LMICs

There was sufficient coverage of traffic mix and speed of different road users in LMIC research to understand the fundamental concepts and issues in this context. Nevertheless, the following gaps in knowledge may impede future actions in speed management for improved safety on LMIC roads:

- There is a need to identify an easy way to communicate heterogeneity of traffic based on broadly accepted vehicle classification, so that LMIC practitioners can quickly apprise and compare traffic mixes across different roads.
- There is a need to better understand the effects of traffic heterogeneity on speed variance and the mean (Sections 4 and 2) and on injury crash risk.
- There is a gap in understanding of how higher traffic heterogeneity affects effectiveness of common road safety interventions. Information is needed on treatments that work better in highly mixed traffic, on different road users, and on road users whose risk is increased by safety treatments (unintended consequences).
- There is a need to explore and test speed management interventions which could improve both safety and traffic flow given LMIC traffic mixes and speeds. This may include LMIC-specific solutions or variants of HIC solutions optimized to different heterogenous traffic mixes (e.g. high proportion of P2W, low PC and high HV).
- Additional research is needed to investigate the effects of intra-vehicle class speeds and speed variations on overall traffic speeds, e.g. mopeds vs. motorcycles, light vs. heavy trucks.

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6. Speed limits and travel time (mobility)

Speed limit changes have been used as a low-cost measure to reduce crashes and injuries. However, there is a common perceived tradeoff between safety and mobility leading to reluctance to adopt this treatment by road managers. This may affect LMIC speed management practice; hence it is important to summarize the available evidence.

A speed limit is, by most definitions, the highest legally permissible speed a driver may drive over an applicable road section. Traffic speed is determined by many other factors. Hence the effects of speed limits on traffic speeds and travel times are limited.

There is a common public perception that reducing speed limit will increase travel time. Drivers tend to overestimate this effect by a significant margin. This bias happens due to several reasons, including human perception of the distance – time relationship, and the lack of appreciation of how travel time is influenced by:

- traffic congestion,
- delays at intersections,
- interactions with other drivers (e.g. following, platoons),
- geometric road constraints and
- weather.

Many simulation studies fail to properly address the relationship between speed limit, traffic speed and travel time, resulting in travel time estimates which may be in the correct direction but not in magnitude. Therefore, this review investigated the evidence of the relationships between speed limit change and travel time drawing on theory, before / after evaluation studies, and studies comparing travel time on similar road sections with different speed limits.

Theoretical change in travel time

Introducing new speed limits most often leads to some changes in the average speeds on a treated road. It is an assumption that change in speed is constant and is not constrained by traffic or road environment. This is rarely true, except for free-flowing traffic on high quality roads (e.g. intercity motorways outside of peak traffic periods).

Still, this theoretical change in travel time can be calculated by multiplying the distance by the difference of inverses of the before and after speeds (D x ($1/V_{before} – 1/V_{after}$). Table 6.1 shows the travel time changes from changing the average speed by 10 km/h. It shows there are more travel time impacts in lower speed environments than in high-speed environments.

Table 6.1. The theoretical relationship between average speed change of +/- 10 km/h and travel time change given initial speeds (for a 10 km road section)

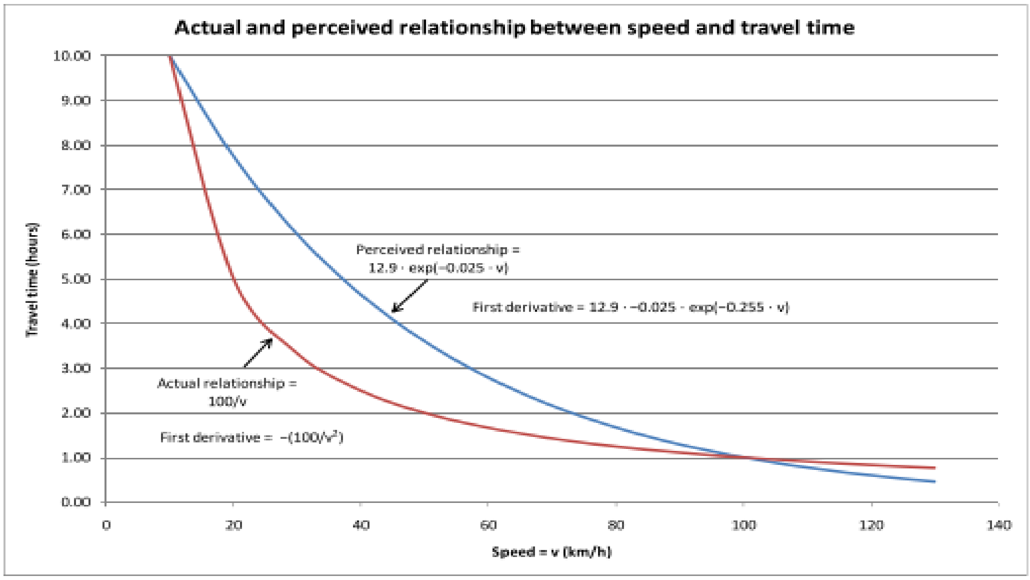
Initial Speed (km/h)	30	40	50	60	70	80	90	100
Travel Time (min): Saved from + 10 km/h	5.0	3.0	2.0	1.4	1.1	0.8	0.7	0.5
Added from – 10 km/h	10.0	5.0	3.0	2.0	1.4	1.1	0.8	0.7

The travel time-saving bias

Travel time savings are greatly overestimated by drivers at higher speeds leading to opposition to speed limit reductions, especially on high-speed roads. Literature refers to this as the *time-saving bias* (Svenson, 2008; Svenson & Treurniet, 2017; Elvik, 2009; Peer, 2011; Peer & Gamliel, 2012). This bias is also a significant contributor to individual choice of speed and speeding as noted in Section 7.

Using the results of a study conducted by Svenson, (2008), Elvik (2009) established a curve to show the relationship between speed and the actual and perceived travel time for a road segment of 100 km length. The curve in Figure 6.1 clearly shows that the additional travel time from reducing speed depends on the initial speed value. At higher speeds, the flatter slope of the curves means that additional travel time is less significant. The blue 'perception' curve sits below the red 'actual' curve meaning that drivers overestimate the effect. This bias has been demonstrated though numerous studies using different methods including driving simulators and questionnaires (e.g. Fuller et al., 2009; Peer, 2010 and Eriksson et al., 2013).

Figure 6.1. Actual and perceived relationship between speed and travel time. Source: Elvik (2009)



The concept of desirability of travel time saved is likely to be a myth. Litman (2021) notes that most working people devote 60 to 80 daily minutes to travel. As a result, an increase in travel speeds leads to more mobility rather than time savings. Hence, if traffic speeds increase, commuters and shoppers expand their destinations, increasing vehicle travel (travel distances), rather than saving time. "…this causes mobility inflation, it ratchets up the amount of travel people require to meet their needs, which is costly to communities and unfair to people with limited mobility…"

Network effects of speed limit reductions on travel time

Most often, speed limit policies are applied only on certain sections of a road or at road function levels (e.g. residential streets). Hence, people often experience speed limit changes just on one part of their journey. The personal effects of reduced speed limits on travel time are thus diluted.

Theoretical scenario modelling by the authors demonstrated how lowering the speed limits on local streets from 50 to 30 km/h may affect only a small proportion of each journey. Again, this assumes that a speed limit reduction translates fully to a reduction in average speed. Studies reviewed further on will challenge this assumption. Table 6.2 shows these theoretical impacts on travel times based on a 10 km journey shared between low-speed local road networks (initially 50 km/h speed limit) and high-speed roads (80 km/h, not changed).

Table 6.2. Theoretical additional travel time from speed limit reductions on low-speed local proportion of the road network

Percentage of the journey kilometers on local roads	Original travel time*	Travel time changes* when local roads speed limit reduced from 50 km/h to:	
		30 km/h	40 km/h
10%	7.95 min	+0.8 min	+0.3 min
20%	8.40 min	+1.6 min	+0.6 min
30%	8.85 min	+2.4 min	+0.9 min

* Assumes that speed limit = average speed.

From this example, it is evident that only seconds to a couple of minutes would be lost when the local roads speed limit is decreased while the other speed limits remain the same. This should be considered an upper limit of travel time impacts.

Studies and evaluations of speed limit reductions

The effects of speed limit change are expected to vary for different road users and different road types. While speed limit change may have noticeable effects on more extended trips, which is usually common on rural roads, the effects on an urban environment with relatively shorter trips and frequent traffic delays may be insignificant. The reviewed studies demonstrate this while illustrating reasons specific to each environment.

Table 6.3 summarizes urban speed limit reductions (or similar) and their measured or simulated effects on travel time. Half of the findings showed no appreciable changes in travel time. Where travel time increases were noted, they were relatively small, adding only seconds or a small percentage to the overall trip time.

For urban roads, the reviewed studies noted that congestion, intersection delays, traffic flow interruptions, and traffic variability were the main factors dampening any theoretical increases in travel time.

Table 6.3. Summary of urban road studies on speed limit reductions and their travel time effects

Authors	Study type	Measures / Location	Travel time effects of lower speed limits
Transport for Wales, 2023	Cross-sectional, speed data, urban roads.	Comparison of operational speeds, travel time, safety, emissions and active travel between 20 mph (32 km/h) trial towns and non-trial 30 mph (48 km/h) towns. Wales, UK.	↓↑ Marginal increases in travel time, < 1 min during peak hours.
Ellison & Greaves, 2015	Naturalistic driving study based on speed data in urban areas	Individual speeds vs. speed limit and travel time saved. Sydney, Australia.	↓↑ Marginal time savings from driving at higher speeds. Average time saving from speeding was 26 sec/day (maximum value of 2 min/day for the most prolific speeder in the cohort).

Kodupuganti & Pulugurtha, 2019	Cross-sectional, based on speed data from multiple sources (loops, radar, probe vehicles); urban roads	Average and 95th percentile travel times. Compared roads with speed limits: a) ≥55 mph (88 km/h) to b) 40 and 55 mph (64 – 88 km/h), and to c) 30 and 35 mph (48 – 56 km/h). USA.	↑ Compared with high-speed roads (a), average travel time was 44 sec/mile higher on mid-speed roads (b) and 102 sec/mile higher on low speed-roads (c). The differences between the three groups were not statistically significant due to high speed and travel time variability, despite large sample sizes.
Mitra et al., 2021	Cross-sectional, based on speed data, urban roads	Comparing average speeds on three roads of same length with 60 vs. 50 km/h speed limits. South Korea.	↑ Night-time average speeds were lower on 50 km/h roads indicating 14% higher average travel time. ↓↑ There was no meaningful difference in travel time during the morning peak. Intersection delays were a key component of travel time (up to 2/3).
SMEC and Nairn (1999), cited in Archer et al., 2006	Computational study based on network-level effects	Reduction of 'cruise speed' by 10 km/h across parts of the road network. Melbourne, Australia.	↑ Urban roads other than freeways: Minimal short term travel time increase of 3%, and 0.6% long-term increase. All urban roads: Minimal 5% short term travel time increase, and 1% long term increase.
Haworth et al., 2001	Computational study based on national average travel time values	Estimating effects of reducing speed limit on local urban roads from 60 km/h to 50 km/h. Australia.	↑ Minor increase in average travel time per trip by only 9 seconds, assuming a 5 km/h reduction in cruise speeds
Jurewicz, 2010	Microsimulation study using calibrated models	Simulating speed and travel time changes from a hypothetical 20 km/h speed limit reduction on urban and outer-metropolitan roads. Australia.	↓↑ Impacts of lower speed limits on travel time were negligible under peak time and interrupted traffic flow conditions due to intersection and congestion-related delays. Travel time increases may become detectable on outer metropolitan motorways but only under free-flow conditions (not in peak time).

A similar review for rural road speed limit reductions and travel time impacts is summarized in Table 6.4. The three studies reviewed suggest travel time increases may be more likely in rural traffic flow. This is not straight forward, however, and the magnitude of increase may be conditional on traffic flow density and vehicle following behavior (platooning vs. free flow). Travel time increases were found to be meaningful only on long trips.

Table 6.4. Summary of rural road studies on speed limit reductions and their travel time effects.

Authors	Study type	Measures / Location	Travel time effects of lower speed limits
Dutschke & Woolley, 2009	Markov simulation model using speed data collected before and after	Travel time following reduction of speed limit from 110 to 100 km/h on rural roads. South Australia, Australia.	↑ Increase in travel times by 2 - 8% for high-density traffic, 4 - 10% for low-density traffic (2.2 – 5.5. min over 100 km trip). Reduced time following slower vehicles and overtaking.
Cerema, 2020	Before / after evaluation travel times based on probe vehicle data	Speed limit reduction from 90 km/h to 80 km/h on rural roads in France.	↑ (i) an average increase in travel time by 1 second per kilometer on daily trips. (ii) somewhat higher travel time increase on weekends than weekdays. (iii) different time increases for different times of the day. Driver surveys confirmed the time-saved bias, as they overestimated additional travel time by factor of two.
Perez-Prada & Monzon, 2017	Macroscopic traffic simulation	Comparing travel time performance on intercity highway sections after speed limit reduction from 90 km/h to 70 km/h. Madrid, Spain.	↓↑ Speed limit reduction led to no substantial change in the travel time performance of the entire road, when adjusted for control sections.

Variable speed limits (VSL), also called dynamic speed limits, provide another means of reducing speed limits and are sometimes used on motorways to better manage traffic flow. VSLs algorithms predict traffic shockwaves and apply lower speed limits to reduce significant variations in vehicle speeds and lane changes detrimental to safety. Research has proven the capability of VSLs in improving travel time, safety and emissions benefits compared with static speed limit options, or in before/after comparisons of real traffic (e.g. Li et al., 2017; Othman et al., 2020; 2022;).

VSL initiatives for speed management do not only benefit mobility efficiency but have significant safety benefits. For example, Burley et al., (2013) highlights the safety benefits of VSL from five studies. These studies show significant benefits between 10% to 50% reduction in crashes.

In summary, nearly all research into the effects of speed limit reductions on travel time was conducted in HICs. Traffic theory suggests that reducing the speed limit (i.e. maximum permissible speed) should reduce the average speed by a proportion of the limit change, and this has known safety effects. This would then have some effect of increased travel time, especially in the lower range of speeds (urban). Time-saving bias leads to drivers and the public to overestimate this additional travel time by a wide margin.

Reviewed urban studies showed that increases in travel time are minimal (half of the studies) or negligible (the other half) for most types of journeys. This is due to a wide range of factors, including: congestion, intersection delays, traffic interruptions and variability. Limited research on rural roads suggested that reduced speed limits may increase travel time slightly which also depends on the traffic characteristics and trip length.

Variable speed limits used on motorways were found to reduce travel times through predictive application of temporary reductions in speed limits.

Knowledge Gaps in LMICs

- There was no practice-oriented research from LMICs on the effects of speed limit reductions on travel time and other mobility metrics. LMIC more diverse traffic composition and flows (Sections 4 and 5) may lead to different mobility and economic outcomes than found in HICs. This is yet to be investigated.
- LMIC perceptions and biases regarding effects of speed, speed limits and speeding on travel time and income were not investigated (also see Section 7). This gap needs to be bridged in order to inform speed limit policies and measures in these countries.
- Existing knowledge does not allow for easy estimation of effects of speed limit change policies or measures in LMICs. A simple tool could be created which would be valid and helpful in illustrating expected changes in mobility in context of future road and intelligent transport projects.
- Variable Speed Limits were shown to improve safety and mobility on high-order roads in HICs. Little is known about their application and success in LMICs, and whether they offer similar or potentially greater benefits.

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7. Cultural differences affecting attitudes to speed

Speeding is a significant risk factor globally, and cultural differences may influence attitudes toward speeding. This review covers general research on factors affecting attitudes towards speed and speeding, and on the differences between HICs and LMICs.

The Theory of Planned Behavior (TPB) by Ajzen (1991) has been used to study speeding behavior. According to the TPB, speeding is determined by the speeding intention, which is influenced by the perceived speeding control, subjective norms, and/or attitudes towards speeding. This approach underpins many of the later developments.

Fleiter & Watson (2006) summarized the factors affecting speeding/speed choice into four categories, which they developed based on past research studies. These include legal, social, person-related, and situational factors influencing speed choice. The World Bank's Speed Management Hub[7] summarizes these factors based on Fleiter (2010), as shown in Table 7.1.

Table 7.1. Factors affecting drivers' speed choice

Speed choice factors		How they influence drivers' speed choice
Personal	Demography	Young and male drivers are likely to speed
	Personality type	Type-A and sensation-seeker personality types are likely to speed.
	Socio-economy	A person with a higher income is more likely to speed
Social	Social norms	Normative beliefs of the community and how 'important others' view speeding impact our speeding decision
	Social availability	Availability and type of individual on which we model our behavior impact our choice of speed
	Social contagion	Social comparison and social contagion play a role when we adapt our speed to the perceived speed of those around us
Situational	Road conditions	We are more likely to speed on wider roads and where speed limits are not self-evident
	Trip circumstances	We are more likely to speed in a hurry
	Traffic situations	Attitudes and perceived behavior of drivers around us impact our choice of speed
	Vehicle features	Some vehicle features such as the height of a driver seat from the pavement are shown to impact speeding behaviors
Legal	Speeding penalty	Enforcement practices and related sanctions are shown to significantly impact speeding behaviors
	Perception of sanctions	Our perception of the presence of surveillance and the chances of being caught speeding impact our choice of speed

These factors may vary at country, state, city and local levels, leading in aggregate to significant variations in speeding choices between countries (Fleiter & Watson, 2006). Comparing speeding behavior between countries recognizes the need for culturally sensitive safety policy interventions.

Reviewed studies of sampled drivers in HICs demonstrated many additional beliefs, responses and behaviors which are inter-related in their influence on the speed choice (e.g. Elvik, 2010; Yannis et al., 2016; Stephens et al., 2017; Stefanidis et al., 2022). Attitudes modelled in media, perception of other drivers' speeding, knowledge of speed limits, fear of enforcement, and enforcement tolerance were some of the factors influencing driver speeds. This diversity and complexity of factors suggested that speeding is not always a rational choice. Most research findings agreed or acknowledged that the presence of clear speed limits was essential in choice of speed, even if such limits may not always be credible to all drivers.

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[7] https://www.roadsafetyfacility.org/speed-management-hub

LMIC studies used in this review showed some similarities with factors found in studies from HICs, e.g. effects of speeds / speeding of other drivers, fear of enforcement, effects of gender and age. Additionally, the LMIC studies showed higher rates of speeding, lower speed limit awareness, and noted work/social pressures contributed to speeding (e.g. Bachani et al., 2013; Zhao et al. 2019; Mamo et al., 2022)

A number of studies focused on comparisons in speeding attitudes of drivers from HIC and LMIC countries. Table 7.2 summarizes the results of studies comparing the speeding attitudes of drivers across different countries. Inference from the study results is also shown, indicating that most reviewed studies found speeding was more acceptable or likely in LMICs due to attitudes and behavioral norms. It is also clear that there were significant differences between LMICs.

Table 7.2. Summary of studies on cross-cultural attitudes to speeding

Author	Countries compared / sample size	Measure	Factors considered	Results per country	Comments
Tankasem et al. (2016)	Thailand (184), Laos (199), Cambodia (187)	Speeding intention	Attitude; Subjective Norm; Perceived Behavioral Control: Intention	Influencing factors for speeding intentions differed + AT significant for Thailand + SN & PBC significant for Laos + PBC significant for Cambodia	Differences in speeding behavior between developing countries
Sheykhfard et al. (2023)	Netherlands (720) Iran (720)	Speeding	Attitude, violations	Iranian drivers had a greater likelihood of getting involved in speeding and overtaking than Dutch drivers	More acceptance of speeding in developing countries
(Wallén Warner et al., 2009)	Turkey (252) Sweden (219)	Speed limit compliance	Attitude (AT); Subjective Norm (SN); Perceived Behavioral Control (PBC): Intention (IT)	Compared to Turkish drivers, Swedish drivers reported a more positive AT, SN, PBC, and IT and spent more time complying with the speed limit	Worse attitude and behavior metrics for drivers from developing countries resulting in more speeding.
(Huang et al., 2018)	China (Shanghai) USA (New York) GPS data from both cities	Taxi driver speeding	drivers, road attributes, and environment variable	+Shanghai drivers were more likely to speed due to their larger working hours (18h) + Speeders in both cities had shorter working hours and longer daily driving distance	More speeding violations for developing countries due to higher working hours and longer distances covered

Author	Countries compared / sample size	Measure	Factors considered	Results per country	Comments
(Nordfjærn et al., 2011)	Ghana (299), Tanzania (559), Uganda (415), Russia (245), India (196), Norway (247)	Speeding	Safer behavior on speeding	+ Sub-Saharan African (SSA) countries reported more safer behavior compared to other countries. + There were observed differences between the SSA countries.	Speeding attitude differs between developing countries and developed countries, But there is also a significant difference amongst developing countries
Suzuki et al., (2022)	Japan (634), China (1517), Qatar (725), United Arab Emirates (480), Italy (871), United K. (486) Egypt (521)	Speeding	Tolerance to exceeding speed limits	+All countries showed more than 50% tolerance to exceeding speeds by 20 km/h on freeways/ highways and by 10 km/h in residential streets and urban areas. + On average, Italy showed the highest tolerance levels followed by Egypt while China showed the least tolerance levels.	There is no significant difference in speeding attitudes between drivers from developed and developing countries

The ESRA project[8] is a joint initiative of different stakeholders aimed at collecting and analyzing comparable data on road safety performance, in particular road safety culture and behavior of road users. The ESRA 2019 survey included 48 countries across six continents (12 African countries, 9 Oceania and Asian countries, 23 European countries and 3 American countries).

Evidence from this project shows that the majority of drivers in LMICs (12 African countries) reported exceeding speed limits, though the extent varies significantly between the countries. The perception of time loss or gain by speeding was also evident for LMICs. There was also some partially supported evidence that many drivers in LMICs were not aware of the speed limits and traffic regulations.

Speed attitude is significantly different amongst LMICs. This suggests that attitudes towards speed are generally specific to a given country; hence LMICs should not be treated as one group in safety analyses.

Knowledge Gaps in LMICs

There was ample research on factors affecting speed choice in both HICs and LMICs, however there are several gaps to be bridged in order to improve speeding interventions in LMICs:

- Speeding and factors affecting it are complex and differ strongly between HICs and LMICs, and even more significantly among LMICs. Therefore, interventions aiming to reduce speeding levels in one country may not necessarily be translated to other countries. Countries are advised to conduct individual studies to understand the local problems concerning speeding.

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[8] esranet.eu.

- There was a need to provide a standardized framework for understanding the complex and interacting factors affecting speeding across social, economic, legal and cultural contexts of each country. This would better inform specific policy interventions aimed at reducing speeding, such as setting of speed limits or enforcement tolerance levels.
- Studies generally failed to consider the subjective rationality of drivers' speed choice due to the presence of other road users in traffic or the effects of mixed traffic. This could be improved in future LMIC studies.

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8. Speed data collection methods

Speed is a key factor in transport externalities such as crash injuries, emissions and travel time (Sections 2, 3 and 6). There is a growing demand in LMICs to collect and understand speeds in a way that will inform speed management and road safety interventions.

Speed data has been collected for many decades using several instrumented methods with known limitations and biases. Additional methods have emerged, taking advantage of new technologies.

This section provides a summary of different speed data collection methods to identify their applicability, advantages, and limitations. These need to be considered in context of practitioner objectives for speed data collection. Typically, speed key performance indicators (KPIs) are sought to inform speed management initiatives: mean speed, standard deviation (hence the population/sample size), 85th percentile speed, speed quantiles, percent of drivers speeding, or percent speeding by ≥ X km/h. As noted in Section 5, mixed LMIC objectives may also call for these to be collected for different vehicle types such as passenger cars, powered-two-wheelers, buses, etc.

Different speed data collection methods offer different types of speed data. Depending on practitioner objectives for speed data, the survey may obtain KPIs based on the following types of speed data:

- speed of all or only of the free-flowing vehicles,
- speeds of all vehicles during a time sample deemed representative (e.g. PM peak, 12 hours, two weeks),
- speeds of a sample of vehicles deemed representative of the target group (e.g. all traffic, and/or different vehicle types),
- spot speeds (time-mean) representing a roadside observer experience, or segment speeds (space-mean) representing a traveler experience,
- speed profile of changes along a route (running or dynamic speeds) representing a traveler experience.

Generally, KPIs from different speed types may not be comparable, however multiple types of speeds can be collected at once depending on the method. Some conversion methods exist (e.g. Mondal et al., 2019) and experienced practitioners should be able to interpret different types of speed data.

There is accepted guidance on types of speed surveys needed for different objectives. For instance, effects of speed changes on safety presented in Section 2 require the mean speed (KPI) based on survey of free-flowing speeds. In short, objectives and speed data needs should be clearly understood before selecting a data collection method and planning a survey. The methods will also depend on technological capabilities and budgets.

Besides ensuring the type of speed data, the quantity is also vital to ensure the accuracy of speed KPIs. Before speed data collection, the field surveyor must identify the sample size (minimum number of vehicles by type) needed for accurate KPIs that will satisfy the objectives. Most guides agree that speed studies require a minimum of 200-500 vehicles to detect small changes in mean speed, provided that precise speed data collection methods are used (Green et al. 2020; WisDOT, 2009).

It is important to consider that there is no ‘ground truth’ for speed as each method has its own limitations and biases. What is important is that an appropriate method is chosen that satisfies the practitioner objective balanced with limitations, and that this method is applied consistently (e.g. before and after a speed management intervention).

Different speed data collection methods

The following methods are based on fixed sensors measuring spot or segment speeds. Some are able to measure all vehicles or a sample during the survey.

Pneumatic road tube counters

This method makes use of two pneumatic rubber road tubes fixed across the road. When vehicle tires roll over a tube, air pressure change generates an electronic impulse in a roadside controller. The time difference between these impulses for a pair of tubes a set distance apart is used to determine the speed of an individual vehicle. The counter also applies proprietary algorithms to convert sequence of tire impulses into vehicle classifications. In general, pneumatic tubes offer several advantages, including spot speeds of all and individual vehicles, no observer-related errors, extended data collection period (up to several weeks), counts across multilane lanes, vehicle flow counts and classification. Tube counters can also provide free-flow speed sample of vehicles not impeded by following others.

However, pneumatic tubes are often visible to drivers, and this may affect their speed choice, posing unknown risk of bias in the recorded data. Their use is also susceptible to damage and vandalism, and they are prone to extreme weather, temperature, or traffic conditions. Tubes cannot be used reliably on gravel or unmade roads. There are also health and safety issues as operators have to manage traffic flow to install them on the road (Green et al., 2020; WisDOT, 2009).

Magnetic/inductive loop detectors

Loops cut into the road pavement use magnetic fields to detect a moving vehicle and capture its speeds. They are usually installed consecutively in a roadway to capture vehicle speeds as periodic or permanent traffic survey stations with dedicated controllers for multiple loops. They are not prone to bad weather conditions and can handle large data quantities. However, loops can be susceptible to pavement damage and may require replacement. Loops generally require a systems approach for maintenance, data processing, management and communication. This makes this method expensive and applicable to high-value asset scenarios such as arterial or motorway traffic management (Fitzpatrick et al., 2016; Leduc, 2008).

Piezoelectric sensors

Similar to loop detectors, piezoelectric sensors placed in a cut groove along a roadway surface. They use energy transformation to measure speed, weight and count vehicles (Leduc, 2008).

Similar limitations apply, noting higher costs and the need for closer pavement quality monitoring. Poor pavement conditions can make the data unusable.

Radar recorders and guns

Radar recorders make use of Doppler effects to obtain vehicle speed. These devices are usually mounted in an unobtrusive and undetectable manner so as not to alter the normal traffic speeds.

Radar recorder installations are not labor-intensive and can collect data for a long period of time. Some recorders offer software that can tabulate traffic volumes and classify vehicles. Reported accuracy is 1.5%. Radars may not correctly distinguish free-flowing vehicles, the direction of travel or speeds for multi-lanes. They require more maintenance and effort in calibrating (WisDOT, 2009).

Radar guns are a portable, handheld version of radar recorders. The operator focusses the gun on an approaching vehicle to measure speed. Some guns store the data, while others require manual logging to build a speed sample. Typically, speeds are collected in one direction, but collection of data from two directions is possible. Collection may not be feasible in heavy traffic. There are technical aspects of operating a radar gun which require some training, e.g. minimizing cosine error, avoiding interference from non-targeted vehicles, optimal distances and angle to traffic, etc. (Fitzpatrick et al., 2016; WisDOT, 2009). Radar guns can be mistaken for enforcement, leading to change in driver behavior, and so locations for recording need to be unobtrusive.

LiDAR: Laser guns

Laser guns obtain speed data through emissions of laser beams from the gun and the reflection off a moving vehicle. They are also handheld or can be mounted on a device similar to a radar gun. Accuracy is reported to be +/- 1.5%.

The nature of beams from laser guns permits the operator to measure exactly the speed of the target vehicles without interference from other vehicles. However, data from Lidar also needs tolerance error correction and may also become sensitive to precipitation and humidity. Lidars can also be mistaken for enforcement, and so locations for recording need to be unobtrusive. Lidars are more expensive than radars (Fitzpatrick et al., 2016; WisDOT, 2009).

Acoustic/ultrasonic sensors

These devices measure speed by emitting sound waves to the vehicle and measuring the time for the signal to return to the device. They do not need to be installed in or on the pavement but generally need to be mounted along or overhead of the road, often on preexisting structures. However, they can be affected by adverse weather conditions such as low/high temperatures and snow (Antoniou et al., 2011; Leduc, 2008).

Infrared

This technology uses multiple infrared beams emitters mounted low near the pavement matched with a receiver on the other side of a carriageway. As a vehicle moves along the road its tires block and unblock each of the beams, and the time for this cycle is detected. This technology can measure individual vehicle spot speeds, height, width, length, traffic flow and classification. Proprietary technologies calculate the speed of each vehicle with high accuracy (0.3-0.5 error level, 1.2 km/h uncertainty).

These are costly devices best installed as permanent stations, otherwise ad-hoc uses entail mounting and calibration. Infrared can be affected by adverse weather conditions (Green et al., 2020; Leduc, 2008).

Stopwatch method, including enoscope or mirror method

The enoscope consists of a simple open housing that contains a mirror mounted on a tripod at the side of the road such that an observer’s line of sight is turned through 90 degrees. The method makes use of two enoscope mirrors (there are one mirror variants) placed within a roadside and set at a defined distance apart (e.g., 30 m). A surveyor, positioned in the middle, starts and stops the stopwatch when a vehicle passes each reference point. Alternatively, tapes or poles or existing roadside objects are used as section start and end references.

The equipment can be quite low cost and simple to use, and usually eliminates errors due to parallax. The method is labor-intensive, and it may be impractical under heavy traffic. (Chai, 2013; Mathew, n.d.).

Radio method

This method consists of two groups of observers positioned at known distances (e.g., 250 m length) within a road section using handheld radio to reference the passing of a vehicle. One group records the travel time over a known section distance (Chai, 2013). The recordings are then used to calculate average speed within the road section. This method is simple and requires minimal training. It is prone to parallax errors, labor intensive, and practical only in light traffic conditions.

License plate recognition

This method involves recording license plate numbers within a defined road distance, employing several techniques. One involves automated license plate recognition using synchronized digital video cameras at the start and end of a road segment. Computer vision software can then read and match most of the plates to produce a segment speed sample (Garibotto et al., 2001). Vehicle classification is usually produced by software.

A simpler variant is the same as the radio method just based on manual recording of plate numbers.

Digital video and closed-circuit television (CCTV) cameras

These usually detect and record traffic video images which are later analyzed using computer vision software. The versatility of this method allows collection of speeds, traffic flows and turning movement counts, vehicle classification, detect gap acceptance, and incidents / near misses. Cameras should meet system design criteria, e.g. low lens distortion, high video resolution and frames per second) and be mounted high above the road.

Temporary applications may require erection of specialized poles ensuring clearances to any overhead wires. Studies show that despite their high initial costs, they are more reliable than loop detectors and require little maintenance as permanent survey stations (Antoniou et al., 2011; Leduc, 2008).

Car following method

This method consists of inferring the speed of a leading, free-flowing car from by a following vehicle carrying a GPS logger measuring speed, position, and acceleration. The following driver attempts to replicate the leading vehicle's speed, keeping the spacing between both vehicles' constant (Echaveguren et al., 2015). Multiple runs provide a speed profile distribution along the driven route (e.g. a mean within standard deviations).

This method has some inherent drawbacks. A random leading vehicle may require some skill to identify and to follow. It may not drive the entire route of interest. Even successful multiple survey runs may produce a small sample size, especially if a route is long. The labor costs are very high. Occupational safety and legal issues arise for surveyors due to speeding by leading vehicles, or speed accuracy tradeoffs have to be made.

Other speed survey methods based on traffic moving along a route are discussed below.

Floating car data (FCD) / probe data

Alternative technologies to fixed sensor or car following methods have emerged to allow collection of speed data, while also providing access to historical data. These methods are based on 'floating' or 'probe' vehicles broadcasting their GPS positions and other data. These methods usually offer lower survey costs than fixed sensors and allow for location specific and network wide monitoring.

FCD methods provide a sample drawn from multiple sources such as in-car navigation systems, cellular phone apps, on-board diagnostic systems, or fleet management systems. These sources have grown exponentially allowing for greater relevance and application.

FCD can replicate a crude speed profile along a route and might show variations in speed which cannot be easily observed using fixed sensor methods. Travel times are nearly always available along with origin / destination data. Sample size, or traffic intensity, is also available providing a relative indication of traffic flows on the network. In addition, FCD is easy to implement without training and allows data integration (Leduc, 2008).

Retrospective surveys are also possible enabling before / after speed evaluation studies to be initiated after delivery of the treatments.

The trade-offs of FCD include lower accuracy than some sensor methods and reliance on proprietary data aggregation and processing. Segment speeds are available, rather than spot speeds, and road segmentation is done by data providers rather than the practitioner. This difference may be irrelevant for short segments in dense urban environments. Moreover, FCD sampling varies between 1% and 30% of traffic, so sample sizes may be low for lower volume roads to be compensated with longer survey periods. Free-flow speeds are available but may be based on assumed conditions of free flow (e.g. at night) rather than measured gaps between consecutive vehicles.

One of the main criticisms of FCD has been that it is based almost completely on cars, vans and trucks with very few two-wheelers currently equipped with GPS devices. Classification of vehicles is also very limited, although this depends on the source.

The licensing of this data from providers may be conditioned, e.g. no sharing or reselling or raw data. Several sub-types of FCD are discussed in more detail below.

FCD from navigation companies

FCD aggregators such as TomTom, HERE, Google and other companies specialized in digital navigation mapping usually have access to vast numbers of GPS-enabled vehicles and other devices. Individual data sources are cleaned, standardized and aggregated by a provider into a standard product. Such probe data provides historical and near-live speed performance analysis.

This type of FCD speed is usually averaged in 5-minute increments and presented with other measures such as mean, minimum, maximum, standard deviation, percentiles, sample size, and basic vehicle classification[9]. Data is presented at road segment level which varies in length depending on road continuity (e.g. presence of a side road intersection, traffic island, etc.). Increasing FCD sample sizes are leading to estimations of traffic flows with some confidence.

FCD based on smart phone apps

Some apps installed in drivers' and passengers' phones capture users' GPS position and time stamp through location services (when enabled), producing speeds and heading direction Examples include Strava, Waze, Facebook, Uber, plus most fleet management apps. Some apps also record the type of vehicle used. Sampling techniques are used to manage privacy concerns; for example, blocking data collection from particular areas such as homes (Herrera et al., 2010).

Most of the app providers sell their data to aggregators such as TomTom or HERE for processing (Fitzpatrick et al., 2016; Leduc, 2008). Some apps may provide their own data products, e.g. Strava which has been useful in some cycling studies. Apps may offer unique opportunities to share data from specific user types, e.g. food delivery services, ridesharing and from micro-mobility devices.

FCD from connected vehicles, e-sim and On-board Diagnostic (OBD) boxes

Increasing number of vehicles are equipped with e-sim cards to facilitate automated emergency call after a crash mandated by some countries. The same e-sim enables transmission of vital vehicle statistics from on-board diagnostics computers back to the manufacturer, e.g. engine condition, mechanical performance, instant speeds, direction, seatbelt status, airbag status, and acceleration including instances of harsh braking.

Similar to other FCD, this data is aggregated by commercial data providers. However, due to specific advantages of this source some companies specialize in providing this rich (if smaller) data at individual vehicle level including type and make (deidentified).

The same data can be obtained from OBDs of vehicles involved in crashes. Such black boxes provide an invaluable source of speed data prior, during and after a crash, and have been used in many scientific studies (Fitzpatrick et al., 2016).

Comparison of speed data collection methods

There have been many studies seeking to compare individual speed data sources against some ground truth, or each other. Some of the reviewed studies showed similarities, while others showed systematic differences between sources. This is to be expected from different types of speed being measured (e.g. spot vs. segment) using different

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[9] https://www.here.com/learn/blog/traffic-analytics-speed-data

methods. The findings sometimes varied as proprietary technologies can produce different results even within the same method. New technologies also improve over time making older comparison studies obsolete.

Generalizing, FCD and other segment speeds (space-mean) tend to be lower than spot speeds (time-mean) collected with tube counters and other spot speeds (Kemp & Twort, 2019). This is due to different biases in computation of both speed types. Secondly, FCD samples any available probe vehicles in traffic, i.e. those leading, following, turning, merging, while spot speed surveys tend to be in locations maximizing free flow speeds (e.g. away from intersections, flat ground).

Table 8.1 provides a summary of different methods along with a qualitative comparison. It is intended to assist practitioners with deciding which method may be most appropriate for the objectives given capability and budgets.

In summary, Floating Car Data technologies emerged to allow real-time and historical speed data collection for local surveys and network wide monitoring, although there are trade-offs. The ubiquitous nature of FCD enables quick and low-cost surveys without much technical training or intrusion into traffic. This includes retrospective surveys.

The trade-offs mean that sensor-based methods will continue to be useful where it is important to capture highly precise speed data for multiple types of vehicles, or to measure highly specific speed KPIs such as free-flow spot speeds.

Knowledge Gaps in LMICs

- There is lack of practitioner guidance on sample size determination for speed data collection on LMIC roads with different traffic mixes, based on understanding of speeds of different road users (refer to Section 5).
- There is a lack of LMIC guidance on when to apply different speed data collection methods.
- Speed data from FCD sources are very promising, especially for urban areas, given the growth and usage of cellular phones. There is a need for standard procedures for FCD speed data use and transparency in its performance.

Research and development are needed to improve the availability and accuracy of FCD speed data for different vehicle types. This includes access to individual vehicle speeds along with their type/make to enable deeper safety analysis, e.g. between free-flow and congested conditions.

Table 8.1. Summary of speed data collection methods

Methods	Type of data collected				Labor	Cost	Advantages	Disadvantages	References
	Spot speeds	Flows	Vehicle Class	Speed profile					
Pneumatic road tube counters	√	√	√	X	L	M	Accurate; large sample sizes obtained with minimal effort; few person-hours; Can collect data for long periods; Can collect all traffic data simultaneously. Accuracy 1.5 to 3 %	Requires greater training; disturbance of traffic; high safety issues for operators; Easily detected by drivers; Does not allow random selection of vehicle data set; Equipment-intensive; requires maintenance or calibration; Can be affected by weather conditions.	Gates et al., 2004; WisDOT, 2009
Magnetic/ inductive loop detectors; piezoelectric sensors	√	√	√	X	L	L	Accurate; large sample sizes obtained with minimal effort; few person-hours; Inductive loops installed consecutively in a roadway provide a more permanent method to capture vehicle speeds	Requires greater training; disturbance of traffic; high safety issues for operators; Installation requires pavement cut; They require algorithms to be installed on the traffic signal controller; They have a shorter life expectancy due to damage by vehicles; Big data requires ongoing systems and management costs.	Antoniou et al., 2011; Fitzpatrick et al., 2016; Leduc, 2008

Methods	Type of data collected				Labor	Cost	Advantages	Disadvantages	References
	Spot speeds	Flows	Vehicle Class	Speed profile					
Radar recorders / gun	√	√ / ?	√ / ?	X	L / H	H / M	Permanent recorders can collect accurate (+/-1.5%) spot speeds and other traffic data for long periods; not affected by weather conditions, less visible to drivers. Portable guns are accurate, and the surveyor can control the sample size.	Issues with determining the direction of vehicles and collecting data for multiple lanes; Does not allow random selection of vehicle sample; May not distinguish free-flowing vehicles; Equipment-intensive, requires maintenance and calibration. Portable guns may be difficult to hide and affect driver behavior. Require technical training to use. Also, surveys are very labor intensive.	Gates et al., 2004; WisDOT, 2009
LIDAR: Laser gun	√	?	?	X	H	M	Accurate, precise, and reliable; Simple to use and easy to track vehicles; Portable, operator control vehicle sample and direction; measures the speed of target vehicle; Accuracy +/- 1.5%.	Portable guns may be difficult to hide and affect driver behavior. Require technical training to use, and equipment maintenance. Also, surveys are very labor intensive.	Gates et al., 2004; WisDOT, 2009

Methods	Type of data collected				Labor	Cost	Advantages	Disadvantages	References
	Spot speeds	Flows	Vehicle Class	Speed profile					
Acoustic/ ultrasonic sensors	√	√	√	X	L	H	Easy to use; Can collect vehicle counts, speed and classification data simultaneously; Can collect data on multi-lane; Insensitive to precipitation	Affected by low temperatures and snow; requires maintenance and calibration.	Antoniou et al., 2011; Leduc, 2008
Infrared	√	√	√	X	L	H	Transmits multiple beams for accurate measurement; multi-lane operation available; 0.3-0.5 error level, 1.2 km/h uncertainty	Affected by adverse weather; requires maintenance and calibration; expensive and hardware based.	Antoniou et al., 2011; Leduc, 2008; Green et al., 2020
Enoscope or the mirror method	√*	?	?	X	H	L	Simple to use; does not require sophisticated equipment; usually eliminates errors due to parallax.	Labor intensive; may be difficult to apply under heavy traffic.	Chai, 2013; Mathew, n.d.
Radio method	√*	?	?	X	H	L	Simple to use; Operator controls vehicle sample and direction; does not require sophisticated equipment other than handheld radio.	Labor intensive; may be difficult to apply under heavy traffic; Prone to parallax errors.	Chai, 2013;
License plate recognition	√*	√	√	X	M	H	High precision; Can generally match a high proportion of vehicles passing through the full segment.	Can be affected by light intensity; requires maintenance and calibration. Expensive to set up.	Garibotto et al., 2001

Methods	Type of data collected				Labor	Cost	Advantages	Disadvantages	References
	Spot speeds	Flows	Vehicle Class	Speed profile					
Digital video and CCTV cameras	√	√	√	X	L	H	Multilane/zones detection; A rich array of data available; Provides wide area detection. Multiple technologies are available. Can provide classification.	Prone to adverse weather or strong wind movements; requires maintenance and calibration. Isolated sites prone to vandalism.	Antoniou et al., 2011; Leduc, 2008
Car following method	√	X	X	√	H	H	Provide more granular speed data and speed profile; Can record spatial and time-varying trends in speed.	Short term only, i.e. during trials. Limited to vehicles used being followed. Very labor intensive.	Fitzpatrick et al., 2016; Kemp & Twort, (2019)
Floating car data (FCD) / probe data including from: - navigation companies - smart phone apps - connected vehicles	√*	X	X	√	L	L	Broad coverage of network; Can record spatial and time-varying trends in speed; Short- and longer-term speed monitoring; Cost-effective and easy; Has no impact on driver behavior; Some apps used by specific drivers can capture speed behaviors. There is emerging estimation of traffic flow. Data from apps and connected vehicles may be more precise and targeted, than aggregated data.	Data is almost always aggregated (exceptions exist) and may require longer monitoring time for low-volume roads. Sample may be limited to cars, vans and heavy vehicles, unless obtained from specific smart phone apps or connected vehicles. Free-flow conditions have to be assumed.	Fitzpatrick et al., 2016; Rose, 2006; Cao et al., 2022; Shariff et al., 2016

NB: √* measures space-mean speed, usually for short distances; L = low: M = medium: H = High; ? = may not be applicable in some situations (e.g. under heavy traffic flow).

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