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A review of effectiveness of speed reducing devices with focus on developing countries

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ABSTRACT: The heterogeneous traffic conditions in India is making things more complicated in urban areas. Traffic accidents in India are increasing at an alarming rate due to the rapid growth of motor vehicles in the past few years. The number of accidents drop only at sites where speed restriction techniques are implemented for different vehicle categories, especially at locations like approaches to level crossings, negotiation points at sharp curves, approaches towards intersections, accident prone locations, residential streets, streets closures at schools and hospitals etc. In developing countries like India, speed humps and speed bumps are primarily used as speed reducing devices both in urban and rural areas, which is not the case in developed countries where speed bumps are used only on private grounds and speed humps are mainly used on residential roads in urban areas. The effectiveness of speed reducing devices are reviewed in this study to elaborate best practices and recognise gaps in research to set up few scopes for future research in this area. The literature review revealed that most of the speed humps in developing countries have faulty geometrical dimensions when compared to codal provisions leading to problems among road users. Though traditionally speed humps are known to reduce speed and increase safety, they too have disadvantages like, increase in travel time, increase in vehicle operating cost, decrease in capacity of roads and undesirable experience to drivers and passengers. Rumble strips on safety on rural roads on either side of a pedestrian crosswalks is an option to be further explored. Finally, in view of the Indian road conditions, it is observed that Indian guidelines concerning design of speed humps IRC 99-2018 are not compatible with best practice. Therefore, there is an imperial need to frame new guidelines for different type of roads.

KEYWORDS: Speed reducing devices, Speed humps, Speed bumps, Traffic calming, Intelligent Traffic Systems, Accident, Traffic safety, Vulnerable Road Users

1. INTRODUCTION[1]

Road crashes are the ninth leading cause of death among all age groups around the world. About 1.3 million people lose their lives on road due to road accidents each year, with an added 20–50 million people anguishing serious injuries with lasting negative health effects. More than 50% of all road crash related deaths are identified as vulnerable road users, e.g. cyclists, pedestrians, and motorcyclists (WHO, 2016). In a developing country like India, around 150 000 people lose their lives due to road accidents every year (MORTH, 2018). According to MORTH 2018, over speeding contributed more than 70 percent of road accidents and around 67 percent of road accident deaths from 2010-17. Among the numerous factors, speeding is considered to be a serious and hazardous factor for safety of road users since speeding upsurges the forces directed against them in a collision and diminishes the reaction time of drivers as well as pedestrians (Yeo et al., 2020).

Traffic engineers practice a diversity of approaches in their efforts to regulate speeds of vehicles and to prevent crashes triggered by over-speeding. One of the most common methods employed for the same is construction of speed humps and other types of speed reducing devices (Lav et al.,2018). Providing speed humps are the most common type of traffic calming devices due to their less price and easy installation (Abdel-Wahed, and Hashim, 2017). In developing economies like India, a high proportion of the population use non-motorized vehicles like bicycle routinely (Patel, and Vasudevan, 2016). According to Patel and Vasudevan (2016), speed humps are placed mainly to increase safety of non-motorized vehicles and pedestrians by providing discomfort, through shocks and vibrations, to the passengers and drivers in speeding cars. Watts (1973) concluded that humps should be longer than the wheelbase of a passanger car.

IRC 99-2018 guidelines are used in India for designing speed reducing devices like speed humps and speed bumps. According to the guidelines, the major difference between a speed hump and speed bump in India is that speed bumps are ready to be installed and precasted that are directly fixed on the road or nailed to the pavement whereas speed humps are direct vertical protrusions on road surface of several varieties, like with a rounded upper surface or with a flat level upper surface. Speed bumps are restricted to low speed zones like parking areas and are suggested for very less populated residential zones whereas the speed humps are provided on residential roads and also on urban arterials and other category of roads even with high traffic volumes. The distinction between both can be seen from Figure 1 (a) and (b) below. In this review, the design of speed humps are crucial since those are universally used for actual purpose of reducing speed. According to the provisions in the code, the minimum chord length should be 3 m and the height of the speed hump 0.1 m respectively, and the maximum reduction in speed should be up to 20 kmph for vehicles to cross the speed hump. Due to faulty design of speed humps, the road user approaching towards the speed hump has to decrease the speed instantly creating sudden deceleration of the leading vehicle which may results in a rear-end collision. According to Abdel-Wahed, and Hashim, (2017) the presence of faulty speed humps negatively affect the roadway level-of-service, since they increase delay due to increased travel times.

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Figure 1 (a) Speed bumps in India

Figure 1 (b) Typical speed humps in India

The operational effectiveness of speed humps play a significant role in terms of traffic safety. Moreover, in developing economies like India, where heterogeneous, mixed, traffic is predominant, so that different traffic categories are mixed, there is not so much research conducted on the effect of speed humps on road users in terms of speed reduction and safety. All though in European countries like Norway, an ideally designed residential street should have a hump every 100 meters. In India, this is not in practice due to heterogeneous vehicle composition and dense traffic. Although it is known that speed humps are given to enhance safety among road users, however in developing countries like India where lane discipline is not followed, improper positioning and design of speed humps is causing hindrances for smooth traffic flow. Further, in European countries, speed reducing devices are not used on aterials in cities and on rural roads. In Sweden speed limit is always set to 30 km/h on streets with speed reducing devices and in Finland to 30 or 40 km/h. In US fourway stop are often used at intersections in residential areas. At higher speeds counter measures like rumble strips and speed cameras are used in Europe and US, and Intelligent Traffic Systems, ITS are opening up new effective measures (Leden, 2021). The maximum speed limit on streets with speed reducing devices in India seems to be too high compared to developing countries. In India on National Highways, the maximum speed limit is around 80 kmph for cars and 65 kmph for two-wheelers which is less compared to developed nations. In such a traffic situation, providing speed humps regularly will only cause more discomfort and delay to road users. Therefore, in the present study, a review of the literature has been conducted to have a comprehensive idea about the recent techniques adapted to evaluate the operational effectiveness of the speed hump characteristics, mainly focusing on developing countries. Various literature have been presented in the subsequent section and a detailed summary with critical review has been presented.

2. EVALUATIONS OF SPEED REDUCING DEVICES

The literature review of speed reducing devices have been presented precisely with inclusion of new techniques like Intelligent Traffic Systems, ITS and simulation. Mostly, older studies concern with traffic calming measures while newer studies concern ITS and review of a few articles of simulation models have been included to explore new facts of speed reducing devices and their functions. Therefore, the present review has been divided into three parts as follows.

(a) Traffic Calming
(b) Intelligent Traffic Systems (ITS)
(c) Simulation and Modelling

Traffic calming

Elvik (2001) presented a detailed analysis of thirty three studies that evaluated the effects on road safety of area-wide urban traffic calming. The meta-analysis showed that area-wide urban traffic calming measures reduced the average number of injuries in accidents by fifteen percent. Elvik et al. (2009) summarized the effects of 128 road safety measures in the handbook of road safety measures an extensive summarizing of key research and a key work in road safety to a large extent based on meta analysis. They have related the road safety measures with respect to patterns of land use, pattern of roads, road furniture, traffic control devices, motor vehicles, police enforcement, and road user behaviors. They have mainly focused on the improvement of road safety.

Dixon et al. (1997) illustrated the motorists' driving behavior as they move towards a pedestrian crossing in the presence and absence of speed humps. They hypothesized that risk perceived by road users normally could be affected by the installation of tactile road stimuli like speed humps. They also employed an experimental design to quantify the reaction of motorists. Their results showed a robust relationship between driver behavior and the presence or absence of speed humps. They also opined that female drivers undertake more precautionary maneuvers than males.

Dixon, and Jacko (1998) studied the effect of speed humps on motorists' behavior at pedestrian crossings by observing 208 motorists at Florida International University in Miami, Florida. They employed the experimental design to identify the motorists' reactions. Like the previous literature, their findings also concluded that female drivers take more preventive actions than male counterparts.

Towliat (2001) concentrated on the safety of the pedestrian and cyclists at crossing facilities on arterials on urban roads and to implement these measures on large scale by creating a 30 km/h milieu at the studied crossings. Towliat included effects on road users´ safety, experieces, mobility and the environmental aspects. He tested three principles lower speed by physical measures, improved information by variable message signs with respect to lower speed, no priority, and improved and relevant information to obtain the desired results. The researcher identified that the interaction of both motorists and non-motorized road users is the biggest challenge for traffic safety. He also discussed the advantages and disadvantages of speed reduction by physical means, traffic safety has improved and noise pollution has drastically decreased, but exhaust levels have increased somewhat.

Pau (2002) attempted a qualitative and quantitative approach to study drivers' and riders´ behavior by observing more than twenty five thousand cars and motorcycles in Italy. He observed that apart from abrupt slow down, deceleration and acceleration before and after speed hump, the drivers tend to perform various other traffic maneuvers to minimize the uneasiness faced when travelling towards speed humps. Results disclosed that improper installation of speed humps induced up to 50% car drivers and 85% motorcyclists to avoid the undulation in order to decrease the level of discomfort.

Bassani et al. (2011) evaluated the effectiveness of trapezoidal speed humps, with an averege spacing of 147 m in reducing the operating speed of vehicles in the city of Turin (Italy). Several speed profiles were collected with different measuring systems including a laser gun, a digital video camera and an instrumental vehicle during two months. Trapezoidal speed humps have a height of 7 cm, flat top of 120 cm, and the two ramps of 40 cm long. They developed a relationship which linked operating speed measured at the midpoint between two consecutive humps to the hump spacing and lane width using multiple linear analysis. They reported that the p-value of the independent variable of the model are less than 0.05, indicating that the control variables affect significantly the operating speed in the middle point between two consecutive humps.12 humps were included in the study. Average speed and the decrease in 85^{th} percentile speed was observed 30 m before the start of 1^{st}speed hump, between two consecutive humps and 30 m after the end of 12th speed hump. The various speed profiles at the midpoint between two humps, while crossing the humps, and before & after the humps were analyzed. They observed that trapezoidal speed humps considerably reduced speed for the given stretch of road which enhance the safety of vulnerable road users. It was observed that trapezoidal speed humps (TSH) cause a significant reduction of speed for extended stretches of the infrastructure. This clearly has a benefit in terms of road safety and security (perceived level of safety) in a very sensitive area where there is a non-negligible presence of vulnerable road users (i.e. pedestrians and bicyclists).

Antic et al. (2013) focused on the influences of speed hump heights with respect to the vehicle speed before and after the implementation.. They compared the 50th and 85th percentile speed. They found that speed humps in the range of 5 to 7 cm height should be provided in localities where vulnerable road users are highly endangered and speed humps of 3 cm height should be provided at less endangered locations. They also found that there had been no remarkable differences between vehicle speed ranging from the 1 day to 1 month after the implementation.

Berthod (2011) studied in detail traffic calming measures using speed humps and speed cushions in Canada. He opined that with an array of traffic calming measures available for use, either individually or in combination, with a planned implementation procedure, it is possible to design locality specific traffic calming measures that would be best adapted to each situation. He also mentioned about fact sheets that are being published by Quebec ministry of transportation for general public to understand the types of traffic calming measures, their requirement and objectives. He has showcased the adopted geometric design of speed humps which is working efficiently in a city. The study would be quite helpful for guideline makers for other developing countries since the article serve as a fundamental research on the same.

Bekheet (2014) evaluated pavement performances in Alexandria Governorate in Egypt. The researcher identified the patterns of pavement failure and also investigated the impact of illegal speed humps. He found that raveling was the most common distress found on the road surfaces. The researcher observed that inappropriate designed speed humps remarkably influenced the pavement condition.

Afrin et al. (2015) focused on the demerits (low visibility conditions, like when there is snow, fog, rain or at night) caused by the excessive use of speed humps and the behavior of the driver at faulty speed humps in Dhaka, Bangladesh. They suggested use of real time monitoring of driver behavior increase safety and concluded that due to faulty infrastructure, speed humps were often unnecessarily provided on national highways, which distracted drivers so they often lost control of the vehicle leading to serious accidents. They concluded that the principal causes for the accidents was the deficiency in the warning methodology when approaching speed humps. A methodology for collecting data to dynamically detect and generate warnings to approaching vehicle drivers was developed. According to authors, the driver are to get an audio warning message about the next speed humps if they are located within 100 m distance from the vehicle's current location.

Patel and Vasudevan (2016) focused on the influence of speed humps on bicycle riders. Vehicle speed, geometry of the hump, and riding posture were correlated to comprehend their distress levels. Vibrations by accelerometers installed on the handlebar, neck, and seat of the rider were recorded. They observed that bicyclists experienced more uneasiness compared to motorcyclists.

Abdel-Wahed and Hashim (2017) evaluated the impact of speed humps on pavement condition and calculated a pavement condition index (PCI). The researcher measured the characteristics of the speed humps, i.e. width, height, and distance from the preceding hump of each speed hump. They concluded that the conditions of the pavement can play a major role for speed humps characteristics.

Arbogast et al. (2018) examined pedestrian safety through speed humps and community engagement. They observed that there was a 37.5% reduction in pedestrian accidents after implementing speed humps. They suggested installation of speed humps near schools and hospitals to enhance pedestrian safety.

Lav et al. (2018) determined speed hump design that performs efficiently when drivers tried to reduce the speed of vehicles to safe levels. They have created a model to simulate the interchange between a car wheel and a speed hump. Their simulation study found that the optimal dimensions of a speed bump are 5.0 cm in width and 2.8 cm in height. This simulation to real field ratio taken by the authors is 1:6 which if calculated gives the optimal design of a speed hump as 30 cm in width and 16.8 cm in height at real conditions. Since, the study is completely based on simulation and scaling of the data to real field, more studies are required to select the optimal width and height of the speed humps for safe traffic movement.

Al-Obaedi (2019) evaluated the effectiveness of speed humps through real traffic data at a median U-turn. The researcher used video recordings for the data collection. He observed that the speed humps caused a remarkable reduction in average time spent for turning traffic. He developed regression models to evaluate merging time spent based on opposing flow rates.

Gedik et al. (2019) investigated the effect of parabolic speed hump profiles. They carried out the simulation tests to evaluate root-mean-square values and concluded that the vehicle speed and height of the speed humps are the primary factors influencing comfort and safety. They concluded that parabolic speed humps are not effective for vehicle speeds above 25 km/h.

Abdulmawjoud et al. (2020) investigated three types of traffic calming measures located in Mosul city. They have collected the data like vehicle headways, travel times, delays, and driving speed at different locations. They observed that speed reduction for various types of speed humps ranged between to 60 to 71%.

Yeo et al. (2020) analyzed pedestrians crash near speed humps. They observed that there is a reduction of speed starting thirty meters before a speed hump and less pedestrian crashes occurred near speed humps. This speed reduction effect is substantial on both local and major roads: 18.4% and 24.0% reduction in speeds, respectively Since the speed reduction is more pronounced on major roads, and are more susceptible to crashes, therefore they concluded that speed humps are an effective measure to improve pedestrian safety mainly on major roads. According to the authors, there are six classes of roadway in South Korea: expressway, major arterial, minor arterial, collector, local and alley. According to them, minor arterials and collectors are designated as major roads and local and alley are designated as local roads. The authors did their study on major and local roads since expressways and major arterials do not have speed humps.

Barbosa et al. (2000) evaluated the impact of traffic calming measures on vehicles. A case study was conducted by them in the City of York (UK) focusing on speed reducing devices such as speed humps, speed cushions and chicanes. They developed an empirical speed profile model by employing multiple linear regression (MLR) techniques based on data collected at three sites. They observed that greater variation of results was reflected in speed humps followed by chicanes and cushions.

Gonzalo-Orden et al. (2018) compared few traffic calming measures to assess the repeatability of their efficiency in various locality. They have compared the speed reduction and evaluated the efficiency of traffic calming measures. They primarily focused on the safety aspects of pedestrians and cyclists. They compared the efficiency of different traffic calming devices with respect to the geometric characteristics and placements on the road. The researchers have observed that traffic calming measures in terms of raised crosswalks, lane narrowing, radar speed camera signs were the most effective types.

Gitelman et. al. (2017) observed changes in road-user behaviours following the installation of raised pedestrian crosswalks combined with preceding speed humps, on urban arterials. Their study included eight sites comprising sixteen pedestrian crosswalks. Two settings of raised crosswalks were applied at the study sites: a 15 cm high trapezoidal hump combined with 8-10 cm high circular humps, and a 10-12 cm high trapezoidal hump combined with 6-8 cm high circular humps. They found that elevated crosswalks were able to reduce the speed of the vehicles. Also, they observed that pedestrian safety has improved. They concluded that elevated crosswalks with preceding speed humps can be used for the improvement of pedestrian safety on busy urban arterials.

Leden et al. (2018) made a meta analysis of traffic calming measures at crosswalks for children based on published studies from three sites in Sweden and three in Israel. They concluded that the speed of the vehicle should be less than 20 kmph at the places where the children aged 7 to 12 years crossing the road without the accompanied by an adult. To achieve this they suggested that speed reduction devices should be placed at least 10 m ahead of an elevated crosswalk if the speed limit is 30 kmph or lower and 15 to 20 m ahead if the speed limit is within 50 kmph. According to Swedish guidelines "Speed reducing devices in residential areas" (report No 4 from the Swedish Road Safety Office, Borlänge,1982, in Leden et al., 2018) (the English version uploaded to research gate books) "Humps should be longer than the wheel base of a passenger car, regardless of the shape of the hump". Otherwise the discomfort diminishes with increasing speed. The shape of the hump has to be adjusted to the type of traffic on the road. The design and shape has to be exact right. Maximum speed has to be adequate and signed appropriately. According to authors, speed cushions are to be used on streets with bus traffic instead of speed humps. The guidelines according to figure 3 and 4 should be adopted for constructing speed cushions.

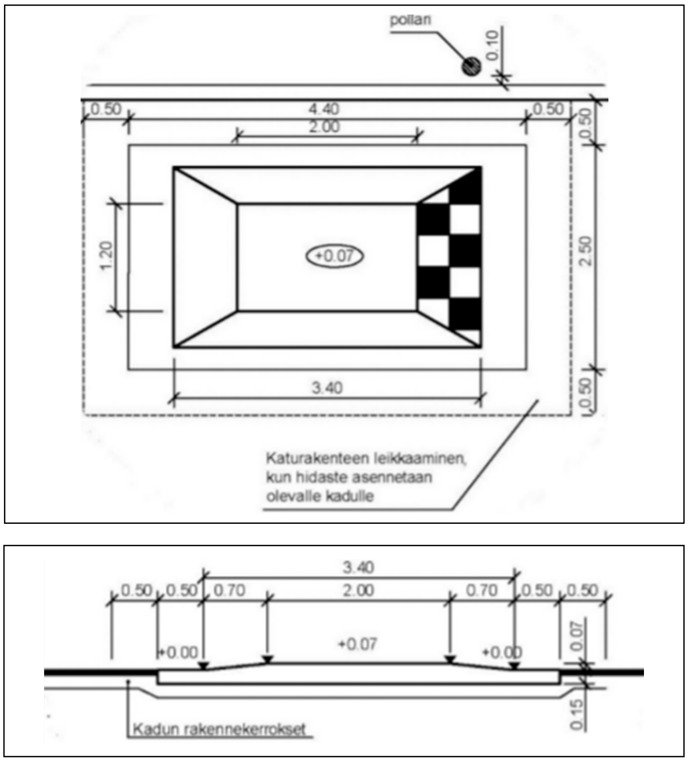

Figure 3 and 4: Finnish speed cushion design detail, and Profile (in driving direction) of Finnish recommendation. (Leden et al., 2018).

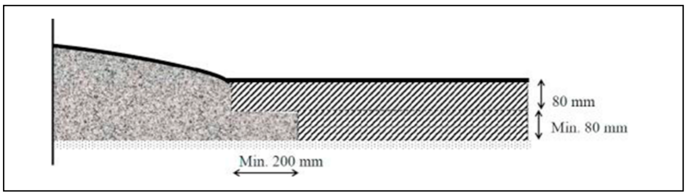

Figure 5. Transition between prefabricated speed cushion and asphalt surface to avoid cracks. (Leden et al., 2018).

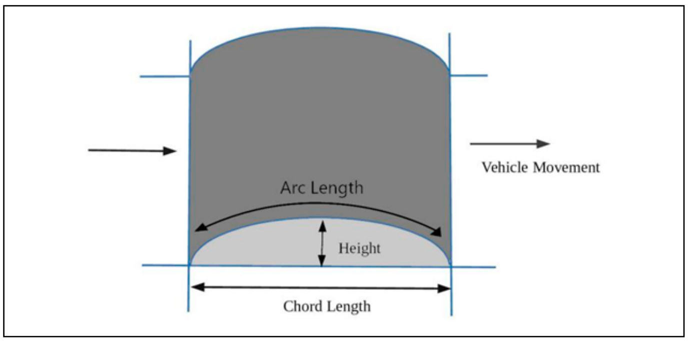

Figure 6 Technical specifications of a speed hump

IRC 99-2018 (Indian Roads Congress code 99-2018) provides the guidelines for design of speed reducing devices in India. According to the code, the guidelines for design of circular speed humps mentions that the minimum speed at which a vehicle should be able to approach a speed hump is 20 kmph with moderate inconvenience to the driver and passengers and no damage to the vehicle. The minimum chord length should be 3 m and the height of the speed hump 0.1 m as shown in figure 6.

Desired speed	Chord length	Bus speed during passage
20 km/h	3.0 m	5 km/h
25 km/h	3.5 m	10 km/h
30 km/h	4.0 m	15 km/h
35 km/h	5.0 m	20 km/h
40 km/h	6.5 m	25 km/h
45 km/h	8.0 m	30 km/h
50 km/h	9.5 m	35 km/h

Table 1. Recommended chord length for circular humps (Maximum rise:10 cm) according to IRC 99-2018

According to Mohanty et al. (2021) due to a faulty designed speed reducing device vehicles decelerate rapidly, which cause more wear and tears in the vehicle along with a higher probability of rear-end collision mainly at higher traffic volumes. Vehicles decelerating fast may lead to skidding or slipping of the vehicle or increase the probability of rear-end collisions. Faulty speed humps not only increase fuel consumption and the overall increase vehicle operating and maintenance costs but also endanger traffic safety. Moreover in India, MORTH (ministry of road transport and highways) specify that on National Highways (NHs) speed humps should not be provided to ensure mobility without any hindrance and without any serious hazards and accidents to the fast-moving vehicle. Furthermore, false designed speed reducing devices cause delay and significant discomfort to vehicle occupants, damage vehicles and add fuel consumption due to acceleration and deceleration. On urban roads, correct designed speed humps should be provided in order to safely regulate the traffic. For locations, where speed control on National Highways are unavoidable like approaches to sharp curves on the level crossing, congested or accident prone locations, etc. MORTH has suggested providing properly designed rumble strips instead of speed humps, which is in accordance with practice in developed countries.

Liu et al. (2011) assessed the effect of transverse rumble strips on safety on rural roads. The study area for speed measurement consisted of two hundred meters road sections on either side of a pedestrian crosswalks. From the t-tests results, they evaluated that transverse rumble strips are effective in reducing road accidents in the vicinity of pedestrian crosswalks on rural roads. Crash data before and after the installation of transverse rumble strips at pedestrian crosswalks suggested that transverse rumble strips almost lowered the crash frequency by about 25% at pedestrian crosswalks. They identified that, the road where the speed limit is 60 km/h, the mean speed reduced by 9.2 km/h at pedestrian crosswalks. Similarly, for the speed limit of 80 km/h it reduced by 11.9 km/h at pedestrian crosswalks. They also studied the 85th percentile speed and observed that the 85th percentile speed was reduced by 9.1 km/h and 12.0 km/h on roads with a speed limit of 60 km/h and of 80 km/h respectively.

Intelligent traffic systems (ITS)

Now a days huge research has been conducted on inteligent traffic system (ITS). However the main scope of our review was speed reducing devices like speed humps, so this part of our review is kept short. Leden (2021) however gives a quite comprehensive summary focusing on the safety of cyclists on the urban network. Leden concludes that Intelligent Speed Adaptation, ISA, of cars would be the most efficient measure to provide a safe environment, if enough political support is available to implement the measure and ensure safe speeds. Recently, this seems to be the case in the European Union with suggestions to mandate ISA on new model cars starting in 2022. However this was not the case when the list of 23 ITS was drawn up. The five ITS systems, which were estimated to have highest potential to improve the safety of cyclists, are Blind Spot Detection (BSD), Bicycle to Vehicle communication (B2V), Intersection safety (INS), Pedestrian and Cyclist Detection System + Emergency Braking (PCDS+EBR) and Vulnerable Road User Beacon System (VBS).

Varhelyi (1998) carried out a survey with almost 1000 Swedish drivers, where he also approached ITS measures and analyzed traffic safety with respect to various influencing parameters such as road surface visibility and weather conditions, roadway geometric features, intersections and zebra crossings and concluded that speed reduction strategies have to be adopted at a zebra crossing. Speed reduction device should be placed at a distance of 10 m from the zebra crossing (see also Leden et al, 2018). Varhelyi also suggested that the speed has to be limited via an in-vehicle equipment and estimated that the reduction in accidents would be around 20% - 40%.

Simulation and modelling

The following reviewed studies on speed reducing devices included simulation and modelling techniques.

Yu et al. (2011) developed a VISSIM module for simulation of highway traffic operations in the vicinity of speed humps. They collected the vehicle speed data at fifteen locations in the vicinity of speed humps. The researchers have used a genetic algorithm for calibration and validation of the Reduced Speed Area (RSA) module. They concluded that on multilane highways the calibrated VISSIM module provided significant results for speed reduction.

Garcia et al. (2011) evaluated the effect of speed reducing devices on their capacity and operating performance using traffic micro simulation VISSIM 5.1. They have calculated average delay and obtained the capacity of the road. They found that the desired speed decision areas were 25 m around the speed reducing devices, upstreams and downstreams. They have also established the level of service depending on the capacity of the road and calibrated and validated driver behavior. However, they did not consider factors like zebra crossings.

Bennett, and Dunn (1995) examined the monitored driver deceleration behavior on a freeway in New Zealand. For the study, the researchers had placed a series of axle detectors over a 500 m interval and the speeds were recorded using a data logger. They have taken the speeds of the same vehicle at different stations along the road for over 1200 vehicles. They observed that the vehicles decelerated over the same distance irrespective of the initial speed. They concluded that the deceleration rate was proportional to the initial speed. They predicted the deceleration behavior of vehicles as a function of approach speed and cumulative time. They observed that drivers on open/rural roads have much higher deceleration rates than urban drivers.

Delhomme et al. (2000) evaluated road safety campaigns under the Transport RDT Program funded by the European Commission. They have collected numerous samples of campaign evaluations and designed the evaluation by using a detailed coding scheme. They further focused on the effects of campaigns on reducing accidents and future road safety campaigns. They used meta-analysis on 72 results out of which 52 were before and during the studies and 20 were before-and-after studies. They observed that the average reductions in accident numbers were 8.5% during the campaign period, and 14.8% after the campaigns but both the results were statistically significant.

Akçelik and Besley (2001) described types of deceleration and acceleration models. The researchers emphasized for calibration of a good model considering specific traffic facilities, various vehicle types, types of road, different levels of traffic demand, and an extensive range of initial and final speeds.

Wang et al. (2004) evaluated the general acceleration behavior of current types of passenger vehicles. They studied the acceleration behaviors of both straight and turning movements as well as the impact of speed limits on rates of acceleration.

Capri et al. (2012) focused on pedestrian safety. They evaluated the probability of collision between vehicle and pedestrian crossing the road using a mathematical model, VISSIM 5.0 micro simulation model. For a quantitative evaluation of the effectiveness of speed control, they have studied vehicle/pedestrian interactions in both the absence and presence of several traffic calming measures. Depending on the position of the objects and the speed of the vehicles, they have evaluated whether the vehicle is able to avoid or not avoid a collision. They compared the traffic calming measures with respect to the probability of collision with a pedestrian, depending of the average spacing, and the average speed at the pedestrian crossing by considering the traffic volume.

Jain et al. (2012) proposed an early warning system that used an application employed on smartphones to alert the driver well in advance when the vehicle is moving towards a speed hump based on surrounding vehicle speeds. They also developed an application that constantly monitored the accelerometer on smartphone to detect beforehand unknown speed-humps. They suggested that further improvement is required for accuracy while using multiple smartphones.

Domenichini et al. (2019) assessed the interaction between driving behavior and psychological characteristics on the effectiveness of different types of speed reducing devices at pedestrian crossings based on the traffic survey consisting of 58 road users. The researcher categorized the 58 survey participants into three groups, i.e. careful, worried and at risk. From the preliminary observation they observed that, all three groups changed their driving behavior, although they reacted differently. They observed that the driving behavior was changing with respect to the driving experience, distance covered by the drivers, anxiety level of drivers, road configuration, and vehicle composition. They categorized the driving behavior on the basis of psychological condition of drivers, driving environment, and human factors. They observed that careful drivers were having low anxiety levels and exhibited more homogeneous driving behavior. They also observed that worried drivers were involved in more mistakes as compared to careful drivers. On the other hand, risky drivers were having a lower level of anxiety compared to worried drivers, but they used to deliberately violate the safe driving norms.

3. SUMMARY AND DISCUSSION

The effectiveness of speed humps can be analyzed through its design, performance, impacts, operation and effect on safety for road users, including pedestrians, drivers as well as vehicles. The various effectiveness measures discussed here show that speed reduction, geometric features of the speed humps, vehicle and driver characteristics are the most commonly parameters used by the researchers. Simulation with VISSIM software, vehicle headways consideration, parameters associated with pavement type and conditions, pedestrian and vehicle crash modeling, including acceleration and deceleration phenomena have also been explored.

Most of the researchers (Bennett, and Dunn, 1995; Dixon et al.,1997; Dixon and Jacko,1998;Pau,2002; Wang et al.,2004; Galante et al.,2010; Afrin et al.,2015; Domenichini et al.,2019) have evaluated the effectiveness of speed humps characteristics with respect to drivers behavior. However apart from a few authors (Dixon et al.,1997; Jacko,1998; Domenichini et al.,2019) none of them have included pedestrian crossings in their studies. After going through all the above mentioned research approaches the study by Domenichini et al. (2019) seems to be the most reliable as it has considered the real-time information for road users including driving behavior and psychological characteristics which were useful to measure the effectiveness of speed humps. Nevertheless, they could have included information like types of speed reducing devices and pavement performance. The study conducted by Pau and Angius (2001), and Bassani et al. (2011) evaluated the effectiveness of speed humps in reducing the operating speed of vehicles. The study conducted by Bekheet (2014), Abdel-Wahed, and Hashim (2017) evaluated the impact of speed humps on the performance of pavement condition, whereas Patel and Vasudevan (2016) focused on the effects of speed humps on bicycle riders.

Barbosa et al. (2000), Antic et al. (2013), Abdulmawjoud et al. (2020), and Yeo et al. (2020) investigated the influence of traffic calming measures on the vehicle speed profile. The study conducted by Antic et al. (2013) was an interesting study as it covered the geometrical features related to the speed humps. The studies conducted by researchers (Akçelik and Besley, 2001; Garcia et al. 2011; Jain et al. 2012) are mostly based on traffic simulation and modeling and can be found in the simulation and modeling section under evaluation of speed reducing devices. Akçelik and Besley (2001) described the acceleration and deceleration models. Garcia et al. (2011) used traffic micro simulation VISSIM 5.1 to estimate the operational performance of the speed reducing devices, whereas Jain et al. (2012) used an early warning system that used a smartphone based application to alert the driver in advance when the vehicle is approaching a speed hump.

Some of the articles (Pau, 2002; Jain et al., 2012; Antic et al., 2013) have presented extreme slow down in speed by vehicles while crossing over the speed humps. They also suggested that speed humps to be acting as a traffic flow constraint results in an unnecessary decrease of speed leading to an undesirable traffic flow scenario. However, except Antic et al. (2013) few studies have been found that tries to explore the causes behind this sudden decrease of traffic flow at speed humps. According to Antic et al. (2013), speed humps of 5 and 7 cm height should be provided at locations where vulnerable road users are at high risk and speed bumps of 3 cm height should be provided at less endangered locations. Further, the safety aspect has also not been considered in many studies.

Elvik, (2001); Johansson et al.,2011; Liu et al.,2011; Capri et al.,2012; Arbogast et al.,2018; Gedik et al.,2019) examined the impacts of speed reducing devices on traffic safety. Out of them, Johansson et al. (2011), Capri et al. (2012) and Arbogast et al. (2018) focused on pedestrian safety. However, only Gedik et al. (2019) investigated the effect of speed humps on riding comfort and driving safety under variable vehicle speeds, which can be considered as one of the most accurate approaches and the result was found to be satisfactory with respect to the effectiveness of the speed humps. Similarly, discussing about the type of speed humps, Leden et al. (2018) reported that circular speed humps are to be used only on residential roads with no bus traffic which is in accordance with the recommended Finnish design (Figure 3 and 4). However, in developing countries no such constraints have been provided in the guidelines. Delhomme et al. (2000) and Elvik (2000) primarily focused on the road safety aspects with the help of meta-analysis. The results of meta-analysis were statistically significant and can be considered as one of the most accurate approaches and the result was found to be satisfactory. Similarly, interesting examples of doctoral thesis studying effects of safety measures for pedestrians and cyclists at crossings on Arterial roads are Towliat (2001) and Várhelyi (1998) who studied dynamic speed adaption based on information technology. However, even though Intelligent Speed Adaption ISA is the most efficient measure to adapt speeds to achieve safe interactions, unfortunately this measure is not yet accepted even in developed countries of Europe and US (Leden, 2021). According to Leden (2021), Intelligent Speed Adaptation, ISA, of cars would be the most efficient measure to provide a safe environment, if enough political support is available to implement the measure and ensure safe speeds. Recently, this seems to be the case in the European Union with suggestions to mandate ISA on new model cars starting in 2022.

In European countries like Norway an ideally designed residential street should have a hump every 100 meters and and speed limit set to 30 km/h. At sites with bus traffic like in Helsinki in Finland the maximum speed limit is 40 km/h and speed cushion are to be used (according to Figure 3, 4 and 5). But in India, this is not practice due to the huge population and heterogeneous vehicle composition. That's why IRC 99-2018 recommends a lower speed hump compared to European countries. Although it is known that speed humps are given to enhance safety among road users, however in developing countries like India where lane discipline is not followed, improper speed humps and speed humps in general is causing hindrances for smooth traffic flow. In order to mitigate this problem, even the apex court (Supreme Court) of India in 2017 laid down guidelines that all the speed humps on urban arterials are to be replaced by rumble strips to decrease car jerkiness along with lesser speed reduction. In European countries, the speed limit on arterials are 50 kmph or even higher if there is no vulnerable road users, but in Indian condition, the average speed of vehicles is less than 40 kmph on urban arterials due to traffic congestion. In such a traffic situation, providing speed humps regularly will only cause more discomfort and delay to road users. Further, it should also be mentioned that if the guidelines would have been followed while constructing speed humps and other speed reducing devices, traffic flow and mobility would not have faced so much problems in developing countries. Faulty design and construction at incorrect locations has made the mobility situation unacceptable. Mohanty et al. (2021) studied 12 speed reducing devices and not a single one complied to guidelines provided in IRC 99-2018. That's the reason this review discusses the shortcomings of speed humps and other speed reducing devices mainly with regards to the developing Asian countries like India.

4. CONCLUSIONS

The operational effectiveness of speed reducing devices have become increasingly problematic in many countries. In developing countries, like India, the heterogeneous traffic conditions are complicated. The impact of implementation of faulty designed and constructed speed reducing devices affect the health, environment, economy, and traffic safety. It is a major concern for researchers to address the issues and suggest comprehensive and new ideas to confront these challenges.

The present review is based on the operational efficiency of speed reducing devices with respect to the road users characteristics and traffic safety. From various literatures, the researchers suggest that although there has been plenty of research in the field of traffic calming measures, still many countries have not been able to solve the associated problems with traffic calming. Most researchers have adopted driver behavior and vehicle speed as a common method to study the effectiveness of traffic calming measures in terms of delays, pavement performance index, rate of acceleration and deceleration, and vulnerable road users' safety. Many researchers have not included the effect on non motorized vehicle in the evaluation of calming measures. Faulty design of the traffic calming measures and improper location of road markings and signs are the main problems for the operational effectiveness of speed reducing devices and related traffic safety in countries like India. Few researchers have also discussed the performances of the pavement condition e.g. how to avoid cracks in the asphalt surface.

In order to design traffic calming measures like speed reducing devices and rumble strips, the guidelines IRC 99:2018 (Indian Roads Congress code) is used in India. According to IRC 99:2018 the minimum speed at which the vehicle should be able to approach towards the speed hump is 20 kmph. Likewise, the minimum chord length should be 3 m and the height of the speed hump 0.1 m for smooth movement of vehicles. However, these values are mere guidelines and not rules under law which leads to wrong design of the speed humps, leading to sudden speed reductions and wear and tear of vehicles. Although traffic calming measures like speed humps are provided to enhance traffic safety, however, faulty geometrical design and improper positioning of speed humps along with no or wrong positioning of road signs are the main responsible factors, which adversely affect the operational effectiveness of the speed humps, leading to unnecessary delays and increased chance of rear end collisions among vehicles. Speed humps, inherently are not disadvantageous, however, the above mentioned factors make the speed humps a questionable traffic calming device for smooth flow of traffic. According to Swedish guidelines (Leden et al., 1982), humps should be longer than the wheel base of a passenger car, regardless of the shape of the hump. Further, on streets with heavy traffic speed cushions has to be used. However, it is tough to design optimal speed reducing devices in developing countries since lane discipline is not observed here. On streets with heavy traffic speed cushions has to be recommended.

Since the design and operational characteristics of traffic calming measures are a widespread problem, many scopes for future studies open up in this field of research. The previous studies are primarily focused on driver and vehicle behavior, which are practically good and economical, however, are to some extent getting old and outdated. New approaches like simulation by VISSIM software, vehicle headways consideration, parameters associated with pavement type and conditions, pedestrian and vehicle crash modeling, acceleration and deceleration phenomena are complementary alternatives as they are accurate and user friendly. In developing countries like India, ITS techniques are usually not available mainly due to the high cost. Better traffic calming counter measures and comprehensive traffic safety management system should be incorporated. It is urgent to explore more into the area of traffic safety and traffic calming to develop new measures not affecting the driving and riding quality so much. Our review provides an insight to how the research has undertaken its path in the area of speed reducing devices and how it can be dealt with in the future to provide a better way to manage the design and management of these devices to discover alternate ways to calm down traffic on roadways for enhancement of traffic safety.

Finally, in view of the Indian road conditions, the current status concerning the implementation and management of speed reducing devices in India are reviewed extensively. It is revealed that Indian guidelines concerning design of speed humps IRC 99-2018 are not compatible with best practice. It seems urgent to get on board expertise to launch new guidelines valid for different type of roads. Circular speed humps are to be used only on residential roads with no bus traffic. On main urban roads with bus traffic speed cushions are to be recommended and on rural roads rumble strips, speed cameras and other types of police enforcement.

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