Audit-based Comparison of Safety Deficiencies at Signalized Intersections: Lessons Learnt from India and Germany

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Abstract: Developing countries report a higher degree of road accidents as compared to the developed countries. This paper attempts to apply a road safety audit-based approach to identify and present the distinct differences in the operation of urban signalized intersections from the perspectives of safety deficiencies for an Indian city, Kolkata, and a German city, Darmstadt. The approach adopted here considers different aspects, viz., road geometry, signs and markings, traffic signal, pedestrian and non-motorized vehicle users, etc. based on a careful review of literature and road safety manuals. This helped to highlight the major safety deficiencies for a developing country. The most contrasting differences were observed in the geometric design and the traffic signal operations with a lack of consideration of needs of all types of road users in the Indian context. Finally, several recommendations were made considering the frequency of occurrence of safety deficiencies and the danger associated with them.

Keywords: Road Safety Audit, Signalized Intersection, Safety Deficiencies, Recommendations, India, Germany.

1. INTRODUCTION

Road accidents are one of the major causes of deaths, disabilities, injuries and property damage in the world every year which makes road safety a big issue globally. However, they show varying degrees of magnitude in developing and developed economies, with a greater impact in developing countries. Research has shown that accident rate in the developing countries is higher than their developed western counterparts (Jacobs et al., 1981; Jadaan et al., 1986; A-Saleh et al., 2012; WHO, 2018). A major reason may be that road traffic in developing countries is usually chaotic, disorderly, and poorly managed which leads to unsafe and stressful travel (WHO, 2018; Mohan et al., 2009). Such downsides have generally been attributed to various infrastructural, institutional, socio-economic, socio-cultural, and educational aspects (Khanal et al., 2014).

A major chunk of the fatal accidents in urban areas in developing as well as developed countries occur at the intersections. A study of non-freeway-motor-vehicle crashes in four urban areas of the United States found that 56% of the crashes occurred at intersections

(Retting et al., 1995). A review of 1,254 urban crashes in England found that almost 70% occurred at junctions (Carsten et al., 1989). As per MORTH (2020), a total of 125498 accidents occurred in India at intersections during the fiscal year 2019 which comprised about 28% per cent of the total accidents recorded in the country. As a result, the high accident risk at or near the intersections has become a serious concern for all the stakeholders involved in road transport, including the citizens and the government. Controlled intersections are expected to address such safety issues as the primary purpose of traffic control is to minimize the risks of conflict. However, it is surprising to note that 32844 (26.2%) accidents took place at intersections that have traffic control measures such as traffic light signals, police control, stop sign and flashing signals/blinkers (MoRTH, 2020). This highlights the fact that despite the measures undertaken to control traffic at such intersections, there is still a great scope of improvement of traffic control mechanism and operation of the controlled intersections in terms of enhancing road safety in the country.

In order to understand the reasons behind higher degree of road accidents in developing countries, it may be useful to compare the road safety issues in developing and developed countries to know where the developing countries are lacking and what improvements are necessary. Both reactive and proactive approaches have been used by researchers to investigate the safety issues at signalized intersections. Reactive approaches involve identification of critical factors causing accidents through the analysis of crash data (Wong et al., 2007; Cunto & Saccomanno, 2008; El-Basyouny & Sayed, 2013). However, such approaches rely heavily on the quality and reliability of crash data and, in many developing countries, like India, either the accident data is not available, or it is not reliable (Agarwal et al., 2013). Moreover, crashes are a rare and distinctly random occurrence and, as a result, it requires long observation periods to collect sufficient amount of crash data for building a database (Chang et al., 2017). Even in cases where some accident database is readily available, they rarely include all the explanatory variables for identifying the major safety deficiencies. Therefore, in such cases, it is more worthwhile to apply proactive approaches (Cheranchery et al., 2019; Mukherjee & Mitra, 2019; Kathuria et al., 2020) which does not require accurate crash data, and is dependent on road features alone to predict crashes and can be applied to new or re-engineered roads as well. The proactive road safety inspection-based approach has been shown to be a valid alternative to the traditional reactive accident-based blackspot approach (Ambros et al., 2016, Huvarinen et al., 2017). A proactive approach to road safety can in fact complement the more traditional, reactive methods (Leur et al., 2003, Mitra et al., 2017).

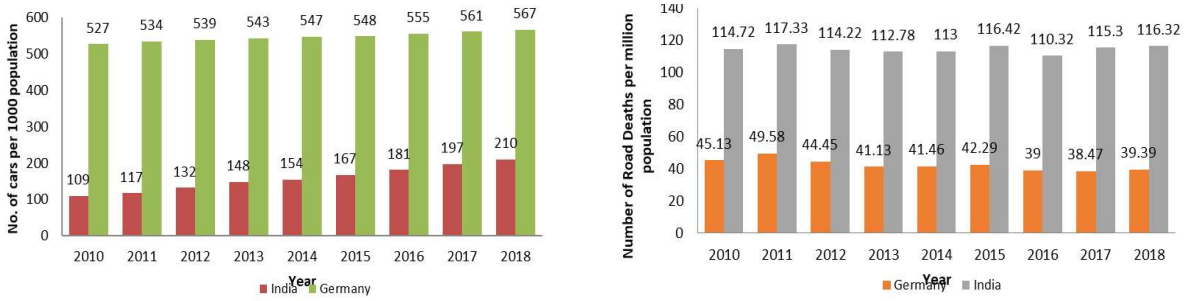
Road Safety Audit, hereby mentioned as RSA, is a well-established proactive safety assessment approach (Ahmed et al., 2013, Huvarinen et al., 2017), where it is attempted to qualitatively estimate and report the potential road safety issues and identify opportunities for improvements in safety for all road users and can be used without recourse to road traffic accident (RTA) records (Soames, 2012). They can address and identify potential road hazards before a probable accident happens. Therefore, with this background, this paper attempts to identify and compare the deficiencies in the operation of signalized urban intersections from the perspectives of road safety in an Indian city and a German city. Multiple Road Safety Audit manuals from different countries were reviewed to prepare a comprehensive checklist for signalized intersection safety evaluation and conduct the audits. This helped to identify all the safety aspects, a few of which might be overlooked by only referring to a single road safety manual. Specifically, ten intersections each in the city of Kolkata in India and the city of Darmstadt in Germany were chosen for identifying the safety deficiencies in each case and performing a comparative study. Although these two cities are different in terms of area, population, population density and road-user behaviour, they were chosen to show the

contrast between the road safety conditions in a developing country and a developed country. Based on the identified safety deficiencies, several key recommendations were formulated to improve the safety. The recommendations were prioritized by considering the frequency of occurrence of the safety deficiencies and the degree of danger associated with such deficiencies.

The remainder of the manuscript is structured in the following five sections. Section 2 comprises a brief description of the road safety scenario and study areas in India and Germany. Established road safety guidelines and manuals available in literature were reviewed to determine the inspections to be performed at signalized intersections and summarized in Section 3 of the manuscript. Based on the findings of the audits conducted, the safety deficiencies of these intersections have been identified which have been described in Section 4 and several interventions have been recommended in Section 5 to improve their safety performance. Finally, the major conclusions from the study and the scope for future research are summarized in Section 6 of the manuscript.

2. STUDY AREA

India has witnessed a rapid economic growth in the last two decades. This economic growth has been coupled with rapid increase in motorization in the country. According to MORTH (2020), the number of passenger cars per 1000 population in India has increased steadily from 109 in 2010 to 210 in the year 2018 as shown in Figure 1a. The number of road deaths (Figure 1b) has also increased from around 114.72 per million population in 2010 to 116.32 per million in 2018. In Germany, on the other hand, although the number of passenger cars per 1000 population is much higher than India, as shown in Figure 1a, and has increased only marginally over time, however, the number of road deaths (Figure 1b) has decreased from 45.13 per million population in 2010 to 39.39 per million population in 2018. This gives an indication that, with focused road safety improvements the number and severity of accidents in the country has reduced in the last few years.



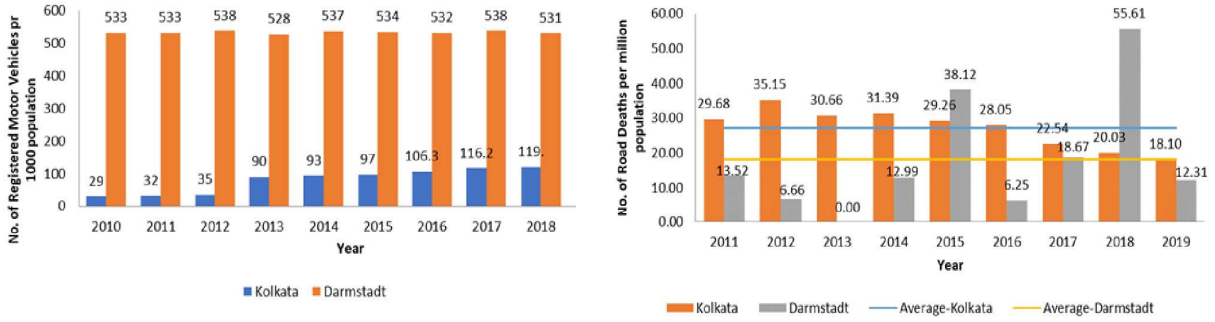
(a) (b)

Figure 1. (a) Number of cars per 1000 population in Indian and Germany (2010-2018). (b) Number of road deaths in India and Germany per million population (2010-2018). (Source: MORTH, India; Eurostats and Federal Statistical Office, Germany)

In this study, Kolkata was chosen as the Indian city. This major metropolitan city of India is characterized by its large and dense population, as well as high traffic density. The number of registered motor vehicles in the city increased from around 29 per 1000 population in 2010 to around 119 per 1000 population in the year 2018, which is a significant growth in the span of mere 9 years. The number of roads deaths in the city has reduced from 29.68 per million population in the year 2011 to 18.10 per million population in 2019 with a mean value of 27.21, as shown in Figure 2b. This indicates a high degree of awareness among the

city authorities towards improvement in road safety, however, there remains a further scope for improvement in the future. Signalized intersections on the Eastern Metropolitan Bypass in the city were selected for safety audit in this study. A total of ten intersections i.e., Patuli, Hiland Park, Ajay Nagar, Mukundapur, Metro Mall, Avishikta, Ruby, Panchanangram, Science City and Chingrighata intersections were observed and studied for identifying the safety deficiencies. The corridor studied is shown in Figure 3a.

The city of Darmstadt was selected as the German city in this study. The city boasts of a well-developed public transportation system and low-to-moderate traffic density, typical of European cities. The number of motor vehicles per 1000 population in the city, as shown in Figure 2a, has marginally decreased from 533 in 2010 to 531 in the year 2019 but still remains similar to the global average in the country. The city boasts of a very good track record when it comes to road deaths, with the numbers fluctuating in single digits; however, in terms of road deaths per million population, there are some variations through the years with the number being as low as 0 in 2013 to as high as 55.61 in 2018 with a mean value of 18.24 as shown in Figure 2b. This might be because of low population of the city and because the year 2018 was an anomaly with a sudden increase in the number of road deaths that year with 9 road fatalities being recorded in total. Overall, the city boasts of a high road safety performance on an average, and it is significantly lower than Kolkata city. RSA was conducted at ten intersections in the city. These signalized intersections lie on two very important and busy road corridors viz. Rhein strasse and Kasino Strasse-Neckar Strasse. The corridors and the signalized intersections studied are shown in Figure 3b.



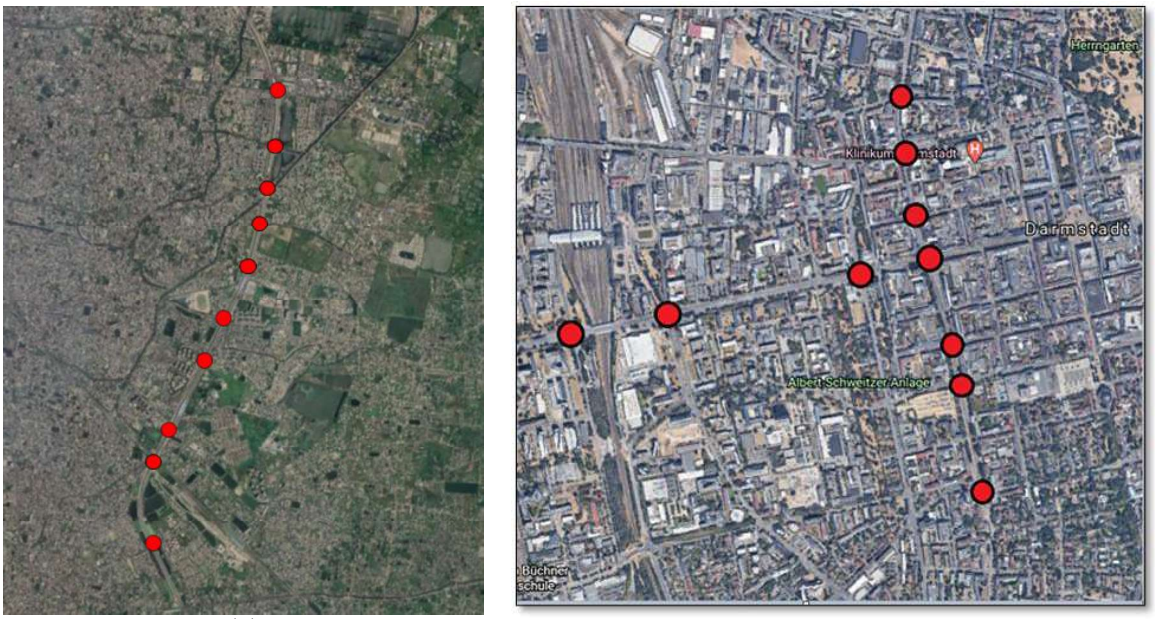
(a) (b)

Figure 2. (a) Number of registered Motor vehicles in Kolkata and Darmstadt per 1000 population (2010-2018). (b) Number of Road Deaths per million population in Kolkata and Darmstadt (2010-2018). [Source: Kolkata Traffic Police and Kraftfahrtbundesamt]

3. SAFETY AUDIT FRAMEWORK

Intersections are merging points of traffic, and hence very critical locations. As such, extra prudence and concern are generally exhibited by auditors while auditing them. Apart from monitoring the usual road safety elements, many more safety elements and issues are required to be addressed at the intersections, ranging from priority and layout to crossings. The type of intersection, whether three legged or four legged, signalized or unsignalized, with or without rotary, at-grade or grade separated, further adds to the complexities. However, some checks and recommendations are common to all intersections and should always be considered. Road Safety Manuals often recommend these checks as a part of the audit. If the intersection is signalized, the placement and functioning of traffic signals also need to be considered. Vulnerable road users need special considerations given they account for high proportion of all road deaths (Ribbens et al., 2003; Otte et al., 2002). In 2017, 21% of all road users who died in Europe were pedestrians while cyclists' death accounted for 8% of all road deaths

(European Comm., 2018). In India, pedestrians, cyclists, and other non-motorized vehicle users accounted for 27.3% of all road deaths in the year 2019 (MORTH, 2020). Road safety manuals often highlight the importance of the safety of vulnerable road users and recommend several checks for the auditors to carry out to identify the safety deficiencies of signalized intersections, as summarized in Table 1.



(a) (b)

Figure 3. (a) Intersections audited on the Eastern Metropolitan corridor, Kolkata. (b) Intersections audited on RheinStrasse and KasinoStrasse, Darmstadt. (Source: Google Earth)

The performance capabilities and behavioral characteristics of road users often affect the utility and safety of signalized intersections. The likelihood of user error is affected by various factors that affect a road user's ability to use an interaction, including the capabilities of human vision, information processing, and memory (Chandler et al., 2013). This makes users with impaired vision and perception-reaction time (e.g., older drivers and pedestrians) more vulnerable than others. So, special attention must be paid to such users not only during the planning and designing phases of roadways, but also after construction and subsequent opening of the project by the safety auditor. In addition to the intersection elements discussed in Table 1, maintenance and management problems, leading to the neglect and misuse of road amenities, are important aspects that need to be also recorded and addressed (Cheranchery et al., 2019). This entails issues like the overall condition of the intersection and roadside furniture, keeping the intersection clear of local encroachment, regulation of traffic movements through proper enforcement, etc. Poor maintenance and management over time leads to deterioration of the infrastructure and degradation of the safety performance of the intersection.

Road user behavior is often influenced by the priority rules at the intersection as well as the design and layout of the intersection and behavior of other road users (Björklund et al., 2005; Horst et al., 1991). In developing countries, such behavior is often disorderly, which can lead to congestion and crashes at the intersections. As a result, auditors should also consider this aspect while conducting the safety audit of existing intersections, as it may be necessary to influence and improve the road user behavior in order to improve the safety performance of an intersection. Out of the road safety manuals, only FHWA guidelines (McGill, 2005) touch upon this aspect of safety audit. Observing road user behavior might

highlight some aspects which are inherently wrong, misleading or absent in the design.

The RSA manuals usually provide some checklists for the reference of the auditors that are used as a guide to ensure that no important matters are overlooked (IRC:SP:88, 2010; GoU-RSAM, 2004; CAREC-SREM, 2018). They are designed as a prompt and are not a substitute for the knowledge of local conditions and experience. Sometimes the checklists are not very detailed and comprehensive, so new checklists have to be prepared, keeping the key principles of the RSA manual in mind (GE-STY-01027, 2017; Chandler, 2013). The RSA-based approach adopted in the present paper takes into account all the above-mentioned aspects to assess the intersection safety deficiencies in different contexts. The safety elements listed in Table 1 were used as a checklist for the audits to compare the safety of signalized intersections in the two cities and identify the safety lacunas. Audits were conducted by experts thrice at every intersection, once each during the morning and evening peak traffic and once during the lean hours at night-time. Every leg of the intersection was audited with respect to various safety aspects and parameters as discussed in this section. The auditors rated the safety elements at every leg of the intersections on a scale of 1 to 5, with 1 denoting very poor, 2 poor, 3 average, 4 good and 5 as excellent. Such approach also gives an idea about the potential of improvement in a specific safety element at the intersection. The auditors then went beyond the safety elements collated from different Road Safety Manuals (Table 1), and recorded all safety deficiencies at the intersections including some that were not considered in the manuals such as encroachment, unruly behavior by the road users etc.

Table 1. A Summary of Safety Elements for Signalized Intersections and Unsatisfactory Cases

Safety Elements	**FHWA -McGill, 2005**	**GoU -RSAM, 2004**	**CAREC -RSEM, 2018**	**GE -STY -01027, 2017**	**IRC: SP: 88, 2010**	**% Unsatisfactory Cases**	
						Kolkata	Darmstadt
Geometric Design Elements							
The layout of the intersection should cater safely for all road users including disabled road Users. It should be adequate for all types of vehicles.	+	+	+	+	+	100%	0%
The route through junction should be simple and clear so that its layout and the priority rules can be recognised by approaching motorists well in time.	+	+	+	+	+	40%	10%
The layout should encourage slow controlled speeds at critical decision points including stop lines and give way lines.	+	+		+	+	100%	10%
The line of sight to the critical decision points should be adequate and unobstructed.	+	+	+	+	+	40%	0%
There should be adequate provision for channelising the different streams of traffic.	+	+			+	60%	10%
There should be no awkward differences in level on the approach to and within the intersection.		+				0%	0%
The intersection should be free of capacity problems that may produce safety problems.	+	+	+			60%	0%

Safety Elements	FHWA -McGill, 2005	GoU -RSAM, 2004	CAREC -RSEM, 2018	GE -STY -01027, 2017	IRC: SP: 88, 2010	% Unsatisfactory Cases	
						Kolkata	Darmstadt
The provision of Bus Stop or Tram Station should be appropriate so as to prevent congestion at the intersection and conflict with other users.		+	+		+	60%	0%
Road Signs and Markings							
The intersection should be furnished with proper road signs and markings to guide and warn the road users including non-motorised vehicles.	+	+	+	+	+	100%	60%
The placement and position of the road signs should be appropriate and not interfere with the line of sight of road users.	+	+		+	+	100%	0%
The road signs and markings should be visible during the night/day and in wet/dry weather conditions.	+	+	+		+	100%	60%
The provision of road signs and markings should be in accordance with the standards.	+	+	+	+	+	100%	0%
Traffic Signals							
At signalized intersections, the placement and functioning of traffic signals should be conspicuous, proper and safe.	+	+	+	+	+	40%	0%
The signal sequence should conform to the standards and regulations to prevent confusion among the road users.	+	+	+	+	+	0%	0%
The signal phases should be reasonable and safe with no conflicting phases.	+	+	+	+	+	0%	0%
The signals should be visible in all conditions and should only be seen by users they are meant for.	+	+	+	+	+	0%	0%
The signal heads should clearly indicate which movements are allowed at a time.	+	+	+	+	+	0%	30%
The turning movements should be protected as far as possible.					+	20%	40%
The pedestrian signals should be positioned properly to ensure its visibility to the pedestrians and should be protected from conflicting traffic movements as much as possible.	+	+		+	+	80%	0%
Adequate time should be provided for all movements at the signal.	+	+	+			60%	0%
Pedestrian and Non-Motorized Vehicles							
The location and type of crossing facilities should be	+	+	+	+	+	60%	0%

Safety Elements	FHWA -McGill, 2005	GoU -RSAM, 2004	CAREC -RSEM, 2018	GE -STY -01027, 2017	IRC: SP: 88, 2010	% Unsatisfactory Cases	
						Kolkata	Darmstadt
appropriate such that pedestrians and other Non-motorized vehicle users are not discourage from making legal crossings.							
Adequate visibility at night should be also ensured at crossings, sidewalks and cycle lanes.	+	+	+	+	+	40%	50%
Dedicated cycle and pedestrian facilities including road markings and signs should be provided to assist them.	+	+	+	+	+	100%	10%
Special provision of facilities for people with mobility impairments must be ensured.	+		+	+		100%	10%
Conflicts between motorised traffic and pedestrians/non-motorized vehicles and other disabled / handicapped road users should be minimized.	+	+	+	+	+	100%	0%
The needs and safety requirements for pedestrians crossing the road and walking safely alongside it should be adequately provided for.	+	+	+	+	+	80%	0%
Adequate sight lines for the safety of all pedestrian groups and other non-motorized vehicle users must be ensured.	+	+			+	40%	0%
The needs of public transport users who can also be pedestrians or cyclists should also be considered.		+	+			100%	0%
There should be no gaps in the network of footways, and it should be ensured that bus/taxi stops, and tram stations should be properly connected with the network of sidewalks and crossings		+				100%	0%
Other Safety Aspects							
There should be proper and adequate provision of lighting at the intersection during the night.	+	+	+	+	+	0%	0%
The vegetation and other obstacles at the intersection should not obstruct the traffic signs, visibility at junctions, stopping sight distances on the mainline, Footways / crossing points.		+		+	+	40%	0%
The surface of the carriageway should have adequate skid resistance.	+	+	+	+		0%	0%

Safety Elements	FHWA -McGill, 2005	GoU -RSAM, 2004	CAREC -RSEM, 2018	GE -STY -01027, 2017	IRC: SP: 88, 2010	% Unsatisfactory Cases	
						Kolkata	Darmstadt
The pavement should be free of potholes or loose material, which could result in safety problems.	+	+	+			0%	0%

4. AUDIT FINDINGS

Road safety audits to compare the safety deficiencies of signalized intersections in the two cities were conducted by the experts during three time periods at every intersection, once each during the morning and evening peak traffic and once during the lean hours at night-time. Every approach of the intersection was audited with respect to various safety aspects and parameters as discussed in Section 2. All the safety deficiencies at the intersections were recorded by the auditors and several recommendations were made to improve the safety of these intersections. In the Audit conducted by experts, if the average score of a safety element was less than or equal to 3 for a leg of an intersection, then it was deemed as unsatisfactory. The percentage of intersections where the safety elements were found to be unsatisfactory have been summarized in Table 1 which clearly shows that the intersections in Darmstadt have much lower deficiencies as compared to their Kolkata counterpart. The general findings of audits conducted in the two cities and the comparison of their safety deficiencies are further discussed in the following subsections.

4.1 Geometric Design

Multiple design issues were found at the intersections studied in Kolkata. First, the layout of every intersection audited in the city did not take the safety of vulnerable road users into account. In a few cases, the intersections (e.g., Ruby Junction) are too big and devoid of provisions such as pedestrian refuge islands, which would enable them to safely wait for a gap in the traffic so that they can finish the crossing. Moreover, the intersections were also devoid of any speed management provisions to encourage slow controlled speeds at critical locations. In many cases, designated bus stop locations are either missing or are too far away from the intersection (at mid-block), causing the buses to stop illegally at the intersections to serve the passengers. Further, bus stops with proper shelter are not provided at a few legs despite buses running and making stops on those legs (Figure 4d) (Mukherjee & Mitra, 2019). For several intersection, the junction layouts are too complicated and not clear enough for unfamiliar road users, making it difficult for approaching motorists to understand the priority rules in time. In a few cases, the line of sight to the cross traffic and road signs is obstructed at certain legs of the intersections, while in some other cases, control and segregation of non-homogenous traffic flows through proper channelization is absent (e.g., AjayNagar and Patuli intersections). Storage lanes for right and left turn traffic movements were also insufficient at some intersections (Figure 5a). In some cases, the stop lines were provided too far from the intersection functional area at the minor approaches of the intersection, forcing the motorists to stop far beyond the stop line.

On the other hand, no major design issues were observed at the intersections studied in Germany. The public transit lines (bus and tram) were, in most cases, segregated from the main carriageway, thereby reducing conflicts. The traffic on carriageways was quite homogenous and orderly. It was also ensured that there were no sight distance issues for the road users at the intersections. Only a few minor issues were found in some intersections. Firstly, motorists were not permitted to make some turns at one intersection, but no sign

boards were installed to inform the unfamiliar motorists, making the route through the intersection unclear to such road users. Secondly, there were no speed management provisions at another intersection leading to many motorists speeding while approaching the intersection. Lastly, the channelizing measures at an intersection (Rheinstrasse/ Kavalleriesand) were found to be inadequate at two legs making it difficult for longer vehicles to negotiate a right turn.

4.2 Road Signs and Markings

At the intersections audited in Kolkata, proper road signs (Figure 4b and 4c) and pavement markings (Figure 4a), to guide the traffic movements, were not adequately provided at every intersection observed. Such improper road signs and markings contributes significantly towards increasing the risk of crash and its severity (Islam et al., 2008; Ezeibe et al., 2019).

In Germany, the provision of road signage was found to be inadequate only in terms of guiding the unfamiliar drivers about the priority rules at some of the intersection. In addition, there were visibility issues with some sign boards at night at several intersections (e.g., Rheinstrasse/Berliner, Alle, Kasinostrasse/Bismarckstrasse, etc.).

4.3 Traffic Signal Operations

At several intersections in Kolkata (e.g., Mukundapur, Patuli, etc.), problems like lack of coordination between the signals at different legs, improper signal heads and timers, were causing great confusion among unfamiliar drivers. In addition, inter-green times provided at majority of the intersections, especially the major ones, were inadequate for the traffic, causing conflicts with the cross-traffic and thereby also triggering additional delays in the clearing of vehicles from the intersection. Furthermore, dedicated pedestrian phases were not provided at some intersections, thereby forcing the pedestrians to cross in a very unsafe manner by finding gaps in the traffic.

On the other hand, the intersections in Germany were installed with properly coordinated, well-placed and optimized traffic signals, with sufficient inter-green times, adequate green times, and appropriate cycle lengths. The biggest safety concern, however, was observed at four of the intersections, where the turning phases on the minor roads were unprotected and permitted along with through traffic, often leading to conflicts, which may lead to severe crashes (Kumara et al., 2005). Moreover, in a few intersections, some signals were confusing due to the absence of directional signs along with them.

(a)

(b)

(c) (d)

Figure 4. (a) Absence of road markings. (b) Improper 'No right turn' sign. (c) Improper 'No U-turn' sign. (d) Absence of proper Bus stop and shelter.

4.4 Pedestrian and Non-Motorized Vehicles

At the intersections audited in Kolkata, no special provisions like separate lanes, road markings and signs, to assist movement through the intersections, were made for the non-motorized vehicle users, forcing them to cross the intersection alongside the motorized vehicles, thereby leading to conflicts. Sidewalks for pedestrians were absent at many legs, and if present, were poorly designed and maintained. Their connectivity with crossings was obstructed or missing at many locations (Figure 5b and 5c). The needs of public transport users, and, also, pedestrians or cyclists, have not been adequately considered in any intersection. No park-and-ride facilities were provided for public transport users who were also cyclists. The bus stop was provided at the mid-block in 60% of intersections without proper walking access for public transport users. On-street parking in front of the public transport waiting area, physical obstruction on the sidewalk connecting the waiting area or the complete lack of connectivity between the sidewalk and the waiting area were some common sights (Cheranchery et al., 2019). These limitations of road facilities and right-of-way for non-motorized transportation modes is a common feature of Indian cities that make them more vulnerable to serious traffic accidents (Datey et al., 2012). No barrier-free access to sidewalks from crossings was provided for users with mobility impairments at any intersection. As mentioned previously, proper pedestrian signals were not provided at several intersections (e.g., Ruby, Mukundapur, Hiland Park), which forced the pedestrians to cross in an unsafe manner by finding gaps between vehicular movements (Chandrappa et al., 2016). Poor visibility was another issue spotted at the crossings and sidewalks of a few intersections. Lastly, in some cases, the line of sight was being obstructed due to the presence of piers of the elevated metro corridor, billboards, encroachment etc. making the vehicles unaware of any crossing pedestrian.

High priority was given to the safety of pedestrians and non-motorized vehicles in Germany and the roads were well equipped with properly connected network of sidewalks, cycle lanes and crossings, to promote walkability and cyclability. Extensive intersection pavement markings were used to identify bicycle and pedestrian crossings within intersections. Shorter cycle lengths were used to reduce waiting time for bicycle and pedestrian traffic. Audible pedestrian signals (with or without pedestrian push buttons) were also provided at certain locations to supplement signal indicators. Despite all these safety practices observed at the intersections in Darmstadt, there were still a few safety deficiencies. The most common issue was poor night visibility at the sidewalks (e.g., Rheinstrasse/Berliner Alle, Heidelbergerstrasse/ Heinrichstrasse, Neckarstrasse/Hugelstrasse, etc.). Low luminance plays a major role in disproportionate number of fatal injuries that occur after dark (Plainis et

al., 2006). Another issue was observed at one of the intersections, where no separate cycle lanes were provided, forcing the cyclists to move on the carriageway. In addition, the subway crossing facility at Kasinostrasse/ Julius-Reiber-Strasse intersection did not have provision of barrier-free access for cyclists and handicapped road users, forcing these users to walk to the next intersection to cross.

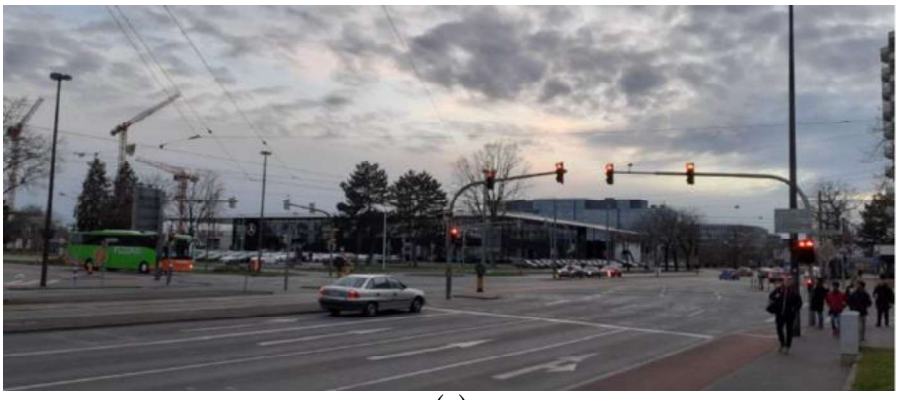
Figure 5. (a) Inadequate Right turn storage lane. (b) Absence of proper crossing facility encouraging jaywalking. (c) Absence of proper sidewalk and crossing. (d) Stop line violation by motorized vehicles. (e) Encroachment by food vendors. (f) Stop line violation by non-motorized vehicles.

4.5 Other Safety Aspects

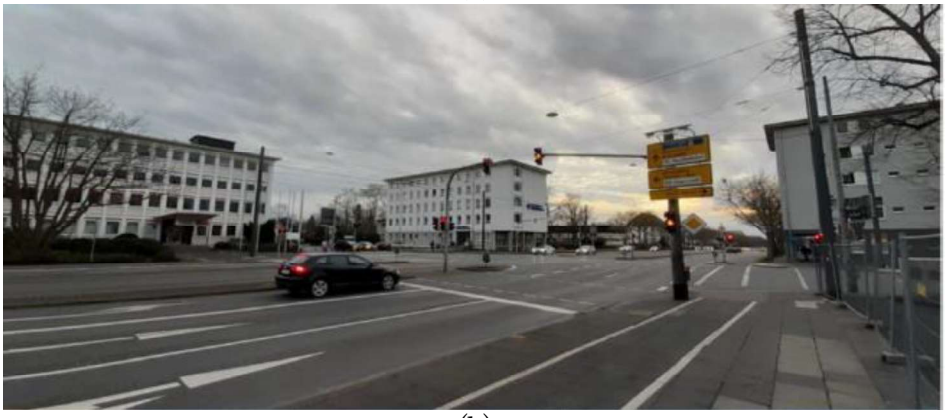
The traffic density during the peak hours was very high at all the intersections assessed in Kolkata. In addition, encroachment by roadside vendors (Figure 5e), buses and Para-transit vehicles were leading to traffic congestions at some intersections. Such encroachments, along with improper placement of billboards and road signs, obstruct the traffic signs and affect

visibility at junctions. These safety deficiencies were also observed in other studies related to similar contexts (Mukherjee & Mitra, 2019; Mukherjee & Mitra, 2020). Moreover, lack of traffic discipline among road users and less strict enforcement make traffic violations (Figure 5d, 5e) a common sight.

On the other hand, in Germany, the roads and intersections were free from encroachment and congestions, with traffic violations being a rarity due to better management and enforcement. Photo enforcement techniques were applied to slow traffic and reduce red-light running. Public transit systems like trams and buses were monitored on real-time basis to ensure punctuality and public safety. Road infrastructure and roadside furniture were in a far better condition due to proper proactive maintenance (Figure 6b and 6c).



(a)



(b)

(c)

Figure 6. (a) A well-developed signalized intersection on Rheinstrasse, Darmstadt. (b) Provision of adequate storage lanes and road markings. (c) Provision of adequate road signs to guide the road users at the intersection.

5. KEY RECOMMENDATIONS

In order to improve the road safety at signalized intersections in Kolkata and India as a whole, several measures are recommended here based on the findings from the road safety audit. The recommendations have been prioritized on the basis of percentage of intersections where the safety elements were found to be lacking (Table 1) and the danger associated with the lack of these elements as established in literature.

5.1 Geometric Design Recommendations

It is estimated that over-speeding led to 71.1% of road accidents in India and 67.3% of the total road fatalities in 2019 (MORTH, 2020). Unsurprisingly, all intersections audited in Kolkata were found lacking in speed control measures. Therefore, under Geometric Design recommendations, it is firstly recommended to execute traffic calming measures such as raised crosswalks to lower the speed of the vehicles (Gonzalo-Orden et al., 2016). Speed limit reductions in conjunction with signal-warning flashers have been also found to be an effective countermeasure (Wu et al., 2013) and may be adopted.

Second, it was observed that elderly and specially-enabled road users take longer to make the crossings due to greater time required by them to observe and react to approaching traffic (the observation–reaction time), cross the carriageway itself, and gain the opposite curb to become fully positioned on the opposite footway (Schoon et al., 2006). All Indian intersections audited in the study were found to be completely ill-equipped and badly designed for such road users. So, provision of refuge islands and narrowing of lanes at crossings are recommended on a case-by-case basis to accommodate the needs of such overlooked and marginalized road users.

Third, channelization of left turn traffic was found to be absent in 60% intersections audited in Kolkata. This can lead to merging conflicts with the cross traffic. Therefore, proper left turn channelization should be provided at intersections with high volume levels and significant proportions of left turn volume (Wang et al., 2006), to reduce such conflicts and waiting time of vehicles (Gowri et al., 2008).

Fourth, a prominent lacuna identified in the audit was inappropriate provision of Bus Stops near 60% intersections assessed in Kolkata which was leading to congestion and conflicts. Fully furnished bus stops with proper shelters should be provided either downstream from the signal or upstream but slightly further away from it and not at the mid-block, so that there is lesser congestion at the approaches and Buses are prevented from stopping illegally at the intersections (Moura et al., 2012). If bus lanes are already provided on the corridor, they should be maintained properly and separated from the carriageway by means of dividers, in order to prevent the road traffic from violating the right-of-way rules and causing conflicts with the bus movements.

Fifth, another deficiency observed in 60% intersections audited in Kolkata was the absence of enough storage lanes for the turning traffic, which was leading to congestion at the intersections. The movement of vehicles from such congested and constrained space to a more open space leads to diverging conflict which, though the least problematic of the conflict types, might eventually lead to sequential conflict. So, in order to reduce such conflicts at the intersection approaches, enough storage lanes should be provided for right and left turn traffic movements (Wang et al., 2006; Kumara et al., 2003).

Sixth, the line of sight was found to be obstructed at many critical decision points in 40% intersections examined in Kolkata. Such line-of-sight obstructions to critical traffic control elements like signals and road signs can even lead to crossing conflicts at the intersection. So, they should also be cleared for all motorists approaching the intersection.

Seventh and last, to facilitate ease of crossing through 40% intersections audited in Kolkata, which were found to have confusing and complex routes through them, they should be installed with proper directional signs and the intersection sign so that the junction type, layout and the priority rules can be recognized by approaching motorists well in advance.

5.2 Road Signs and Markings

First, the provision of proper road markings has been found to improve road safety in multiple studies (Miller, 1992; Moses, 1986, Babić et al., 2020). They become especially important from the safety point of view during night when the amount of light available to the drivers reduces, thereby narrowing and shortening their field of vision and impairing their ability to perceive colour, shape, texture etc. So, it must be ensured that all intersections are provided with proper road markings for all road users including the non-motorised vehicles, in accordance with the standards (IRC: 35-1997), with proper retro-reflectivity to increase their night-time visibility. The location of stop lines were also found to be improper and too far away from the intersection approach in many cases. This resulted in stopline violations and also the need for additional time for vehicles in clearing the intersection. Therefore, stop lines should be moved near the intersection functional area to prevent violations by the motorists from stopping far beyond the stop line and to efficiently utilize the green time.

Second and last, the deficit of well-maintained road traffic signs in developing countries to guide the road users safely through dangerous spots on the roads is a major cause of accidents (Ezeibe et al., 2019) and their provision can help in reducing accidents significantly (International Road Federation, 2006). So proper and adequate road signs should be provided at every intersection in India in line with the established guidelines (IRC: 67-2012). The same should be done in Germany at intersections that have confusing routes through them. Furthermore, it has been found that the level of fixation of drivers on road traffic signs is lowered during the night by the intensity of road traffic despite the reflective elements present in them (Madleňák et al., 2018). Therefore, it should be also ensured that they are visible during all times and in dry/wet weather conditions, by equipping them with retroreflective materials and ensuring proper illumination at the approaches and the intersection.

5.3 Traffic Signal Operations

First, since pedestrians are amongst the most vulnerable road users and since it has been observed that 80% signals studied in Kolkata either don’t have pedestrian signal heads or are positioned improperly even when present, it should be ensured that the signalized intersections should be provided with proper pedestrian signals while ensuring their visibility to pedestrians. Studies have shown that absence of such signals in India might be a significant contributing factor of pedestrian fatalities (Mukherjee et al., 2019; Mukherjee et al., 2020), and that the presence of pedestrian signals along with provision of adequate clearing time can positively affect the safety of pedestrians at signalized intersections (Brosseau et al. 2013).

Second, in 60% of the intersections studied in India, it was found that the inter-green times provided were inadequate, leading to insufficient clearing time for the vehicles and thereby causing conflicts with the cross traffic. This can lead to crossing conflicts amongst the traffic streams and cause great loss to life and property. If an All-Red Clearance Interval (ARI) of adequate length is used, drivers will have a lower probability of being involved in a right-angle crash (Schattler et al., 2004). As such, it is recommended that signals should be programmed with adequate Amber and All Red intervals, like in case of Germany, at every intersection in India.

Third, 20% intersections audited in India and 40% intersections audited in Germany

had unprotected/ permitted turning movements. Studies have shown that the absence of protected turning phases is one of the major contributing factors of road accidents at signalized intersections (Wang et al., 2006; Kumara et al., 2003) and their presence lowers the risk of collision at intersections, thereby increasing safety (Zhang et al., 2003, Polders et al., 2015). It is therefore recommended to make the turning movements protected at such intersections as far as possible.

Last, problems like lack of coordination between the signal heads, improper signal head and timers (at 40% intersections assessed in India), and provision of turning signal heads without directional signs (at 30% intersections in Germany), can cause great confusion among the motorists and lead to conflicts, thereby completely nullifying the purpose of providing signals in the first place. Such issues should be dealt with utter urgency and the functioning of signals should be proper, conspicuous and safe.

5.3 Pedestrians and Non-Motorized Vehicles

In the year 2019, 17% of the total road fatalities in India were that of pedestrians and 5 percent of the road deaths were that of Cyclists and Other Non-Motorized Vehicle users (MORTH,2020). So, it was surprising that all Indian intersections audited were found to be lacking in terms of facilities for these road users. Thus, special considerations should be given to the safety of pedestrians and non-motorized vehicle users and there should be provision of improved rights of way for them. First, taking inspiration from the operation in German intersections, facilities like wide sidewalk and crossings, cycle lanes, pedestrian/bike traffic signals, signs and markings should be provided, since non-motorized transport infrastructure is essential to road safety (Pucher et al., 2005; Tiwari et al., 2016). This would help in minimizing the conflicts between the motorized traffic and such vulnerable road users.

Second, as discussed earlier in section 2, users with disabilities are more vulnerable than others. So, barrier-free access between the sidewalks and the crossings should be provided for vulnerable road users with special provision of facilities for people with disabilities (Chandler et al., 2013). These include designing the sidewalks and crossings keeping the dimensions of wheelchairs and baby-strollers in mind, provision of curb ramps, refuge islands, detectable warning surfaces (DWS) and audible crossing signal indicators (Fong et al., 2003).

Third, the needs of public transport users who are also pedestrians or cyclists for some part of their trips should be also considered. Every intersection audited in India was extremely lacking in this regard. There should be provision of parking facilities for cyclists who are also public transport users, proper Bus-stops with shelter and furniture should be provided near the intersections and not at mid-blocks to encourage walking. And most importantly, the waiting area should be well connected with the sidewalks and crossings to ensure that they are not forced to stand or walk on the carriageway (Cheranchery et al., 2019).

Fourth, night visibility at crossings, sidewalks and cycle lanes was found to be poor at 40% intersections in India and 50% intersections in Germany. This is one aspect that needs great improvement in both countries and is one of the factors that significantly contributes to the safety of vulnerable road users at night (IRC:SP:88-2010; Anjana et al., 2015; Lee et al., 2005). Therefore, improved visibility for drivers approaching the crossing facilities is one of the potential countermeasures to improve their safety (Polders et al., 2015; Elvik, 1995).

Fifth and last, simply providing crossing facilities is not enough. It should be ensured that the location and type of crossing facilities are appropriate so that pedestrians and other non-motorized vehicle users are not discouraged from making legal crossings. Elderly pedestrians and women generally dislike grade-separated crossing like underpasses and footoverbridges due to aspects such as greater crossing time, accessibility and fear of crime

(Chandrappa et al., 2021; Anciaes et al., 2018). However, these can be provided at large and complex intersections, where it might take longer for pedestrians to cross the road through the signalized crossings as long as they are equipped with ramps and proper lighting at night to ensure safety.

5.3 Other Safety Aspects

First, encroachment by roadside vendors, buses and Para-transit vehicles were leading lead to traffic congestions at 40% intersections audited in India. They along with road-side billboards were also obstructing line of sight at many locations. So, the roadside traders should be relocated, and proper measures should be taken for their rehabilitation. Furthermore, illegal parking by buses and para-transit vehicles at the intersections should be strictly penalized and there should be separate stop locations for para-transit vehicles near these intersections.

Last but not the least, apart from the aspects covered by the safety manuals summarized in Table 1, another safety aspect noticed by the auditors was the unruly behaviour by road users at the intersections audited in India. So, in order to deal with such disorderly behaviour of road users, photo enforcement techniques (Fong et al., 2003) or Integrated Traffic Management Systems (ITMS) like Stop-Line Violation Detection System (Saha et al., 2013) and Red-Light Violation Detection System (Saha et al., 2010) can be installed at the intersections to improve enforcement of traffic rules and prevent violations. In addition, road accidents can be permanently reduced if enforcement is at a sufficiently high level to deter drivers and not reduced once it is successful (Bjørnskau et al., 1992). Allocating enforcement resources according to chance mechanism (and not according to police estimates of violation probability) and implementing automatic traffic surveillance techniques, can make enforcement effects last. Combining these enforcement strategies with public information campaigns, educating young children about road safety, and driver improvement and rehabilitation programs can lead to significant improvement in driver behavior, reduction in child accidents and have an impact on the involvement of offenders (Groeger et al., 1998).

6. CONCLUSIONS

The safety-audit based approach adopted in the present study highlights the various safety deficiencies at urban signalized intersections in an Indian city in comparison to its counterpart in Germany. The present study will be important to road safety practitioners across different countries and regions to adopt a similar audit methodology and compare the intersection safety. The work may also be of interest to researchers and encourage them to develop a comprehensive framework for the safety assessment of signalized intersections in developing countries, to not only identify deficiencies but also assign safety levels to these intersections.

From the present study, the overall safety provisions for signalized intersections in Germany was concluded to be much better than India which clearly brings out the gross imbalance in the quality of measures adopted to improve road safety between the developing and the developed world. The most visible differences were observed in terms of higher priority to pedestrians and non-motorized vehicles, improved geometric design and roadside furniture, and better compliance of various road users to the traffic rules and regulations. The management related issues like encroachment and traffic violations are dealt in a better way in Germany than in India by utilizing modern enforcement techniques like photo-enforcement.

The comparative study helped to bring out some key recommendations on the basis of the frequency of occurrence of the safety deficiencies and the associated danger to improve the safety of signalized intersections in Kolkata. Some of these include: improving right of way for pedestrians and non-motorized vehicles, provision of proper road signs and markings

for all road users, provision of furnished bus-stops either downstream or upstream slightly away from the intersection, installation of ITMS techniques to improve enforcement, channelization at intersections with significant left turn traffic, provision of barrier free access to vulnerable road users and installation of proper signal heads with timers and proper coordination in accordance with the guidelines at the intersections.

There are a few limitations in the present study which lay out the scope for future research in this area. Firstly, the two cities compared are different in terms of population and population density. This results in different traffic volumes and densities on the road networks of the two cities. While most of the safety aspects are not expected to change, it might be interesting to see if there is a change in the road user behavior for more densely populated cities in Germany. Moreover, a system to evaluate and quantify the safety level of intersections can also be developed to compare their overall safety.

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REFERENCES

Agarwal, P. K., Patil, P. K., & Mehar, R. (2013). A methodology for ranking road safety hazardous locations using analytical hierarchy process. Procedia-Social and Behavioral Sciences, 104, 1030–1037.

Ahmed, I., Puan, O.C. and Ismail, C.R., (2013). A comparative review of road safety audit guidelines of selected countries. Jurnal Teknologi, 65(3).

Al-Saleh K, Bendak S (2012) Drivers' behaviour at roundabouts in Riyadh. Int J Inj Contr Saf Promot 19: 19-25.

Anciaes, P.R. and Jones, P., 2018. Estimating preferences for different types of pedestrian crossing facilities. Transportation research part F: traffic psychology and behaviour, 52, pp.222-237.

Ambros, J., Havránek, P., Valentová, V., Křivánková, Z. and Striegler, R., 2016. Identification of hazardous locations in regional road network–Comparison of reactive and proactive approaches. Transportation research procedia, 14, pp.4209-4217.

Anjana, S. and Anjaneyulu, M.V.L.R., 2015. Safety analysis of urban signalized intersections under mixed traffic. Journal of safety research, 52, pp.9-14.

Babić, D., Fiolić, M., Babić, D. and Gates, T., 2020. Road markings and their impact on driver behaviour and road safety: a systematic review of current findings. Journal of advanced transportation, 2020.

Björklund, G.M. and Åberg, L., (2005). Driver behaviour in intersections: Formal and informal traffic rules. Transportation Research Part F: Traffic Psychology and Behaviour, 8(3), pp.239-253.

Bjørnskau, T. and Elvik, R., (1992). Can road traffic law enforcement permanently reduce the number of accidents?. Accident Analysis & Prevention, 24(5), pp.507-520.

Brosseau, M., Zangenehpour, S., Saunier, N. and Miranda-Moreno, L., 2013. The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal. Transportation research part F: traffic psychology and behaviour, 21, pp.159-172.

Carsten, 0. M. J., Tight, M. R., Southwell, M. T., & Plows, B. (1989). Urban accidents: Why do they happen? Leeds, United Kingdom: AA Foundation for Road Safety Research.

Chandler, B.E., Myers, M., Atkinson, J.E., Bryer, T., Retting, R., Smithline, J., Trim, J., Wojtkiewicz, P., Thomas, G.B., Venglar, S.P. and Sunkari, S.R., (2013). Signalized Intersections Informational Guide (No. FHWA-SA-13-027). United States. Federal Highway Administration. Office of Safety.

Chandrappa, A.K. Bhattacharyya, K., and Maitra, B. (2016). Estimation of Post-Encroachment Time and Threshold Wait Time for Pedestrians on a Busy Urban Corridor in a Heterogeneous Traffic Environment: An Experience in Kolkata. Asian Transport Studies, 4(2), 421-429.

Chandrappa, A.K. Bhattacharyya, K., and Maitra, B. (2021). Measures for improving pedestrian crossing facilities based on perceptions of urban commuters: An Experience in Kolkata. Case Studies on Transport Policy, 9(2), 965-973.

Chang, A., Saunier, N. and Laureshyn, A., 2017. Proactive methods for road safety analysis (No. WP-0005). SAE Technical Paper.

Cheranchery, M. F., Bhattacharyya, K., Salih, M., & Maitra, B. (2019). A proactive approach to assess safety level of urban bus stops. International journal of injury control and safety promotion, 26(3), 260-270.
Cunto, F., & Saccomanno, F. F. (2008). Calibration and validation of simulated vehicle safety performance at signalized intersections. Accident analysis & prevention, 40(3), 1171-1179.
Datey, A., Darji, V., Patel, T. and Mahadevia, D., (2012). Walking and cycling in Indian cities: A struggle for reclaiming road edges. Center for Urban Equality (CUE).
De Leur, P. and Sayed, T., 2003. A framework to proactively consider road safety within the road planning process. Canadian Journal of Civil Engineering, 30(4), pp.711-719.
El-Basyouny, K., & Sayed, T. (2013). Safety performance functions using traffic conflicts. Safety science, 51(1), 160-164.
Elvik, R., (1995). Meta-analysis of evaluations of public lighting as accident countermeasure. Transportation Research Record, 1485(1), pp.12-24.
European Commission, 2018. Road safety in the European Union: Trends, statistics and main challenges. Technical Report.
Ezeibe, C., Ilo, C., Oguonu, C., Ali, A., Abada, I., Ezeibe, E., Oguonu, C., Abada, F., Izueke, E. and Agbo, H., (2019). The impact of traffic sign deficit on road traffic accidents in Nigeria. International journal of injury control and safety promotion, 26(1), pp.3-11.
Fong, G., Kopf, J., Clark, P., Collins, R., Cunard, R., Kobetsky, K., Lalani, N., Ranck, F., Seyfried, R., Slack, K. and Sparks, J., (2003). Signalized intersection safety in europe (No. FHWA-PL-04-004).
GE-STY-01027. "Road Safety Audit Guidelines". December 2017. Transport Infrastructure Ireland (TII) Publications. Ireland.
Gonzalo-Orden, H., Rojo, M., Pérez-Acebo, H. and Linares, A., 2016. Traffic calming measures and their effect on the variation of speed. Transportation research procedia, 18, pp.349-356.
Gowri, A. and Sivanandan, R., (2008). Evaluation of left turn channelization at a signalized intersection under heterogeneous traffic conditions. Transport, 23(3), pp.221-229.
Groeger, J.A. and Rothengatter, J.A., (1998). Traffic psychology and behaviour. Transportation research part F: traffic psychology and behaviour, 1(1), pp.1-9.
Huvarinen, Y., Svatkova, E., Oleshchenko, E., & Pushchina, S. (2017). Road safety audit.
Transportation Research Procedia, 20, 236–241.
International Road Federation (2006). Maintenance of road signs, mark-ings and other safety assets: A cost effective means of optimizing road safety. Switzerland: International Road Federation.
IRC: 35-1997. "Code of Practice for Road Markings". Indian Road Congress, New Delhi, India.
IRC: 67-2012. "Code of Practice for Road Signs". Indian Road Congress, New Delhi, India.
IRC: 93-1985. "Guidelines on Design and Installation of Road Traffic Signals". Indian Road Congress, New Delhi, India.
IRC: SP: 88-2010. "Manual on Road Safety Audit". Indian Road Congress, New Delhi, India.
Islam, M.B. and Kanitpong, K., (2008). Identification of factors in road accidents through in-depth accident analysis. IATSS research, 32(2), pp.58-67.
Jacobs GD, Sayer IA, Downing AJ. (1981). A preliminary study of road user behaviour in developing countries. TRRL Report SR 646. Crowthrone (UK); Transport Research Laboratory.
Jadaan KS. (1986). Kuwait accident patterns and cost evaluation. Aust Road Res, 16: 241-249.
Kathuria, A. and Vedagiri, P., 2020. Evaluating pedestrian vehicle interaction dynamics at un-signalized intersections: a proactive approach for safety analysis. Accident Analysis & Prevention, 134, p.105316.
Khanal, Mandar. (2014). Road Safety in Developing Countries. Journal of Civil & Environmental Engineering. 04. 10.4172/2165-784X.S3-001.
Kumara, S.S.P. and Chin, H.C., (2005). Application of Poisson underreporting model to examine crash frequencies at signalized three-legged intersections. Transportation Research Record, 1908(1), pp.46-50.
Kumara, S.S.P., Chin, H.C. and Weerakoon, W.M.S.B., (2003). Identification of accident causal factors and prediction of hazardousness of intersection approaches. Transportation Research Record, 1840(1), pp.116-122.
Lee, C. and Abdel-Aty, M., 2005. Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida. Accident Analysis & Prevention, 37(4), pp.775-786.
Madleňák, R., Hoštáková, D., Madleňáková, L., Drozdziel, P. and Török, A., 2018. The analysis of the traffic signs visibility during night driving. Advances in Science and Technology. Research Journal, 12(2).
McGill, J. (2005). FHWA Road Safety Audit Guidelines. Washington, D.C., Federal Highway Administration, Office of Safety.
Miller, T. R. (1992). Benefit–cost analysis of lane marking. Transportation Research Record, 1334, 38–45.
Mitra, S., Geedipally, S.R. and Lord, D., 2017. Safety Analysis of Urban Signalized Intersections in Kolkata, India Using a Combined Proactive and Reactive Approach (No. 17-06331).

Moses, P. (1986). Edge lines and single vehicle accidents. Western Road, April 9–8.
Mohan D, Tsimhoni O, Sivak M, Flannagan M (2009) Road Safety in India: Challenges and Opportunities. (UMTRI-2009-1), Ann Arbor: University of Michigan, Transportation Research Institute.
MoRTH. (2020). Road Accidents in India 2019, Transport Research Wing, Ministry of road transport & highways, Government of India, New Delhi.
Moura, J.L., Alonso, B., Ibeas, Á. and Ruisánchez, F.J., (2012). A two-stage urban bus stop location model. Networks and Spatial Economics, 12(3), pp.403-420.
Mukherjee, D. and Mitra, S., (2019). Impact of road infrastructure land use and traffic operational characteristics on pedestrian fatality risk: A case study of Kolkata, India. Transportation in developing economies, 5(2), p.6.
Mukherjee, D. and Mitra, S., (2020). A comprehensive study on factors influencing pedestrian signal violation behaviour: experience from Kolkata City, India. Safety science, 124, p.104610.
NHTSA, U.S., (2018). Traffic Safety Facts 2017.
Otte, D. (2002). Possibilities and limitation for protective measures for injury reduction of vulnerable road users. International Journal of Crashworthiness, 7, 441-461
Plainis, S., Murray, I.J. and Pallikaris, I.G., (2006). Road traffic casualties: understanding the night-time death toll. Injury Prevention, 12(2), pp.125-138.
Polders, E., Daniels, S., Hermans, E., Brijs, T. and Wets, G., 2015. Crash patterns at signalized intersections. Transportation research record, 2514(1), pp.105-116.
Pucher, J., Korattyswaropam, N., Mittal, N. and Ittyerah, N., (2005). Urban transport crisis in India. Transport Policy, 12(3), pp.185-198.
Retting, R. A., Wiliams, A. W., Preusser, D. F., & Weinstein, H. B. (1995). Classifying urban crashes for countermeasure development. Accident Analysis and Prevention, 27(3), 283-294.
Ribbens, H. (2003). Strategies to promote the safety of vulnerable road users in developing and emerging countries: South African experience. Transportation Research Record, 1846, 26-30
Road Safety Audit Manual (2004). Government of Uganda. Ministry of Works, Housing and Communications. Entebbe. PO Box 10.
Saha, S., Basu, S. and Nasipuri, M., (2013). Development of a Stop-Line Violation Detection System for Indian Vehicles. In Handbook of Research on Computational Intelligence for Engineering, Science, and Business (pp. 200-227). IGI Global.
Saha, S., Basu, S., Nasipuri, M. and Basu, D.K., (2010). Development of an automated red light violation detection system (RLVDS) for Indian vehicles. arXiv preprint arXiv:1003.6052.
Schattler, K.L. and Datta, T.K., 2004. Driver behavior characteristics at urban signalized intersections. Transportation research record, 1862(1), pp.17-23.
Schoon, J.G. and Hounsell, N.B., 2006. Access and mobility design policy for disabled pedestrians at road crossings: exploration of issues. Transportation research record, 1956(1), pp.76-85.
Secretariat, C.A.R.E.C., (2018). CAREC Road Safety Engineering Manual 2: Road Safety Audit.
Soames Job, R. F. (2012). Advantages and disadvantages of reactive (black spot) and proactive (road rating) approaches to road safety engineering treatments: When should each
be used? Australasian Road Safety Research, Policing and Education, 1–9.
Tiwari, G., Jain, D. and Rao, K.R., (2016). Impact of public transport and non-motorized transport infrastructure on travel mode shares, energy, emissions and safety: Case of Indian cities. Transportation research part D: transport and environment, 44, pp.277-291.
van der Horst, R., (1991). Video analysis of road user behaviour at intersections. In Near miss reporting as a safety tool (pp. 93-109). Butterworth-Heinemann.
Verma, A., Velumurugan, S., Chakrabarty, N. and Srinivas, S., (2011). Recommendations for driver licensing and traffic law enforcement in India aiming to improve road safety. Current Science, pp.1373-1385.
Wang, X., Abdel-Aty, M. and Brady, P.A., (2006). Crash estimation at signalized intersections: significant factors and temporal effect. Transportation Research Record, 1953(1), pp.10-20.
WHO, ed. (2018). Global Status Report on Road Safety 2018 (official report). World Health Organisation (WHO), Geneva. ISBN 978-92-4-156568-4. Retrieved 5 May 2019.
Wong, S. C., Sze, N. N., & Li, Y. C. (2007). Contributory factors to traffic crashes at signalized intersections in Hong Kong. Accident Analysis & Prevention, 39(6), 1107-1113.
Wu, Z., Sharma, A., Mannering, F.L. and Wang, S., 2013. Safety impacts of signal-warning flashers and speed control at high-speed signalized intersections. Accident Analysis & Prevention, 54, pp.90-98.
Zhang, L. and Prevedouros, P.D., 2003. Signalized intersection level of service incorporating safety risk. Transportation Research Record, 1852(1), pp.77-86.