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Principles for development of safer rural highway systems for conditions prevailing in low and middle-income countries

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Principles for development of safer rural highway systems for conditions prevailing in low and middle-income countries

Geetam Tiwari

1 INTRODUCTION

Road traffic safety has been recognized as a global health problem by all stakeholders in the new millennium. Since 2004 several international organisations have committed themselves to work towards reducing the burden of road traffic injuries (RTIs) such as the World Health Organisation (WHO), the World Bank, and the United Nations etc. Following statements have been reiterated in several reports:

- A disproportionately high burden of road traffic deaths and injuries occur in low and middle-income countries (LMICs) (90%) and the burden is expected to increase due to rapid urbanization and motorization in LMICs.
- Globally, the number of fatalities per 100,000 population (mortality rate) ranges from less than 3 to almost 40. The rate is less than 9 in high-income countries (HICs) but averages around 20 in LMICs, with the African region demonstrating the highest rate (26.6) (WHO, 2015).
- Road traffic injuries are predictable and preventable. Despite the growing burden of RTIs globally, multiple intervention strategies and projects have contributed to a significant reduction of the burden of road traffic injuries in many high-income countries (Peden et al., 2004).
- Empirical evidence for effective interventions is extensive, including enforcement of legislation on speed control and alcohol consumption, promotion of seatbelt and helmet utilization, and safer design and use of roads and vehicles (Peden et al., 2004).

A recent study (Staton et al., 2016) published a systematic review and a meta summary of effectiveness of road traffic injury measures in LMICs. The authors referred to the Global Plan for the Decade of Action for Road Safety 2011–2020 prepared by the WHO (WHO, 2011). The plan has been developed to guide efforts at national and local levels to reduce the forecasted level of road traffic fatalities around the world. One of the important objectives of the plan is to strengthen institutional capacity on road safety management and improve the health system for post-crash response. Researchers have pointed out that most of the analysis to date has been conducted in high-income settings and has focused on vehicle occupants rather than the vulnerable road users in LMICs (Ameratunga, Hijar, & Norton, 2006; Staton et al., 2016).

The study included a search of 8,560 articles and out of that 18 met all the inclusion criteria. Table 1 gives the list of included studies and type of intervention identified. Nine studies out of 18 deal with effect of legislation, followed by education in 5 studies, enforcement in 2 studies

Table 1. Road traffic injury prevention study characteristics (Source: Staton et al., 2016).

Authors*	Geographic Region	Prevention Type	Study Design	Targeted Population	Risk of Bias	Outcome Measures
Abegaz et al., 2014	Ethiopia	Legislation	Interrupted time series	All road users	Low	RTC per 10,000 vehicles, RT deaths per 10,000 vehicles
Andreuccetti et al., 2011	Brazil	Legislation	Interrupted time series	Vehicle drivers	Low	RT Injuries, RT deaths
Bacchieri et al., 2010	Brazil	Education	Non-randomized intervention-Longitudinal with steeped wedge design	Cyclist	Low	Cyclist crashes, Cyclist “near miss”
Bishai et al., 2008	Uganda	Enforcement	Interrupted time series/ Cost effectiveness	All road users	Low	RT deaths, RT crashes
Chandran et al., 2014	Mexico	Multifaceted (legislation and education)	Interrupted time series	All road users	Low	RT Crashes, RT Injuries, RT deaths
de Andrade et al., 2008	Brazil	Legislation	Interrupted time series	All road users	Low	RT deaths
Espitia-Hardeman et al., 2008	Colombia	Legislation	Interrupted time series	Motorcyclist	Low	RT deaths
Farange et al., 2002	Brazil	Legislation	Cross-sectional	All road users	Moderate	TBI cases, RT crashes, RT deaths
Gomez-Garcia et al., 2014	Mexico	Legislation	Interrupted time series	All road users	Low	Alcohol RT Crashes, Alcohol-related RT Injuries
Guanche Garcell et al., 2008 [27]	Cuba	Enforcement	Cross-sectional/Time-series	Vehicle drivers	High	RT Crashes, RT deaths, RT Injuries
Ichikawa et al.,	Thailand	Legislation	Interrupted time series	Motorcyclist	Low	Motorcycle crashes
Nadesan-Reddy & Knight, 2013	South Africa	Speed Control	Interrupted time series	All road users	High	Pedestrian/Vehicle RT injuries
Passmore et al., 2010	Viet Nam	Legislation	Interrupted time series	All road users	Moderate	Risk for head injuries among RT injuries patient, RT deaths
Poli de Figueiredo et al., 2001	Brazil	Legislation	Interrupted time series	All road users	Moderate	RT Crashes, RT deaths
Rahimi-Movaghar, 2010	Iran	Community	Cross-sectional/ Community comparison	All road users	Moderate	RT Injuries, RT deaths
Salvarani et al., 2008	Brazil	Education	Interrupted time series	Vehicle drivers	Moderate	RT Injuries, RT trauma severity, RT deaths
Swaddliwudhilpong et al., 1998	Thailand	Education	Community RCT	Motorcyclist	Low	RT Injuries
Zimmerrian et al., 2015	Tanzania	Road Improvement	Non-randomized intervention-Longitudinal with steeped wedge design	All road users	Low	RT Injuries rate

* All references from Staton et al., 2016.

and speed control and road improvement in one study each. Important conclusions from the study include the following:

- Legislative interventions had the strongest evidence for reduction in crashes and injuries.
- Enforcement of legislations had an impact on the success of intervention.
- Educational interventions had limited effect.
- Road improvements (paved vs unpaved road) lead to increase in crashes.
- Two studies which included environmental changes by including speed humps resulted in lower crashes and injuries.
- Studies which included changing pedestrian behaviour to use pedestrian bridges and underpasses failed due to perceived risk and inconvenience and led pedestrians to increase their personal risk by creating their own path through the traffic.
- Further evaluations of road safety audits and implementation initiatives should be undertaken given the complex road environments found in LMICs.

This summary shows a focus on legislation and educational measures for improving road traffic safety problems in LMICs which have been evaluated. Only two studies evaluated impact of paved roads and speed humps.

More than 90% of studies selected by the authors to evaluate the effectiveness of legislation and educational strategies reflects the safety focus in these countries. This also implies that standards used for designing and constructing roads will ensure safety, therefore, only appropriate legislation regarding seat belt use, speed limits and alcohol control are required to improve traffic safety in LMICs. Often road standards (geometric design standards) in most LMICs have been based on either UK or USA design manuals. There are two important concerns in using or developing highway design standards mainly based on those in use in USA or UK. The traffic mix for which these standards have been developed is very different from the traffic existing in LMICs. Second concern is whether the design standards are based on traffic safety science even in the HICs (Ezra Hauer, 1988).

In the next section we show how the traffic and crash patterns are substantially different in LMICs. Therefore, highway design standards applicable to HICs highways may not have the same level of effectiveness in ensuring safe movement of traffic in LMICs.

2 HIGHWAY TRAFFIC AND CRASH PATTERNS IN LMICS

A substantial proportion of population in Asian and African LMICs continue to live in rural areas. Sixty nine percent of Indian population lives in rural areas at present and this will change to sixty percent by 2030. Most African countries will also continue to have larger proportion of populations living in rural areas. Expansion of urban areas will continue along the highways in many LMICs as has been experienced in the past few decades in India. Therefore, the number of habitations along the highway will continue to grow. Presence of villages and small towns along the highways has resulted in a mixed traffic patterns on highways in most LMICs posing traffic safety challenges to road designers.

Table 2 shows presence of motorised two-wheelers (MTW), bicycles and other slow moving vehicles on segments of national highways in India (Dey, Chandra, & Gangopadhaya, 2006). Similar patterns were reported in an earlier study (Tiwari, Fazio, & Pavitravas, 2000) covering different types of highways in India.

These highways experience high speed variations also as shown in Table 3 (Dey et al., 2006; Tiwari et al., 2000). A large portion of highways pass through habited areas in North India (Table 4) (MoRTH, 2010; NHAI, 2007, 2011, 2015, 2016; NHIDCL Sikkim, 2016). Similar trends are observed in Bangladesh, Myanmar and Cambodia (Table 5) (ADB, 2008, 2009; Ministry of

Table 2. Traffic mix in selected segments of rural highways in India (Source: Dey, Chandra, & Gangopadhaya, 2006)

Highway No.	Traffic Vol.	Composition (%)							Ratio of fast and slow moving vehicles	Sample Size
		Fast Moving Vehicles				Slow Moving Vehicles				
		Car/ jeep	Truck/ bus	MTW	3-Whee-ler	Bi-cycle	Tractor	Others		
NH-58	244	31.9	40.2	9.00	-	6.90	8.7	3.3	81.1: 18.9	405
NH-73	408	34.3	5.90	29.7	6.1	16.5	5.0	2.5	76:24	756
NH-31	412	22.3	26.9	23.8	4.9	17.7	2.9	1.5	77.9:22.1	780
NH-31	250	26.4	36.8	11.2	-	15.2	6.8	3.6	74.4:25.6	459
NH-73	412	16.5	28.2	22.8	1.7	19.7	4.8	6.3	69.2:30.8	752
SH-67	839	21.5	5.60	41.1	1.3	25.3	0.5	4.7	69.5:30.5	1,407
NH-74	1,032	21.4	6.30	40.4	1.0	25.3	0.8	4.8	69.1:30.9	1,672
NH-30	480	16.7	21.2	11.7	11	27.3	6.3	5.8	60.6:39.4	877
NH-58	580	27.0	32.4	12.6	1.6	18.6	4.5	3.3	73.6:26.4	1,031
NH-7	1,211	36.5	19.0	16.5	6.8	9.50	10	1.7	78.8:21.2	1889
SH-5	228	42.1	17.1	24.6	2.2	6.10	6.6	1.3	86:14	393
SH-6	428	29.2	9.40	32.9	6.8	14.7	4.9	2.1	78.3:21.7	756
SH-14	623	21.5	7.50	41.6	1.8	17.2	9.0	1.4	72.4:27.6	1,073
SH-59	600	22.5	13.0	35.0	-	20.0	8.0	1.5	70.5:29.5	1,107
SH-47	425	17.0	26.6	31.5	3.3	8.90	10.1	2.6	78.4:21.6	735
SH-47	578	23.9	16.1	38.1	2.4	7.10	11.9	0.5	80.5:19.5	993
NH-73	293	16.0	27.7	30.4	3.4	15.0	6.1	1.4	77.5:22.5	547

There are two important concerns in using or developing highway design standards mainly based on those in use in USA or UK. The traffic mix for which these standards have been developed is very different from the traffic existing in LMICs. Second concern is whether the design standards are based on traffic safety science even in the HICs.

Traffic and crash patterns are substantially different in LMICs. Therefore, highway design standards applicable to HICs highways may not have the same level of effectiveness in ensuring safe movement of traffic in LMICs.

Table 3. Speed variation observed on selected highway segments in India (Source: Dey et al., 2006).

Highway Number	Traffic Volume	V_{85}	V_{50}	V_{15}	$(V_{85}-V_{50})/(V_{50}-V_{15})$
NH-58	244	51.6	37.8	17.8	0.69
NH-73	408	63.6	48.6	15.4	0.452
NH-31	412	39.8	27.2	15.6	1.086
NH-31	250	48.0	35.6	13.4	0.559
NH-73	412	45.6	33.2	11.8	0.579
SH-67	839	37.4	27.6	10.6	0.576
NH-74	1032	43.2	31.0	11.4	0.622
NH-30	480	28.6	20.6	11.6	0.889
NH-58	580	45.0	35.4	20.2	0.632
NH-7	1211	54.8	44.8	18.2	0.376
SH-5	228	55.8	45.4	18.2	0.382
SH-6	428	49.2	35.2	24.8	1.346
SH-14	623	45.0	34.6	15.0	0.531
SH-59	600	45.0	34.8	17.4	0.586
SH-47	425	60.4	35.2	17.4	1.416
SH-47	578	59.0	34.8	20.8	1.729
NH-73	293	59.2	34.6	21.6	1.892

External Affairs (India), 2013). Density of small towns and villages along the highway and presence of tractors, MTW and three-wheelers on the highway along with cars, buses, trucks and truck trailers presents a very different traffic mix as compared to North America and Western Europe where most of the highway standards have been developed.

Figure 1 shows traffic movement on a typical 2 lane undivided highway in India. Paved shoulders are used by bicyclists while fast moving heavy trucks pass on the adjacent lane. Figure 2 shows four lane divided highway. Most of the National highways have this configuration in India. Left lane and shoulders are used by three-wheelers, two-wheelers and bicyclists (India observes left-hand traffic rules). All these vehicles are exposed to high speed motorised traffic moving on the right lane.

Table 4. Villages settlement along selected rural highways in India per 100 km (Source: MoRTH, 2010; NHAI, 2007, 2011, 2015, 2016; NHIDCL Sikkim, 2016).

NH No.	State	Total length (km)	Section (From-To)	Percentage passing through developed area (%)	Number of villages	Frequency of settlements (km/village, km/town)
NH 510	Sikkim	33	Singtam to Rabangal	79	18	1.8
NH 34	West Bengal	84	Barasat to Krishnagar	68	66	1.3
NH 33	Jharkhand	56	Mahulia to Baharogora	NA	75	0.75
NH 6	Jharkhand	16	Baharagora to Chichra	NA	28	0.55
NH 74	Uttarakhand	99	Nagina to Kashipur	NA	48	2.9
NH 8E	Gujarat	210	Gadu to Dwarka	NA	29	7.2
NH 59	Madhya Pradesh	155	Indore to Jhabuwa	NA	80	1.93

Table 5. Villages in the influence zone of highways in LMICs.

Country	Project Name	Total Length (km)	Section	Number of Villages	Frequency of Settlement (km/village, km/town)
Myanmar*	Preparation of Detailed Engineering Project Report for Two Lane Road from Paletwa to Zorinpui (India Myanmar Border) in Chin State of Myanmar, 2013	109.20	Paletwa to Zorinpui (Indo-Myanmar Border)	24 (Along the project road)	1.8
Bangladesh#	Road Network Improvement and Maintenance Project – II, 2008	241.47	6 road segments	9154 (In zone of influence)	0.02
Cambodia$	Primary Roads Restoration Project, 2009	577	3 major Roads (NR 5, NR6, NR7)	132 (Beneficiaries)	

* ADB, 2008 # Ministry of External Affairs (India), 2013 $ ADB, 2009

Figure 1. Mixed traffic on a two-lane undivided highway in India

Figure 2. Mixed traffic on a four-lane undivided highway in India

Figure 3. Mixed traffic on a four-lane divided highway in India.

Figure 4. Highway passing through habitation: mixing of long-distance traffic and local traffic

Figure 3 shows traffic moving on a four-lane divided highway in India. A tractor and other slow-moving vehicles are on the left lane, heavy vehicles use the right most lane. Other motorised traffic overtakes from the left lane (passenger side), because heavy traffic is on the right lane. Heavy vehicles find it difficult to use the left lane due to presence of parked vehicles, tractors, bicyclists and motorcyclists. Figure 4 shows a four-lane highway passing through a small habitation. Traffic mix is very similar to what is often observed in an urban area. These highway segments have presence of long distance traffic as well as local traffic.

Pedestrian and motorcyclist involvement in fatal crashes on rural highways is greater than that of other road users. These highway crash patterns are similar to those observed in urban areas.

Traffic crash patterns in LMICs are also substantially different as compared to North America and Western Europe. Table 7 shows crash patterns observed in highways in India (Mohan, Tiwari, & Bhalla, 2017). Pedestrian and motorcyclist involvement in fatal crashes on rural highways is greater than that of other road users. These highway crash patterns are similar to those observed in urban areas.

Road standards that have evolved to make access controlled highways safe for motorised vehicles may not ensure safety to other road users present on LMICs highways.

In North America, 10% of the fatal crashes on highways involve pedestrians. Presence of motorcycles is negligible and long stretches of roads pass through wilderness. A large proportion of the highways are access controlled and designed for four-wheeled motorised traffic. Therefore, the road standards that have evolved to make an access controlled highways safe for motorised vehicles may not ensure safety to other road users present on LMICs highways. However, in India standards similar to those in HICs have been adopted (IRC, 2007; MoRTH, 2010). In the past two decades, major investments have gone into expanding the national highway system in India. Yet the number of fatalities have continued to grow. Density of highways in a state and number of fatalities seem to have a strong correlation. There is a strong reason to question the safety aspects of current standards in use.

Table 7. Crash patterns observed on selected highway segments in India (Source: Mohan, Tiwari, & Bhalla, 2017).

	Location	Fatalities by type of road users, percent						
		Pedestrians	Bicycle	Motorised two-wheeler	Car	Bus	Truck	Unknown & Others
Urban	Mumbai (2008-2012)	58	2	29	4	0	0	7
	Delhi (2013)	47	10	26	3	4	3	7
Rural Highways	Highways (1998)	32	11	24	15	3	14	1
	2-lane NH 8 (2010-2014)	20	2	42	14	9	13	1
	4-lane NH24 (2010-2014)	27	5	44	8	7	4	4
	6-lane NH1 (2010-2014)	34	3	10	6	5	41	1

3 ROAD STANDARDS AND SAFE ROADS

Ezra Hauer (1988) has discussed extensively the role road standards can play in ensuring safety. Giving numerous examples from AASHTO and MUTCD, Hauer states that "What civil engineers do has a major effect on road safety. However, contrary to appearances, the level of safety built into roads is largely unpremeditated. Standards and practices have evolved without a foundation knowledge. At times the safety consequences of engineering decisions are not known, at others some knowledge exists but is not used". Hauer explains how "There are no safe highways …. However, it is correct to say that *highways can be built to be safer or less safe*. Road safety is a matter of degree." Perhaps this statement is applicable to all highways regardless of region and geographical location. In LMICs we have to investigate the safety of a road measured by the frequency and severity of crashes occurring on it.

Hauer further explains "Not all is known about the relationship between road design and safety. However, from research and experience, mostly from HICs, we have learned that building a wider median, placing obstacles further from the travelled lanes, providing more pavement friction, consistently designing curves with larger radii, providing full illumination, etc., all make for safer highways". However, the impact of these measures when the highway traffic consists of motorised two-wheelers and non-motorised vehicles (NMV) is not known. Impact of wide shoulders, paved shoulders etc. are also unknown in case of mixed traffic on highways.

Highways in LMICs do not appear to have become safer. In India, up-gradation of undivided highways into divided highways from 2 lanes to 4 lanes have increased rate of traffic fatalities (Naqvi & Tiwari, 2015). Pedestrian fatalities form a very small proportion of fatalities in HIC highways, whereas many LMICs continue to have 20-40% pedestrian fatalities on highways (Mohan et al., 2017).

The law of diminishing marginal returns to safety improvement measures is discussed by Hauer:

> "Many highway design decisions are about dimensions for which there is no sharp border between safe and unsafe, only a gradual change diminishing in magnitude. Thus, e.g., increasing the width of the median from 50m to 60m will save fewer crashes than an increase of the median width from 5m to 15m. Eventually there is a width at which one says: "widening the median further cannot be justified because the improvement in safety is too small."

This kind of detailed information is not available for LMICs highways. Detailed studies have not been carried out in Africa or Asia where major expansion in highway network is expected in the coming decades. Wide medians and wide shoulders require more land acquisition resulting in higher costs or constrained by non-availability of land. In India, most highways pass through villages and towns with heavy density of pedestrians and bicycles and other NMVs. Wider medians and wider shoulders may be used by these vehicles and the adjacent traffic lanes carry motorised vehicles moving at 80-100 km/h. The impact on traffic safety because of the presence of NMVs on wide shoulders and median is unknown. The relationship between highway features like lane width, shoulder width, median design and safety is not known with the kind of precision that is possible in other engineering disciplines that allow experimentation.

The relationship between highway features like lane width, shoulder width, median design and safety is not known with the kind of precision that is possible in other engineering disciplines that allow experimentation.

Ezra Hauer (1988) also questions the current practice of conducting safety audits where the focus is on mere compliance with the current standards. Hauer (1988) states:

"No road in use is entirely crash-free, and therefore, in the interest of honest human communication no road can be called safe. The safety of a highway does not change abruptly when some highway dimension changes slightly. It follows that meeting or not meeting a dimension standard does not correspond to a road being 'safe' or 'unsafe'. Also, highway design standards evolve with time. We used to build lanes 3.6m (12 feet) wide, now the standard calls for 3.75m wide lanes. This does not mean that the entire stock of old highways with 3.6m lanes is unsafe. It means only that the information, the judgements, and the economic considerations that go into the formulation of design standards change in time. In short, highway design standards are not the demarcation line between what is safe and unsafe. They are a reflection of what a committee of professionals of that time considers to be overall good practice."

No road in use is entirely crash-free, and therefore, in the interest of honest human communication no road can be called safe.

Hauer (1988) has provided useful insights into the relationship between safety and highway standards, however it is true that a large number of road safety measures have been found to be effective in HICs and major improvement in road safety has been observed in many countries since 1970s.

Speed is an important factor affecting road accidents both in terms of accident occurrence and severity.

4 AN OVERVIEW OF FACTORS AFFECTING ROAD TRAFFIC CRASHES

There is a broad range of factors affecting road traffic crashes. These factors are usually related to traffic and road characteristics, drivers and other road users, vehicles, and environment. Traffic characteristics (such as traffic flow and speed) and road characteristics (such as road geometry and the quality of infrastructure) might affect road accidents. Factors which seem to have a strong correlation with traffic crashes are discussed in the following section. These have been discussed in an exhaustive review by Wang, Quddus, and Ison (2013).

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

4.1 Speed

Speed is an important factor affecting road accidents both in terms of accident occurrence and severity (R. Elvik, Peter Christensen, & Astrid Amundsen, 2004). It seems reasonably safe to assume that increased speed would mean that the accidents that have occurred would be more severe, if other factors (e.g., environment and vehicle design) remain the same.

Large number of studies have shown this by both Newtonian physics and empirical data (Ezra Hauer, 2009; Kockelman & Kweon, 2002; O'donnell & Connor, 1996; Shankar, Mannering, & Barfield, 1996). Between speed and number of accidents, most of the studies suggest that increased speed is associated with more accidents or higher accident rates (Aarts & van Schagen, 2006; Rune Elvik, Peter Christensen, & Astrid Amundsen, 2004; Nilsson, 2004; Taylor, Baruya, & Kennedy, 2002). The effect of change in speed on road safety has been extensively investigated by Nilsson (2004) who employed before-after studies in Sweden using the Power Model. It was found that changes in the number of accidents (or accident rate) can be associated with the changes in speed according to a power function. Positive associations between changes in speed and accidents were found, though the magnitude depends on types of accidents (e.g. fatal and injury). Similarly, Rune Elvik et al. (2004) undertook an extensive evaluation on the effect of speed on accidents again using the Power Model. They concluded that there is a causal relationship between changes in speed and changes in road accidents. In addition, it has been speculated that it is the dispersion of vehicle speeds (i.e. speed variance rather than speed itself) that affects the accident frequency (Lave, 1985). Lave (1985) found that the fatality rate was strongly associated with speed variance rather than average speed, thus it was argued that speed variance caused safety problems instead of speed itself. A later study (Davis, 2002) however argued that such a claim of ‘‘variance kills’’ may be subject to ecological fallacy. Therefore there remains the question of the role of speed variance in road safety.

4.2 Traffic density

The relationship between traffic density and accidents has been investigated in a few studies, often using other variables to represent density, for example Volume by Capacity ratio (V/C) (Ivan, Wang, & Bernardo, 2000; Shefer, 1994). Examination of the hourly accident rates (per million vehicle kilometres) and the V/C ratio on a US interstate highway showed that the relationship follows a U-shaped pattern and accidents involving injury and fatalities tended to decrease while the V/C ratio increases (Zhou & Sisiopiku, 1997). Results of investigation of single and multi-vehicle highway accident rates and their relationship with traffic density (Ivan et al., 2000) while controlling for land use, time of day and lighting conditions on two lane highways found a negative exponential relationship with density (volume/capacity ratio), meaning that the accident rate is the highest at low V/C ratio.

A freeway segment study (Lord, Washington, & Ivan, 2005) based analysis on the relationship between accident, density and the V/C ratio found that both density and V/C ratio have an overall inverse relationship with the number of accidents (per year per km). Accident-density and accident-V/C relationships were also examined according to different accident categories such as total, single-vehicle, and multi-vehicle accidents. It is found that there is a U-shaped relationship for total and single-vehicle accidents but a positive relationship for multi-vehicle accidents.

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

4.3 Traffic flow

Many researchers have examined the relationship between traffic flow and accidents (Belmont & Forbes, 1953; Ceder, 1982; Ceder & Livneh, 1982; Gwynn, 1967; Turner & Thomas, 1986). Earlier studies found that the accident rate increases linearly with the hourly traffic flow for two-lane road (Belmont & Forbes, 1953). Later Ceder and Livneh (1982) focused on single and multi-vehicle accident rates and their associations with the hourly traffic flow by using power functions. They found that for different types of accidents, the relationships between accident rates and hourly traffic flow are different. For example, hourly traffic flow was found to be inversely related with accident rates for single-vehicle accidents in all cases; while in some cases hourly traffic flow was found to be positively related with accident rates for multi-vehicle accidents. Ceder

(1982) further analysed the relationship between the accident rate and hourly flow under different flow conditions and found that the relationship between the total accident rate and hourly flow follows a U-shaped curve under free flow conditions while for the case of ‘‘congested’’ flow data the accident rate increases more sharply. This study implies the importance of investigating the impact of traffic flow on accident rates under different traffic flow conditions. Martin (2002) investigated the relationship between accidents and traffic flow on French motorways, and found that accident rates are highest in light traffic compared to heavy traffic, especially on three-lane motorways. There is no significant difference between daytime and night-time accidents. However, if accident severity was considered, hourly accidents were much worse in a night-time and light-traffic situation. Therefore, the author concluded that light traffic (low traffic flow) is a safety problem both in terms of accident rate and severity. As many things could affect road safety during night time however such as lighting, this is an area requiring further study.

Overall, research studies suggest that the total number of accidents increases as traffic flow increases. In terms of accident rates, it seems to have a U-shaped relationship with hourly traffic flow.

Similar work by Golob and Recker (2003) demonstrated how accidents are related to traffic flow conditions just prior to the occurrence of each accident. It was shown that accident severity generally tracks the inverse of traffic volume. Overall, research studies suggest that the total number of accidents increases as traffic flow increases. In terms of accident rates, it seems to have a U-shaped relationship with hourly traffic flow.

An increase in the number of lanes and lane widths was associated with increased fatalities; and an increase in the outside shoulder width was found to be associated with reduced accidents.

4.4 Road characteristics

Engineering theory suggests that road designs - lane width, shoulder presence, number of lanes, median design - influence driving behaviour (operating speeds, lane changes etc.), therefore, one could expect that roads themselves play an important role in road safety, and improved geometry design and infrastructure could in turn help to improve road safety. Choice of different operating speeds depending on the context shows that safety is an important goal in highway design (Lamm, Psarianos, & Mailaender, 1999). Findings from several researchers support this hypothesis. Shankar, Mannering, and Barfield (1995) explored the effects of various roadway geometrics (e.g. horizontal and vertical alignments) on road accident frequency and found that the increased number of horizontal curves per kilometre on rural freeways increase the possibility of an accident resulting in ‘possible injury’ relative to ‘property damage only’. Another study (Milton & Mannering, 1998) observed the annual accident frequency on sections of principal arterials in Washington State. By using a negative binomial model, it was found that short sections are less likely to experience accidents than longer sections; narrow lanes (less than 3.5 m) and sharp horizontal curves tend to decrease accident frequency in Eastern Washington. They also found a positive relationship between accident frequency and the tangent length before a horizontal curve. These findings confirmed that road infrastructure designs do affect road safety. However, the authors did not consider spatial correlation – i.e. an accident on one road segment may be correlated to the one on the adjacent segment as they are sharing

Four studies found that road curvature is a protective factor meaning that more curved roads in an area result in less road accidents. This is counter-intuitive and also contradicts some of the existing studies.

From the behavioural aspect, drivers may drive more slowly and cautiously on curved roads. On the other hand, on straight roads as mentioned above, drivers are more likely to fall asleep or feel bored similar traffic, infrastructure or environment conditions. Noland and Oh (2004) analysed the county-level highway data from the State of Illinois in the US. Their results revealed that an increase in the number of lanes and lane widths was associated with increased fatalities; and an increase in the outside shoulder width was found to be associated with reduced accidents. Positive relationship between increased number of lanes and accident numbers was reported by Kononov, Bailey, and Allery (2008) also.

Four important studies have reported relationship between road curvature and its association with traffic accidents (Haynes, Jones, Kennedy, Harvey, & Jewell, 2007; Haynes et al., 2008; Milton & Mannering, 1998; Wang, Quddus, & Ison, 2009). All four studies found that road curvature is a protective factor meaning that more curved roads in an area result in less road accidents.

This is counter-intuitive and also contradicts some of the existing studies. For example Abdel-Aty and Radwan (2000) found that the degree of curve increases the number of accidents on a road segment. Wang et al. (2009) have given an explanation for this:

> "This may be because different curvature measurements were used, such as minimum radius, number of horizontal curves per mile, mean horizontal deflection angle, degree of horizontal curve per 100 m arc, bend density (Abdel-Aty & Radwan, 2000; Haynes et al., 2007; Noland & Oh, 2004; Shankar et al., 1995). In addition, these studies were conducted at different scales, which may also be subject to the modifiable areal unit problem (MAUP) (Openshaw, 1984). Curvature may be risky considering its engineering effect; however, from the behavioural aspect, drivers may drive more slowly and cautiously on curved roads. On the other hand, on straight roads as mentioned above, drivers are more likely to fall asleep or feel bored (physiological theory). Therefore the overall safety effect of road curvature (compared to straight roads) is likely to be mixed".

In the context of LMICs, if presence of curvature on the road reduces speed, number of crashes are likely to reduce. However, this has to be established with data from LMICs.

Road infrastructure improvements (e.g., road upgrading and pavement) and roundabout design are also found to be beneficial for safety. In the case of HICs, not only does better vehicle design, but also improvements in road safety engineering reduce the severity of whiplash injuries when accidents occur, and this could be done by enhanced signal visibility or through complex intersection geometric upgrades (Navin, Zein, & Felipe, 2000; Perez, 2006).

In the case of LMICs, the safety benefit of roundabouts is clear, however, up gradation involving improved pavement surface, wider lanes, wider shoulders may lead to higher speeds and increase opportunities for lane changing and conflicts. Pedestrians and slow vehicles on the curb side lane or shoulders will be exposed to motorised vehicles moving at much higher speeds. Safety benefit of road up gradation using present standards is unclear for LMICs.

The *Handbook of Road Safety Measures* gives a comprehensive overview and illustration of how various interventions impact road safety (Elvik, Vaa, Hoye, & Sorensen, 2009). Almost all the research in the Handbook comes from studies done in HICs and very little for LMICs. Can this knowledge be simply transferred to LMICs?

5 SAFETY SCIENCE AND SAFETY VISION

Study of international literature of how countries have improved their safety performance over the years, shows a multitude of potential explanations. Researchers have developed benchmarking methodologies to learn from international comparisons (Koornstra et al., 2002; Fred Wegman & Hagenzieker, 2010). This is a difficult task due to presence of confounding factors. Fred Wegman (2017) states "It is, to the best of our knowledge, fair to say that no country has a full explanation of the progress made. However, it is also fair to say that our knowledge and understanding of why countries made progress has increased significantly over the last few decades".

In the last few decades traffic safety measures have been focussed on the following:

- Improving human behaviour (speed, alcohol, seat belts, and helmets) through legislation, enforcement, and campaigns.
- Safer infrastructure through planning and design.
- Safer vehicles through better crashworthiness, active vehicle safety, and vehicle inspections.

There has to be a fundamental vision or theory which drives what data should be collected and what should be evaluated. For example, if the theoretical understanding is that driver error causes traffic crashes and driver training can reduce traffic crashes the data collection process focusses on collecting driver related data and modelling impact of driver characteristics and knowledge about driving rules.

We examine these interventions in the context of theories of safety science to understand what role different interventions may have on safety consequences.

It has been a tradition in road safety to analyse road safety data for understanding why crashes occur, which factors influence risks, and what determines crash severity, and based on this understanding, to arrive at reliable conclusions on how to prevent them most effectively and efficiently. We call this a data-driven approach. In this approach, we derive priorities by using crash data, background data, exposure data, and data of safety performance indicators. This is what the researchers call a scientific method and evidence based interventions. However, there has to be a fundamental vision or theory which drives what data should be collected and what should be evaluated. For example, if the theoretical understanding is that driver error causes traffic crashes and driver training can reduce traffic crashes the data collection process focusses on collecting driver related data and modelling impact of driver characteristics and knowledge about driving rules. If the theoretical understanding is that driving behaviour is influenced by the road and traffic characteristics, then road geometry and traffic characteristics (operating speeds, traffic volume, type of vehicles) are modelled for controlling traffic crashes.

Traffic crashes present an excellent example of complex systems, uncertainties and nonlinear interactions between human beings, vehicles and the road environment. This makes a strong case for moving away from focusing on the errors that road users make to concentrating on road and vehicle designs that can reduce the propensity and severity of crashes.

J. Stoop, de Kroes, and Hale (2017) provide a detailed discourse on safety science in general and its application to transportation safety. They highlight the development of three basic notions as the cornerstones for safety science as a scientific discipline, no matter what domain it is related to: interdisciplinarity, problem-solving orientation and systems approach.

Interdisciplinarity is a first necessary condition to deal with complex phenomena that exist in reality: such phenomena cannot be reduced to paradigmatic notions within one scientific domain. However, a decomposition of their complexity is a prerequisite for unravelling their control laws, properties, relations, variables and performance indicators.

Problem orientation: Achieving consensus on a common problem definition is considered a second prerequisite for a scientific approach of safety. Interdisciplinary discourses may result in controversies and rivalries, up to the level of schools of thinking. It also may lead to individual antagonism, defining minorities as dissenting voices in a homogeneous scientific community.

Systems approach: While an interdisciplinary approach may provide coverage of broad issues on which a variety of actors, disciplines and stakeholders may have achieved consensus, resolution of the problem and enhancement of the actual safety level of performance to the required level requires a third necessary condition: the application of a systems theory. Systems theory facilitates in structuring a complex reality. A decomposition in elements, components, aspects and relations provides oversight and coherence across levels and entities that interact with each other. Putting events in the context of systems in which they operate, requires a distinction between event and system, similar to a patient and the health system or a convict and the judicial system. While accidents should be prevented for the sake of their unacceptable consequences, the object of research for safety interventions is at the systems level (ESReDA, 2009; J. A. Stoop, 2015).

Perrow (1984) has discussed some fundamental properties of complex systems in terms of tight and loose coupling between different elements and non-linear interactions between elements, and therefore, the need for building systems which do not depend on user or operator alone to ensure safety. Traffic crashes present an excellent example of complex systems, uncertainties and nonlinear interactions between human beings, vehicles and the road environment. This makes a strong case for moving away from focusing on the errors that road users make to concentrating on road and vehicle designs that can reduce the propensity and severity of crashes. Safety science has had a major influence on the traffic safety theories in the last fifty years.

5.1 Traffic safety theories

R. Elvik et al. (2004) have discussed two important road safety theories that are related to engineering and human behavioural effects. Road safety measures could affect road safety by influencing relevant factors through engineering effect and behavioural adaptation. This suggests that engineering and human behaviour related factors are two important sources of risks. For example, road lighting improves visibility (engineering effect) but road users tend to be less alert (behavioural adaptation). Most factors can be related to either engineering or human behavioural effects. Vehicle related factors can also be explained through engineering effects. For instance compared to cars large trucks have unique characteristics, most notably high gross weight, long vehicle length, and poor stopping distance, which can be associated with different levels of risk (Chang & Mannering, 1999).

Many other safety theories can be explained based on the engineering and behavioural theories. For instance, drivers can modify their behaviour based on what they see on the road ahead of them (e.g. increasing speed or reducing attention), especially when the lower risk is brought about by a road design countermeasure (Assum, Bjørnskau, Fosser, & Sagberg, 1999; E. Hauer, 2017). Physiological theory may be related to both engineering and behavioural theory to some extent. For instance it was suggested that drivers are more likely to fall asleep or feel bored on straight, monotonous, dual carriageway roads with little traffic (Sagberg, 1999). In this case, drivers changed their behaviour on certain types of road (e.g. straight and monotonous roads); and on the other hand, road engineers could alter the road environment in order to reduce driver boredom. However, in some cases fatigue or boredom are linked more to the characteristics of the person themselves rather than engineering or behavioural adaption. For instance, it was found that individuals with a higher level of anxiety may be more likely to feel fatigue (Jiang et al., 2003). In addition, some groups of people (e.g. older people) are inherently more vulnerable than others, thus more likely to be involved in an accident or to be more seriously injured if an accident occurred (Bedard, Guyatt, Stones, & Hirdes, 2002).

Safety science has influenced the traffic safety interventions in HICs, primarily leading to the emergence of safe systems approach in The Netherlands and Vision Zero in Sweden.

Vision Zero accepts, as a basic starting point, that human beings make conscious and subconscious mistakes. That is why accidents occur, and the safety work must in the first instance be directed at those factors which can prevent accidents leading to death and serious injury. Accidents in themselves can be accepted, but not their serious consequences.

According to Vision Zero, the principal cause as to why people die and are seriously injured is that the energy to which people are exposed in a traffic accident is excessive in relation to the energy that the human frame can withstand. Vision Zero is, among other things, based on the research that the famous American road safety expert William Haddon conducted in the 1960s (Haddon Jr, 1968, 1970, 1973, 1980). Knowledge of energy and tolerance has to a great extent served as a basis for the development we have seen of the passive safety characteristics of vehicles and for the development of different protection systems such as child safety seats, helmets, seat belts, etc. One important consequence of Vision Zero as a general policy for safety work is that the view of knowledge which has served as a basis for the development of a sub-component in the road transport system, namely the vehicle, also has become a general principle for the entire road transport system (Belin, 2016).

Vision Zero accepts, as a basic starting point, that human beings make conscious and subconscious mistakes. That is why accidents occur, and the safety work must in the first instance be directed at those factors which can prevent accidents leading to death and serious injury. Accidents in themselves can be accepted, but not their serious consequences.

According to Vision Zero, it is not the individual road-user who has the ultimate responsibility but rather the so-called system designers. The responsibility for safety is thus split between the motorists and the system designers (i.e. infrastructure builders and administrators, the vehicle industry, the haulage sector, taxi companies and all the organizations that use the road transport system professionally), on the basis of the principles that:

- The system designers have ultimate responsibility for the design, upkeep and use of the road transport system, and are thus responsible for the safety level of the entire system.
- As before, the road-users are still responsible for showing consideration, judgment and responsibility in traffic and for following the traffic regulations.
- If the road users do not take their share of the responsibility, for example due to a lack of knowledge or competence, or if personal injuries occur or for other reasons that lead to risk, the system designers must take further measures to prevent people from being killed or seriously injured.

Most effective measure for speed compliance in LMICs will be by design: active speed control measures.

In Vision Zero, the responsibility for safety is a chain of responsibility that both begins and ends with the system designers (Belin, 2016).

Given the complexity of traffic safety science and its implementation in field, continuous experimentation is required in LMICs to develop safe highways based on the principles of safe systems approach.

Sustainable safety approach of The Netherlands is based on similar principles. (Fred Wegman, 2017) has noted that:

"There are two good reasons why the traditional approach (working on reducing "spikes in distributions") will become less effective and efficient in countries with mature road safety policies. The first reason lies in the fact that serious road crashes will occur as long as we leave the inherent unsafe conditions in road traffic untouched: the inherent risks come from a combination of the physical vulnerability of the human body and the levels of kinetic energy in crashes (a combination of speed and mass). These inherent risks also stem from the fact that the road transport system cannot be designed from the perspective of the human being as long as it fails to defend against human errors and offenses that can result in crashes. Because of this, we are almost fully dependent on how well drivers, riders, and pedestrians perform their tasks. It is remarkable that, while the road transport system puts its faith in individual driving skills, the rail system and the aviation system are designed from a safety perspective—and even well-trained professionals like train drivers and airplane pilots are only allowed to operate under rather strict conditions. A second good reason lies in the fact that our traditional policies have become less effective and efficient. Traditional interventions dealing with reducing relatively high risks are in the process of coming to the ends of their life cycle, suggesting that they may be subject to the law of diminishing returns. In the Netherlands, these two underlying reasons have triggered a paradigm shift and resulted in the development of Sustainable Safety, the Dutch version of the Safe System approach."

6 PRINCIPLES FOR SAFE HIGHWAYS IN LMICS

Given the understanding from traffic safety theories of the last fifty years, the systems approach and Vision Zero, we can propose some basic principles which can form the corner stones for developing safe highways in LMICs.

Safe systems approach has three key principles (H. Y. Chen & L. Meuleners, 2011; Transport Research Centre, 2008):

- Principle 1 Recognition of human frailty
- Principle 2 Acceptance of human error
- Principle 3 Creation of a forgiving environment and appropriate crash energy management.

Current highway standards for geometric design of highways can be reviewed in the context of these three basic principles. Principle 1 and 2 must recognize that highways in LMICs will have presence of NMVs and pedestrians along with motorized traffic. Principle 3 becomes the operational principle for setting appropriate speed limits for ensuring a forgiving environment for all road users. Pedestrians will make mistakes in judging the possible risk in the system whereas, drivers can make mistakes in adopting an appropriate speed.

Design speed and design vehicle are the two most important elements which have been used to set highway standards in the past. Stopping distance of a modern car is very different from a tempo (three-wheeler) or 2-axle trucks present on LMICs highways. Therefore, selection of a design vehicle itself becomes important for setting the minimal standards for stopping distance, sight distance and overtaking distances.

Design Speed governs the design of horizontal curve, vertical curve and the safe stopping distance. Conventional practice of keeping design speed higher than operational speed has been questioned by several researchers. Therefore, the design speed must be in line with the requirement of principle 3 "Creation of a forgiving environment and appropriate crash energy management". This implies that for setting appropriate design speed, presence of NMVs, presence of activities along the highway, and density of built up area along the highway, frequency of towns and villages through which the highway passes must be taken into consideration. Design speed may vary from 30 km/h to 90km/h with a road cross-section designed for appropriate crash energy management depending on the surrounding landuse present along the highway.

Speed compliance by design: We started this paper quoting the success of legislation and enforcement, however, taking lessons from number of studies in HICs, most effective measure for speed compliance in LMICs will be by design: active speed control measures. LMICs have weak institutional capacity, weak enforcement of legislation, therefore, speed control by texture change, audible markers, rumble strips, change in geometric standards, median designs, lowering speeds at intersections by introducing roundabouts, raised stop lines and speed humps on minor roads are expected to be more successful in speed compliance by all road users-good drivers, bad drivers, young drivers, knowledgeable drivers, drivers with poor driving education etc., ensuring compliance with the principle 2.

Many of the current standards for highway cross section require revisions (H. Chen & L. Meuleners, 2011; Mohan et al., 2017) to comply with the principle 3. Appropriate design of service roads, width of shoulders, and design of medians, have to be reviewed to ensure safe designs for NMVs and different kinds of vehicles on the road.

Experience from HICs is that standards alone cannot ensure safe roads for all unless the safety performance is evaluated. Vision zero accepts that it is possible to design a transport system that will not have any deaths and serious injuries. Therefore, realization of vision zero also requires generation of new knowledge and establishing a process which enables generation of new knowledge to ensure safe highways in LMICs. Given the complexity of traffic safety science and its implementation in field, continuous experimentation is required in LMICs to develop safe highways based on the principles of safe systems approach.

REFERENCES

Aarts, L., & van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention, 38*(2), 215-224.

Abdel-Aty, M. A., & Radwan, A. E. (2000). Modeling traffic accident occurrence and involvement. *Accident Analysis & Prevention, 32*(5), 633-642.

ADB. (2008). *Road network improvement and maintenance Project II: Final resettlement action plan* (No. 34415-013). Manila: Asian Development Bank.

ADB. (2009). *Project performance evaluation report of the Primary Roads Restoration Project.* Manila: Asian Development Bank.

Ameratunga, S., Hijar, M., & Norton, R. (2006). Road-traffic injuries: confronting disparities to address a global-health problem. *The Lancet, 367*(9521), 1533-1540.

Assum, T., Bjørnskau, T., Fosser, S., & Sagberg, F. (1999). Risk compensation—the case of road lighting. *Accident Analysis & Prevention, 31*(5), 545-553.

Bedard, M., Guyatt, G. H., Stones, M. J., & Hirdes, J. P. (2002). The independent contribution of driver, crash, and vehicle characteristics to driver fatalities. *Accident Analysis & Prevention, 34*(6), 717-727.

Belin, M.-A. (2016). Vision zero as a new way of thinking. *Journal of the Australasian College of Road Safety, 27*(3), 60.

Belmont, D. M., & Forbes, T. W. (1953). Effect of average speed and volume on motor-vehicle accidents on two-lane tangents. *Highway Research Board Proceedings, 32*, 383-395.

Ceder, A. (1982). Relationships between road accidents and hourly traffic flow—II: Probabilistic approach. *Accident Analysis & Prevention, 14*(1), 35-44.

Ceder, A., & Livneh, M. (1982). Relationships between road accidents and hourly traffic flow—I: analyses and interpretation. *Accident Analysis & Prevention, 14*(1), 19-34.

Chang, L.-Y., & Mannering, F. (1999). Analysis of injury severity and vehicle occupancy in truck-and non-truck-involved accidents. *Accident Analysis & Prevention, 31*(5), 579-592.

Chen, H., & Meuleners, L. (2011). A literature review of road safety strategies and the safe system approach.

Chen, H. Y., & Meuleners, L. (2011). *A literature review of road safety strategies and the safe system approach*. Perth: Curtin-Monash Accident Research Centre (C-MARC), Curtin University.

Davis, G. A. (2002). Is the claim that 'variance kills' an ecological fallacy? *Accident Analysis & Prevention, 34*(3), 343-346.

Dey, P. P., Chandra, S., & Gangopadhaya, S. (2006). Speed distribution curves under mixed traffic conditions. *Journal of transportation engineering, 132*(6), 475-481.

Elvik, R., Christensen, P., & Amundsen, A. (2004). Speed and road accidents. *An evaluation of the Power Model. TØI report, 740*, 2004.

Elvik, R., Christensen, P., & Amundsen, A. (2004). *Speed and road accidents: an evaluation of the Power Model* Oslo: Institute of Transport Economics.

Elvik, R., Vaa, T., Hoye, A., & Sorensen, M. (2009). *The handbook of road safety measures: second edition*. Bingley, UK: Emerald Publishing Limited.

ESReDA. (2009). *Guidelines for Safety Investigations of Accidents*. Kaunas, Lithuania: European Safety Reliability and Data Association.

Golob, T. F., & Recker, W. W. (2003). Relationships among urban freeway accidents, traffic flow, weather, and lighting conditions. *Journal of transportation engineering, 129*(4), 342-353.

Gwynn, D. W. (1967). Relationship of accident rates and accident involvements with hourly volumes. *Traffic Quarterly, 21*(3).

Haddon Jr, W. (1968). The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based. *American journal of public health and the Nations health, 58*(8), 1431-1438.

Haddon Jr, W. (1970). On the escape of tigers: an ecologic note. *American Journal of Public Health and the Nations Health, 60*(12), 2229-2234.

Haddon Jr, W. (1973). Energy damage and the ten countermeasure strategies. *Human Factors, 15*(4), 355-366.

Haddon Jr, W. (1980). Advances in the epidemiology of injuries as a basis for public policy. *Public health reports, 95*(5), 411.

Hauer, E. (1988). *A case for science-based road safety design and management.* Paper presented at the Highway safety: at the crossroads: proceedings of a conference.

Hauer, E. (2009). Speed and safety. *Transportation Research Record: Journal of the Transportation Research Board*(2103), 10-17.

Hauer, E. (2017). Road safety research and practice: problems of coexistence. University of Toronto.

Haynes, R., Jones, A., Kennedy, V., Harvey, I., & Jewell, T. (2007). District variations in road curvature in England and Wales and their association with road-traffic crashes. *Environment and Planning A, 39*(5), 1222-1237.

Haynes, R., Lake, I. R., Kingham, S., Sabel, C. E., Pearce, J., & Barnett, R. (2008). The influence of road curvature on fatal crashes in New Zealand. *Accident Analysis & Prevention, 40*(3), 843-850.

IRC. (2007). Manual of specifications & standards. New Delhi: Indian Roads Congress.

Ivan, J. N., Wang, C., & Bernardo, N. R. (2000). Explaining two-lane highway crash rates using land use and hourly exposure. *Accident Analysis & Prevention, 32*(6), 787-795.

Jiang, N., Sato, T., Hara, T., Takedomi, Y., Ozaki, I., & Yamada, S. (2003). Correlations between trait anxiety, personality and fatigue: study based on the Temperament and Character Inventory. *Journal of psychosomatic research, 55*(6), 493-500.

Kockelman, K. M., & Kweon, Y.-J. (2002). Driver injury severity: an application of ordered probit models. *Accident Analysis & Prevention, 34*(3), 313-321.

Kononov, J., Bailey, B., & Allery, B. (2008). Relationships between safety and both congestion and number of lanes on urban freeways. *Transportation Research Record: Journal of the Transportation Research Board*(2083), 26-39.

Koornstra, M., Lynam, D., Nilsson, G., Noordzij, P., Pettersson, H.-E., Wegman, F., et al. (2002). *SUNflower: A comparative study of the development of road safety in Sweden, the United Kingdom, and the Netherlands*. Leidschendam: SWOV.

Lamm, R., Psarianos, B., & Mailaender, T. (1999). *Highway design and traffic safety engineering handbook*. New York: McGraw-Hill.

Lave, C. A. (1985). Speeding, coordination, and the 55 mph limit. *The American Economic Review, 75*(5), 1159-1164.

Lord, D., Washington, S. P., & Ivan, J. N. (2005). Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. *Accident Analysis & Prevention, 37*(1), 35-46.

Martin, J.-L. (2002). Relationship between crash rate and hourly traffic flow on interurban motorways. *Accident Analysis & Prevention, 34*(5), 619-629.

Milton, J., & Mannering, F. (1998). The relationship among highway geometrics, traffic-related elements and motor-vehicle accident frequencies. *Transportation, 25*(4), 395-413.

Ministry of External Affairs (India). (2013). *Preparation of detailed engineering project report for two-lane road from Paletwa to Zorinpui (India Myanmar border) in Chin State of Myanmar, Detailed Project Report, Volume IV: environmental impact assessment report*. New Delhi: Ircon Infrastructure & Services Limited.

Mohan, D., Tiwari, G., & Bhalla, K. (2017). *Road safety in India: Status report 2016*. New Delhi: Transportation Research & Injury Prevention Programme, Indian Institute of Technology Delhi.

MoRTH. (2010). *Manual for specifications and standards for four laning of highways*. New Delhi: Ministry of Road Transport & Highways, Government of India.

Naqvi, H. M., & Tiwari, G. (2015). *Assessing risk factors for pedestrian fatal crashes on National Highways in India.* Paper presented at the EASTS, Cebu, Philippines.

Navin, F., Zein, S., & Felipe, E. (2000). Road safety engineering: an effective tool in the fight against whiplash injuries. *Accident Analysis & Prevention, 32*(2), 271-275.

NHAI. (2007). *Consultancy Services for preparation of Feasibility cum Preliminary Design for 4/6 Laning of Indore to Gujarat/MP border section of NH-59 (NHAI/BOT II/ DPR/04) to be executed as BOT (Toll) project on DBFO Pattern under NHDP Phase III*. New Delhi: Wilbur Smith Associates Pvt. Ltd.

NHAI. (2011). *Feasibility and detailed project report for rehabilitation and upgrading to 4/6 lane divided carriageway of Barasat - Baharampore (km 31 to km 193) section of NH 34 in the state of West Bengal, Package 1*. New Delhi: The Louis Berger Group Inc.

NHAI. (2015). *Final detailed project report Volume I (Main Report) Mahulia-Baharagora-JH/WB border at Chichra (NH-33 &NH-6)*. Gurugram, Haryana: SMEC and Rodic Consultant Pvt Ltd.

NHAI. (2016). *Consultancy services for preparation of feasibility study for 4/2 laning with paved shoulder of Gadu-Dwarka section ofNH-8 from km 263.00 (design chainage km 287.430) to km 473.00 (design chainage km 497.320) in the state of Gujarat through public private partnership (PPP) on design, build finance, operate and transfer (DBFO) toll basis*. Mumbai: STUP Consultants Pvt. Ltd.

NHIDCL Sikkim. (2016). *Detailed project report for widening to 2-Lane of NH 510 (Singtam-Tarku-Rabongla-Legship-Gyalshing) in the state of Sikkim*. Gurugaon, Haryana: CM Engineering & Solution.

Nilsson, G. (2004). Traffic safety dimensions and the power model to describe the effect of speed on safety. *Bulletin-Lunds Tekniska Högskola, Inst för Teknik och Samhälle, Lunds Universitet, 221*.

Noland, R. B., & Oh, L. (2004). The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data. *Accident Analysis & Prevention, 36*(4), 525-532.

O'donnell, C., & Connor, D. (1996). Predicting the severity of motor vehicle accident injuries using models of ordered multiple choice. *Accident Analysis & Prevention, 28*(6), 739-753.

Openshaw, S. (1984). Concepts and techniques in modern geography number 38: the modifiable areal unit problem. *Norwick: Geo Books*.

Peden, M., Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., et al. (2004). *World report on road traffic injury prevention*: World Health Organization Geneva.

Perez, I. (2006). Safety impact of engineering treatments on undivided rural roads. *Accident Analysis & Prevention, 38*(1), 192-200.

Perrow, C. (1984). Normal accidents: Living with high risk systems: New York: Basic Books.

Sagberg, F. (1999). Road accidents caused by drivers falling asleep. *Accident Analysis & Prevention, 31*(6), 639-649.

Shankar, V., Mannering, F., & Barfield, W. (1995). Effect of roadway geometrics and environmental factors on rural freeway accident frequencies. *Accident Analysis & Prevention, 27*(3), 371-389.

Shankar, V., Mannering, F., & Barfield, W. (1996). Statistical analysis of accident severity on rural freeways. *Accident Analysis & Prevention, 28*(3), 391-401.

Shefer, D. (1994). Congestion, air pollution, and road fatalities in urban areas. *Accident Analysis & Prevention, 26*(4), 501-509.

Staton, C., Vissoci, J., Gong, E., Toomey, N., Wafula, R., Abdelgadir, J., et al. (2016). Road traffic injury prevention initiatives: a systematic review and metasummary of effectiveness in low and middle income countries. *PLoS One, 11*(1), e0144971.

Stoop, J., de Kroes, J., & Hale, A. (2017). Safety science, a founding fathers' retrospection. *Safety science, 94*, 103-115.

Stoop, J. A. (2015). *Challenges to the investigations of occurrences: concepts and confusion, metaphors, models and methods*. Baden: The European Safety, Reliability and Data Association.

Taylor, M. C., Baruya, A., & Kennedy, J. V. (2002). *The relationship between speed and accidents on rural single-carriageway roads*: TRL.

Tiwari, G., Fazio, J., & Pavitravas, S. (2000). *Passenger car units for heterogeneous traffic using a modified density method.* Paper presented at the Proceedings of fourth international symposium on highway capacity.

Transport Research Centre. (2008). *Towards zero: Ambitious road safety targets and the safe system approach*. Paris: International Transport Forum, OECD.

Turner, D., & Thomas, R. (1986). Motorway accidents: an examination of accident totals, rates and severity and their relationship with traffic flow. *Traffic Engineering and Control, 27*(7-8), 377-383.

Wang, C., Quddus, M., & Ison, S. (2009). The effects of area-wide road speed and curvature on traffic casualties in England. *Journal of Transport Geography, 17*(5), 385-395.

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

Wegman, F. (2017). The future of road safety: a worldwide perspective. *IATSS research, 40*(2), 66-71.

Wegman, F., & Hagenzieker, M. (2010). Editorial safety science special issue road safety management. *Safety Science, 48*, 1081-1084.

WHO. (2011). *Saving millions of lives: decade of action for road safety 2011-2020*. Geneva: World Health Organisation.

WHO. (2015). *Global status report on road safety 2015*. Geneva: World Health Organization.

Zhou, M., & Sisiopiku, V. (1997). Relationship between volume-to-capacity ratios and accident rates. *Transportation Research Record: Journal of the Transportation Research Board*(1581), 47-52.

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www.icorsi.org

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