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Original research article

Empirical and Simulation Based Safety Evaluation of Forced Gap Behaviour at an Urban Unsignalised Intersection under Mixed Traffic

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ABSTRACT

Unsignalised intersections present significant safety risks due to uncontrolled conflicts between vehicles on major and minor roads, especially during right-turn manoeuvres. This study examines the impact of speed bumps in reducing forced gap behaviour at an unsignalised intersection using a variety of surrogate safety indicators. Forced gap behaviour occurs when vehicles on a major road reduce their speed in response to aggressive right-turn manoeuvres from minor roads. Data was collected using a videographic technique at a T-intersection in the Thiruvananthapuram district of Kerala, India. The study analyses changes in the forced gap behaviour of vehicles at unsignalised intersections using various surrogate safety indicators, including Post Encroachment Time (PET), Occupancy Time at the conflict area (OT) and Speed Differential Percentage (SDP). The study found that when no speed bump was present, PET values ranging from 0 to -5 seconds accounted for 36.57% of the total sample size. However, this percentage increased to 55.72% when a speed bump was implemented indicating a reduced forced gap behaviour. A VISSIM simulation-based analysis indicated that the presence of higher proportion of motorised two-wheelers increases the forced gap behaviour (PET $\in$ [-5, 0]) even under the presence of a speed bump.

Keywords: Forced gap behaviour; Post encroachment time; Speed differential percentage; Simulation; Unsignalised intersection

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1. Introduction

Many developing countries, including India, have heterogeneous traffic, and the majority of intersections are unsignalised, resulting in unsafe vehicular movements. Rising trends in vehicle ownership and inherent safety issues have led to an increase in accidents at unsignalised intersections, underscoring the urgent need to prioritise safety at these sites. A traffic conflict can be defined as ”an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain the same” by Chin et al. (1997) [1]. To analyse traffic conflicts, Surrogate Safety Measures (SSMs) are useful and life-saving tools that efficiently evaluate vehicle and pedestrian conflicts on the road, and also assist in choosing appropriate preventive measures to lower the probability of collisions at unsignalised intersections (Bonela and Kadali, 2022), [2]. Researchers have developed several proximal indicators to assess the safety of traffic facilities using the traffic conflict technique, which measures how close a scenario is to a potential accident. Common indicators include time to collision (TTC), post-encroachment time (PET), and deceleration rate, among others. TTC and PET are the most extensively used, as they use specified threshold values established by past research to distinguish between major conflicts and reasonably safe interactions. PET, as a time-based indicator, primarily reflects collision likelihood. However, in nations like India, where traffic indiscipline is common, PET alone may not correctly reflect safety circumstances. Drivers on major roadways frequently use evasive manoeuvres to avoid high-speed crossing conflicts, resulting in serious accidents. As a result, this study combines a speed component with PET to detect significant crossing conflicts and demonstrates a link between observed conflicts and related crash types.

2. Literature Review

According to Goyani et al. (2021) [3], SSMs are used to assess road safety by substituting alternative indicators that represent safety for crash data. The definitions, benefits, and drawbacks of several surrogate safety measures that are employed in the field to evaluate safety issues for both cars and pedestrians were reported by Klinberg and Ratick (2017) [4]. Among the various SSMs used, Post Encroachment Time (PET) and Time-To-Collision (TTC) are the most commonly used surrogate safety indicators worldwide for safety evaluation. PET is the most commonly used indicator in studies on the safety of right-turning vehicles within an unsignalised intersection conflict area. A conflict area is a location on the road where the intersecting roads merge, or cross, creating a potential point of collision. PET is the time elapsed between the end of the offending vehicle’s encroachment and the time the conflicting vehicle arrives at the potential collision point. Offending vehicles (Goyani et al., 2021) [3] are those that make right turns from minor roads onto major roads. Conflicting vehicles are those major road vehicles that perform straight movement along the major road. Previous studies, such as those by Advani et al (2020) [5], have quantified forced gap behaviour based on percentage speed reduction. Researchers such as Paul and Gosh (2018) and Paul and Gosh (2017) [6, 7] have applied the critical speed formula (PET×2×a×f) in their studies. However, only limited studies have analysed the forced gap behavioural changes using

the surrogate safety measure and simulation process. Paul and Gosh (2017) [6] have analysed the variation in the positive and negative PET values for various intersections using box plots. Fulwadiya et al (2025) [8] have done a simulation-based analysis on autonomous vehicles as a solution to various traffic externalities, including safety concerns such as crashes. The present study evaluates the safety aspects of forced gap behaviour under varying traffic conditions using empirically based field data and also by using the simulated data from simulation software, such as PTV VISSIM.

The present study mainly focuses on analysing the forced gap behaviour of vehicle-to-vehicle interaction at an unsignalised intersection using various surrogate safety indicators, including PET, Occupancy Time (OT), and Speed Differential Percentage (SDP). Furthermore, this study explores the variation in forced gap behaviour under two different scenarios - with and without the presence of speed bumps. Based on the literature review, it is observed that only limited studies are reported on assessing the effect of forced gap behaviour on safety, especially in situations with and without speed bumps.

3. Objectives

A comprehensive literature review was conducted to identify the current state of the art and research gaps about forced gap behaviour, with a specific focus on the impact of speed bumps. Considering the research gaps, the following objectives are formulated:

- To estimate and compare the safety impact of speed bumps on the forced gap behaviour using field-observed surrogate safety indicators.
- To perform simulation-based analysis to capture the variations in forced gap behaviour for a wide range of traffic scenarios.

4. Methodology

Cross-traffic movements in developing countries like India frequently happen in unsignalised intersections, especially when vehicles on the major road go at high speeds. To better understand the behaviour of conflicting vehicles, whether involved in a forced gap or not, the current study monitored their speeds before and after the conflict area. Data collection was done using a videographic technique at a T-intersection on Thiruvananthapuram-Kanyakumari Highway, Killipalam, in Thiruvananthapuram district in Kerala, India. The field data extraction involves the extraction of traffic volume, PET, conflicting speed, and occupancy time using a video data extraction software (Data From Sky (DFS)). VISSIM-based simulation analysis is also performed to determine the influence of speed bumps on forced gap behaviour for a wide range of traffic volume and composition. Fig. 1 below illustrates the methodology flow chart for the study.

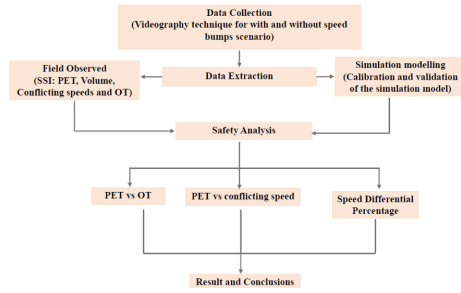


Fig. 1. Methodology flow chart.

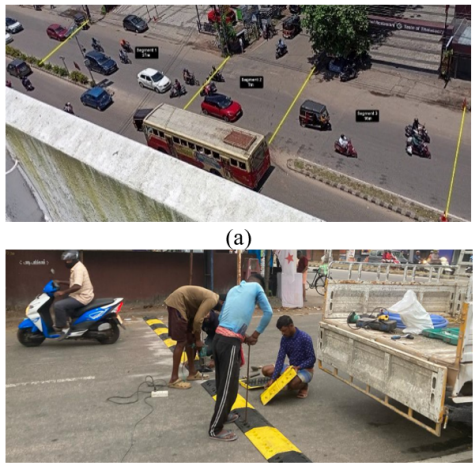
4.1 Data collection

At an unsignalised T-intersection designated as a black spot (MoRTH, 2015)

in the Thiruvananthapuram district of Kerala, India, data collection was conducted using a videography technique. Data were collected for each scenario: with and without a speed bump on the minor road, over the duration of two hours. The study was conducted under daytime conditions during peak period on a sunny weekday.

The speed bump was installed 8m from the stop line, in accordance with IRC:99 (2018) regulations.

Fig. 2 illustrates images of the study site, including speed bump installations. To conduct a safety analysis of forced gap behaviour, the study area was extended beyond the conflict area to include sections both before and after it.



(a)

(b)

Fig. 2. Images of the study site at the CIT road intersection (a) Intersection view with segments, (b) Speed bump installation.

5. Safety Analysis of Forced Gap Behaviour

Safety analysis of the intersection was conducted, using multiple SSMs for both scenarios, with and without a speed bump. To investigate the effect of speed bumps on forced gap behaviour, analysis was conducted using field-observed data. The vehicles identified in the study area are classified into four different categories: LMV (Light Motor Vehicle), MTW (Motorised Two Wheeler), MThW (Motorised Three Wheeler), and HMV (Heavy Motor Vehicle). The study mainly focuses on analysing the forced gap behaviour of vehicle-to-vehicle interaction at an unsignalised intersection using various surrogate safety indicators, including PET, Occupancy Time (OT), and Speed Differential Percentage (SDP).

5.1 Analysis based on PET values

A method for identifying critical conflicts using PET is applied, where lower PET values, either negative or positive, indicate higher risk. Higher PET values, either negative or positive, indicate lower risk, as described by [9]. A positive PET happens when the offending vehicle completes the manoeuvre, and then the conflicting vehicle arrives at the potential collision point. A negative PET occurs when the conflicting vehicle completes the manoeuvre first, and then the offending vehicle reaches the potential collision point. This study examines the variation in forced gap behaviour using positive and negative PET values. Table 1 below presents the total number of conflicts recorded for scenarios with and without speed bumps, including both positive and negative PET values.

In the absence of a speed bump, 36.57% of the 1050 conflicts showed negative PET values. However, the placement of a speed bump increased the proportion of conflicts for negative PET values to 55.72%. The increase in the percentage of negative PET values suggests a reduction in forced gap behaviour among minor road vehicles.

The Kolmogorov-Smirnov test (K-S

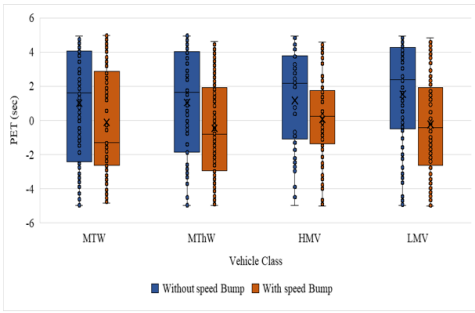


Fig. 3. Box plot of PET for different vehicle categories for the scenarios without and with the speed bump scenario.

test) was conducted to test the distribution of PET values for scenarios: with and without speed bumps. The results show that the *p*-value for the scenarios with speed bumps (*p*-values 0.086 > 0.05) and without speed bumps (*p*-values 0.085 > 0.05) follows a normal distribution. ANOVA was used to compare PET data for scenarios with and without speed bumps, providing insight into changes in forced gap behaviour. Based on the results of ANOVA, it is observed that between-group variation i.e., 1.24, is much lower than within-group variation i.e., 6919.42, which suggests that the within-group variations of PET values are significantly different. Fig. 3 shows a box plot comparing PET ranges of +5 to -5 seconds across all vehicle classifications, for a scenario without and with a speed bump. The mean values are higher without a speed bump than with a speed bump across all vehicle categories. The MThW vehicle category exhibits the greatest reduction in mean PET value, dropping from 1.05 seconds without speed bumps to -0.1 seconds with speed bumps, resulting in a 1-second difference due to the scenario changes.

Table 1. Box plot of PET for different vehicle categories for the scenarios without and with the speed bump scenario.

Scenarios	Total No of Conflicts	Percentage of Negative PET (%)	Percentage of Positive PET (%)
Without Speed Bump	1050	36.57	63.43
With Speed Bump	770	55.72	44.28

5.2 Analysis based on vehicle occupancy time

Occupancy time refers to the time it takes for the offending vehicle to make a right turn along the major road within the conflict area. Conflicts involving offending vehicles in forced entry are classified by vehicle type and displayed against ranges of PET values for various scenarios, including those with and without a speed bump. Fig. 4 illustrates the variation in average occupancy time across different PET ranges.

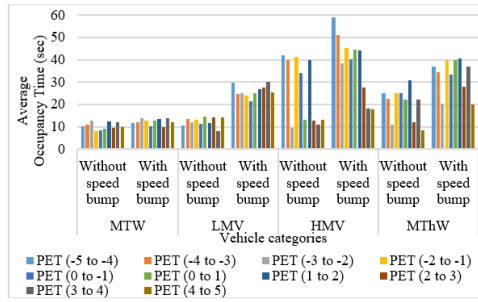


Fig. 4. Variation in occupancy time for offending vehicles across all PET ranges.

All vehicle categories involved in forced entry had occupancy times ranging from 8 seconds to 60 seconds. Notably, HMV demonstrated the largest shift in occupancy time after the installation of a speed bump on the minor road. Without a speed bump, HMV exhibited an average occupancy time of 13.28 seconds within the PET range of 0 to 1 seconds, which increased to 44.66 seconds with the presence of a speed bump. The largest shift in

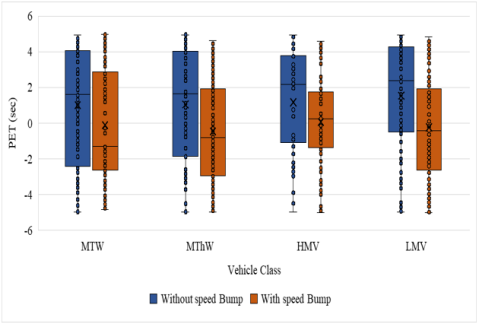


Fig. 5. Occupancy time for different vehicle categories for the scenarios without and with the speed bump.

average occupancy time occurs for HMV primarily due to the installation of speed bumps on the minor road, which reduced forced entries within the 0 to 1 second PET range. Fig. 5 displays the box plot comparison of occupancy time for different vehicle categories under both scenarios, with and without speed bumps. As shown, the average occupancy time increases across all vehicle categories, from the scenario without speed bumps to the scenario with speed bumps. Among all vehicle categories, MTW demonstrated the largest average occupancy time differential of 8.56 seconds, where the average occupancy times for the scenarios without and with speed bumps are 9.26 seconds and 17.82 seconds, respectively.

5.3 Analysis based on vehicle speed change along the major road

Vehicle speeds were recorded over a 50 m section of the major road to examine speed changes before and after conflict areas. The data pertaining to PET values ranging from 0 to ±5 s were used for analysis. The variation in conflicting speed for each one-second PET interval is shown in Figs. 6-7. When MTW is both conflicting and offending, the highest increase in speed within the conflict area was observed in the PET range of -3 to -2 seconds, where the speeds for the scenario without a speed bump and with a speed bump were 10 kmph and 20.67 kmph, respectively. Similarly, when LMV is both conflicting and offending, the highest increase in speed within the conflict area was observed in the PET range of 2 to 3 seconds, where the speed was 20 km/h in the scenario without a speed bump and 31.56 km/h in the scenario with a speed bump. The results obtained from Figs. 6-7 indicate that the decrease in the forced entry of offending vehicles into the major road is the primary reason for the increase in speeds of conflicting vehicles within the conflict area. This trend was observed across all vehicle categories when comparing scenarios with and without a speed bump.

Average speeds for all vehicle types were measured over various PET value ranges to analyse safety aspects and compare them with and without speed bump scenarios. The PET range of -3 to -2 seconds showed the highest increase in speed, rising from 12.5 km/h in the absence of a speed bump to 24.9 km/h in its presence. Fig. 8 shows the speed variation along the major road for each PET range and for various vehicle categories. In the scenario without speed bumps, the speeds of major road vehicles along the conflict area were lower due to the higher forced gap behaviour exhibited by the offending vehicles. For the scenario with speed bumps, the speeds of major road vehicles along the conflict area were higher due to the lower forced gap behaviour exhibited by the offending vehicles.

5.4 Analysis based on Speed Differential Percentage (SDP)

The Speed Differential Percentage (SDP) is defined as the average percentage change in speed over 3m intervals across

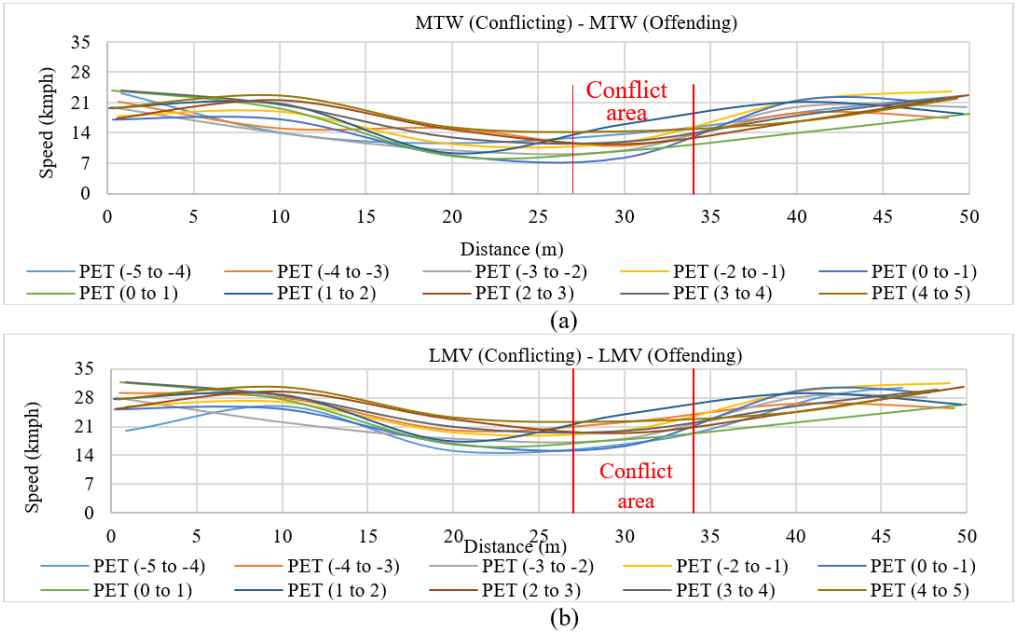


Fig. 6. Variation of speed along a major road without a speed bump when (a) MTW as the conflicting vehicle and MTW as the offending vehicle (b) LMV as the conflicting vehicle and LMV as the offending vehicle.

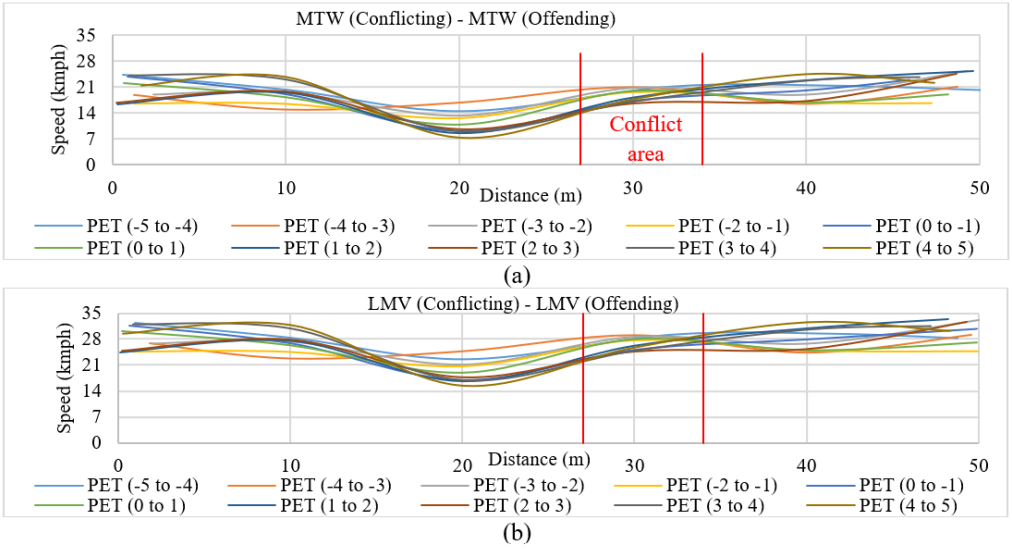


Fig. 7. Average variation of speed along major roads across all PET ranges for (a) without a speed bump and (b) with a speed bump scenario.

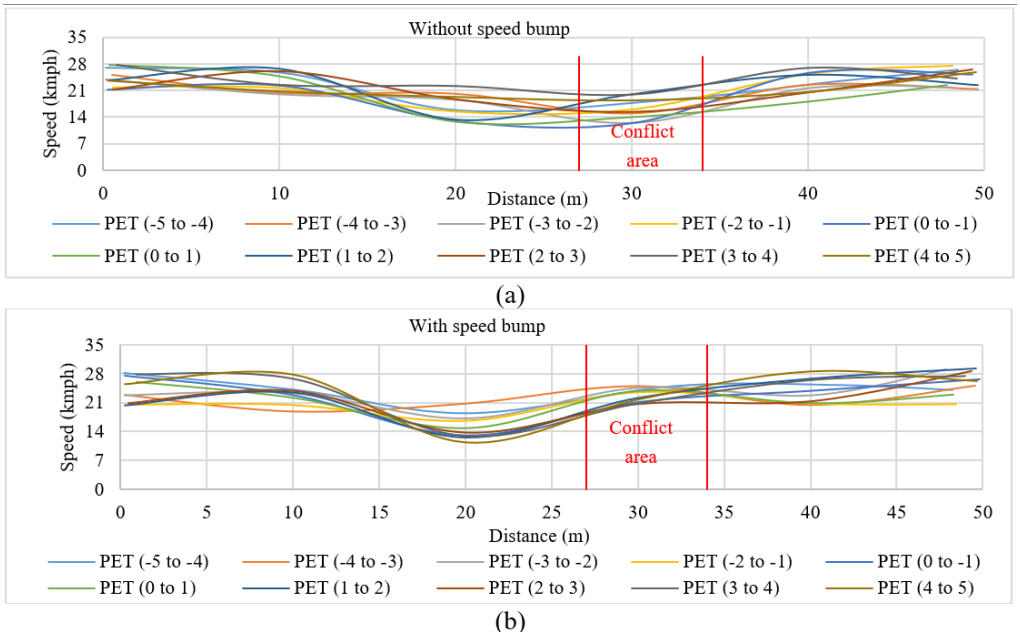


Fig. 8. Variation of speed along a major road for with a speed bump when (a) MTW as conflicting and MTW as offending (b) LMV as conflicting and LMV as offending.

a 21m segment just ahead of the conflict area, estimated across PET ranges (+5 to -5 sec). Fig. 9 depicts the change in SDP across all PET ranges in scenarios with and without a speed bump. The PET range of -4 to -3 seconds exhibited the highest variation in SDP, with 13.58% in the scenario without a speed bump and 26.75% with a speed bump, resulting in a net difference of 13.17%. The comparison of SDP values under the scenario without a speed bump with the scenario in which a speed bump is installed revealed that SDP increases due to the presence of a speed bump. This is due to the fact that the observed speed difference along vehicle trajectories was lower due to higher forced gap behaviour in the absence of a speed bump, whereas the presence of a speed bump resulted in higher speed difference along vehicle trajectories due to lower forced gap behaviour.

5.4.1 Percentage distribution of high, medium, and low-risk conflicts

Previous research on PET threshold detection, based on the association between collisions and conflicts, was conducted at signalised intersections in developed countries, where homogeneous traffic conditions generally prevail. In developing nations like India, where traffic is heterogeneous, using PET thresholds (Shangguan et al., 2024) [10] may be misleading due to changing vehicle characteristics and a lack of dependable thresholds for unsignalised intersections. For the analysis, the observed traffic volume was divided into three levels: Volume 1 (65 to 293 veh/hr), Volume 2 (295 to 439 veh/hr), and Volume 3 (444 to 731 veh/hr). A two-tailed t-test was then carried out, and the results showed that the differences between the volume ranges were statistically significant at the 95% confidence level. To further explore the safety effects at each volume level, the percentage distri-

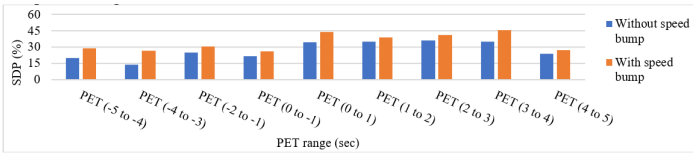


Fig. 9. SDP variation across all PET ranges for with and without speed bump scenarios.

bution of low, medium, and high-risk conflicts was evaluated for scenarios with and without speed bumps on minor roads. The classification of conflict risk was based on three surrogate safety indicators: PET, conflicting speed, and SDP.

5.4.2 Identification of risk of conflicts using PET

To validate the proposed threshold identification approach, a qualitative assessment was carried out to find the most appropriate PET threshold. (Shangguan et al., 2024) have classified conflict risk levels as follows: high-risk (PET range of 0 to ±1.5 seconds), medium-risk (PET range of ±1.5 to ±2.5 seconds), and low-risk (PET range of ±2.5 to ±5 seconds). Fig. 10 shows the percentage of low, medium and high-risk conflicts in scenarios without and with speed bumps on the minor road and volume ranges. Table 3 shows the number and percentage of low, medium, and high-risk conflicts when compared with total conflicts without and with speed bumps on the minor road and volume ranges. Table 2 shows that speed bumps on minor roads had a lower percentage of high-risk conflicts than those without speed bumps, and this was consistent across all three volume levels. This is because speed bumps help in reducing the forced gap behaviour of the offending vehicle.

5.4.3 Identification of risk of conflicts using conflicting speed

A box plot analysis was carried out to classify the conflicts based on their average conflicting speeds into low, medium, and high-risk categories. The average conflicting speed for each conflict was calculated, and the conflicts from both scenarios, with and without a speed bump, were considered together. The resulting box plot is presented in Fig. 11. Based on the quartile ranges of conflicting speeds, three speed ranges were identified: 12–20 km/h for low-risk conflicts, 20–50 km/h for medium-risk conflicts, and 50–60 km/h for high-risk conflicts. The conflicts identified within the upper quartile range speeds were categorised as high risk, while those in the intermediate quartile range speeds represented medium-risk conflicts. The conflicts observed with conflicting speeds at lower quartile range represented low risk conflicts. Using these three speed ranges, the conflicts were grouped into low, medium, and high-risk categories, and their respective percentages were calculated. Fig. 12 presents the percentage distribution of conflicts in each risk category based on conflicting speed. The number of conflicts and their corresponding percentages for both scenarios are given in Table 3. The results show that, at all three traffic volume levels, the proportion of high-risk conflicts was lower when a speed bump was provided on the minor road in comparison with the case when no speed bump was present. This reduction in high-risk conflicts is related to the decrease in forced gap behaviour caused by the presence of the speed bump.

It is seen from Table 3 that across all three volume levels, the percentage of high-

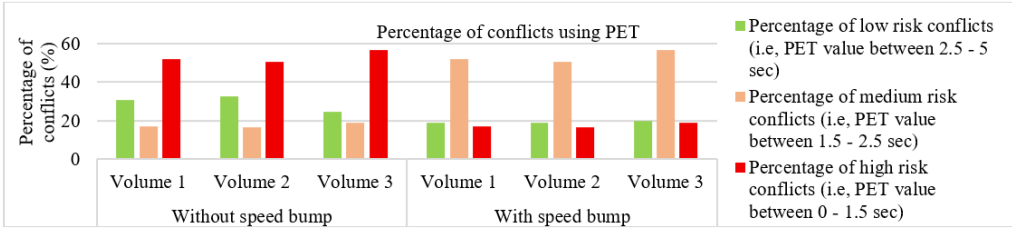


Fig. 10. Percentage Conflict based on PET across scenarios.

Table 2. Number and percentage of conflicts based on PET across scenarios.

Scenarios	Volume levels	Total Number of observed conflicts	Number of low-risk conflicts using PET	Number of medium-risk conflicts using PET	Number of high-risk conflicts using PET
Without a speed bump	Volume 1	595	184 (30.91%)	103 (17.27%)	308 (51.81%)
	Volume 2	213	70 (32.70%)	36 (16.83%)	108 (50.48%)
	Volume 3	242	59 (24.56%)	46 (18.86%)	137 (56.58%)
With a speed bump	Volume 1	128	24 (19.08%)	66 (51.81%)	22 (17.27%)
	Volume 2	243	47 (19.19%)	123 (50.48%)	41 (16.83%)
	Volume 3	399	79 (19.84%)	226 (56.58%)	75 (18.86%)

Table 3. Number and percentage conflict based on conflicting speed across scenarios.

Scenarios	Volume levels	Total Number of observed conflicts	Number of low-risk conflicts using the conflicting speed	Number of medium-risk conflicts using the conflicting speed	Number of high-risk conflicts using the conflicting speed
Without a speed bump	Volume 1	595	195 (32.74%)	100 (16.82%)	300 (50.45%)
	Volume 2	213	81 (37.84%)	33 (15.54%)	99 (46.62%)
	Volume 3	242	79 (32.59%)	41 (16.85%)	122 (50.56%)
With a speed bump	Volume 1	128	36 (28.17%)	69 (53.87%)	23 (17.96%)
	Volume 2	243	83 (34.12%)	120 (49.41%)	40 (16.47%)
	Volume 3	399	126 (31.59%)	205 (51.31%)	68 (17.10%)

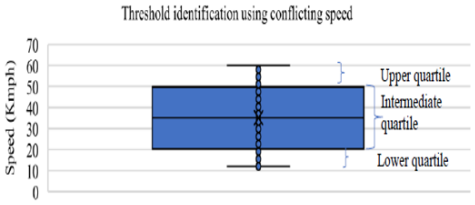


Fig. 11. Boxplot for conflicting speeds across scenarios.

risk conflicts is lower in scenarios with a speed bump on a minor road, when compared to the scenarios that do not have a speed bump on a minor road. This decrease can be attributed to the reduced forced gap behaviour under the presence of a speed bump. A Sankey chart depicting risk levels based on conflicting speeds and PET values has been plotted and is depicted in Fig. 13.

In Fig. 13, it was observed that PET alone across both scenarios with and without a speed bump did not represent the actual risk level. Out of the 600 conflicts classified as low risk based on PET, 99 were found to be high-risk conflicts when the conflicting speed was also considered. This shows that conflicting speed also plays an important role in determining the risk level, and therefore, PET alone may not be sufficient as a surrogate safety indicator.

5.4.4 Identification of risk of conflicts using SDP

The box plot is used to categorise SDP into three risk categories: low, medium, and high-SDP ranges based on quartile ranges across both scenarios (with and without the speed bump scenario). Fig. 14 below shows the box plot obtained for SDP values, which are used as the basis

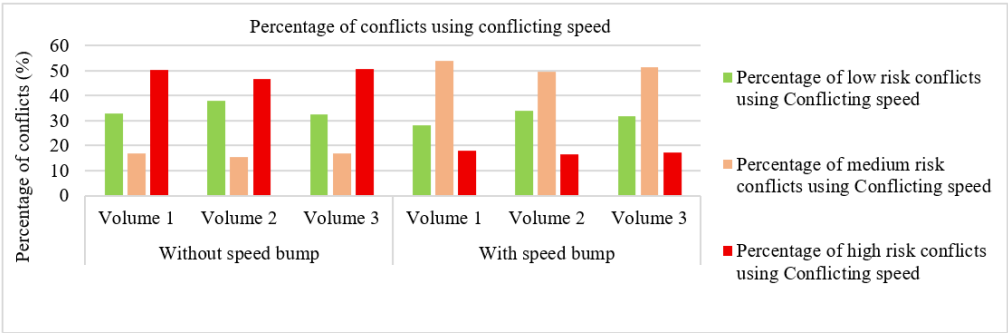


Fig. 12. Percentage conflict based on conflicting speed across scenarios.

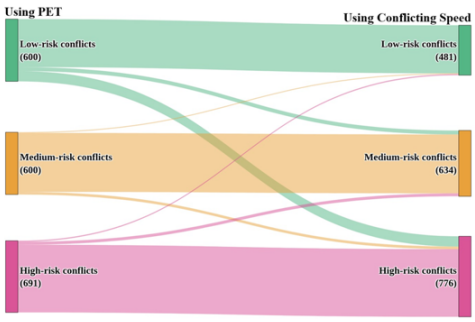


Fig. 13. Risk levels based on Conflicting Speed PET values.

for categorising risks into three levels: low, medium and high risk.

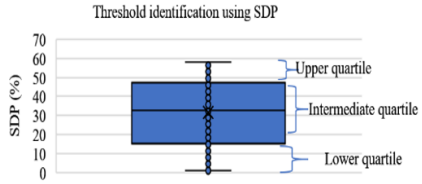


Fig. 14. Box plot for SDP across scenarios.

Fig. 14 shows conflict quartiles categorised into three ranges based on risk levels and SDP ranges resulting from forced gap by the offending vehicle: Lower quartile (1-16%), Intermediate quartile (16-48%), and Upper quartile (48-58%). After plotting the box plot and identifying three distinguished quartiles and obtaining three ranges of SDP linked with the risk levels, the percentage of low, medium and high-risk conflicts is plotted. Fig. 15 depicts the percentage of low, medium and high-risk conflicts based on SDP. Table 4 presents the number and percentage of low, medium, and high-risk conflicts in comparison to the total conflicts in both scenarios. Table 4 demonstrates that high-risk conflicts identified based on SDP thresholds are higher in scenarios without speed bumps on minor roads at all volume levels in comparison with the scenario where speed bumps on minor roads were absent.

6. Simulation Modelling

Simulation modelling technologies can precisely capture changes in traffic conditions and quantify their impact on forced gap behaviour and various surrogate safety indicators. In the present study, simulation modelling is used for studying the effect of speed bumps for diverse volumes and compositions. PTV VISSIM simulation software is used in this study to simulate such scenarios.

6.1 Calibration and validation of simulation model

Calibration is a process of adjusting the default calibration parameters to mirror observed data and observed site conditions to an acceptable level so as to satisfy

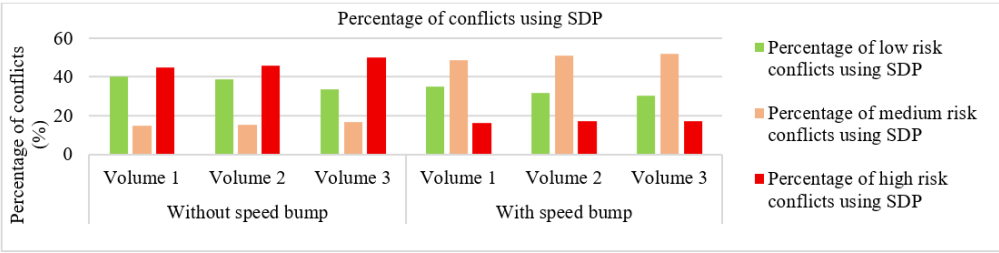


Fig. 15. Percentage conflict based on SDP across scenarios.

Table 4. Number and percentage of conflicts based on SDP across scenarios.

Scenarios	Volume levels	Total Number of observed conflicts	Number of low-risk conflicts using SDP	Number of medium-risk conflicts using SDP	Number of high-risk conflicts using SDP
Without a speed bump	Volume 1	595	239 (40.21%)	89 (14.95%)	267 (44.84%)
	Volume 2	213	83 (38.91%)	33 (15.27%)	98 (45.82%)
	Volume 3	242	81 (33.49%)	40 (16.63%)	121 (49.88%)
With a speed bump	Volume 1	128	45 (35.21%)	62 (48.59%)	21 (16.20%)
	Volume 2	243	77 (31.82%)	124 (51.14%)	41 (17.05%)
	Volume 3	399	122 (30.50%)	208 (52.13%)	69 (17.38%)

the applicability of the developed simulation model. Various simulation studies conducted by previous researchers were used as the basis for identifying and adjusting parameters that needed calibration ([11] and [12]). The simulation model was calibrated using field-observed travel and occupancy times for five random seeds through a trial-and-error approach. The calibrated model resulted in Mean Absolute Percentage Error (MAPE) values of 6% for travel time and 8% for occupancy time based on one hour field traffic video data. According to the Lewis scale [13], a MAPE value of 10% or less is generally considered highly accurate. The GEH statistic [14] is calculated by comparing the field-observed and simulated traffic volumes.

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}},$$

where: M is simulated traffic volume(veh/h), C is observed traffic volume (veh/h). The GEH value was obtained as 4.61. If the GEH is below 5, then it is considered indicative of a good fit, showing good agreement between the field and simulated traffic volumes [14]. The internal validation involved evaluating the calibrated model using a separate field-observed dataset to verify the model's acceptability to simulate various scenarios. Internal validation performed with second-hour video resulted in a MAPE value of 5.39%. The vehicle characteristics and calibrated parameter set given as input to VISSIM are listed in Table 5.

Table 5. Calibrated driving behaviour parameters.

Parameter	Default	Calibrated Parameters			
		MTW	MThW	LMV	HMV
Standstill distance (m)	1.50	0.47	1.00	1.20	2.00
Headway Time (sec)	0.50	0.43	1.20	0.81	0.94
Maximum Acceleration (m/s^2)	-	2.60	1.50	3.10	1.60
Maximum Deceleration (m/s^2)	-	-2.10	-1.20	-2.80	-1.60

6.2 Safety analysis based on simulation

Safety evaluation at different levels of traffic volume and varying composition at the study intersection for scenarios with-

out a speed bump and with a speed bump is conducted. The extraction of PET was done using the SSAM software. Table 6 presents the volume and composition values adopted for simulation in this study.

6.2.1 Simulation-based descriptive analysis

The changes in positive and negative PET values obtained from simulated data were analysed for both with and without speed bump scenarios. It was observed that with an increase in the composition of MTW, the percentage of PET values in the range of 0 to -5 seconds decreased, indicating an increase in forced gap behaviour even in the presence of a speed bump. Across all the volume ranges, the combination of Volume III and Composition III exhibited the highest proportion of positive conflicts at 78.25%, with the highest MTW composition for the scenario without a speed bump. The highest proportion of negative conflicts was noted as 69%, for the combination of Volume I and Composition I, with the highest LMV composition for the scenario with the speed bump. Table 7 summarises the simulated PET conflict variations over different volumes and compositions.

In the simulation-based analysis, SDP showed an increase with the implementation of a speed bump across different PET ranges, for various compositions and volume levels. Fig. 16 shows that an increase in volume and MTW composition resulted in a higher SDP variation. The highest SDP variation was observed at the PET range of 4 to 5 seconds for a combination of Volume III and Composition III. For this combination, the SDP for the scenarios without and with a speed bump was 9.09% and 69.23%, respectively.

6.3 Percentage distribution of high, medium, and low-risk conflicts based on simulation

To acquire deeper insights through simulation, the study examined the distribution of high, medium, and low-risk conflicts in two scenarios: with and without speed bumps on minor roads, with an emphasis on the percentage breakdown of each risk category. Within each scenario, the study identified high, medium, and low-risk conflicts using three surrogate safety indicators: (1) PET, (2) Conflicting speed, and (3) SDP.

6.3.1 Identification of risk of conflicts using PET based on simulation

Table 8 shows the number and percentage of low, medium, and high-risk conflicts when compared with total conflicts without and with speed bumps on the minor road for varying compositions and volume ranges.

Table 8 shows that the scenario with speed bumps on minor roads had a lower percentage of high-risk conflicts than those without speed bumps, and this was consistent across all three volume levels. This is because speed bumps help in reducing the forced gap behaviour of the offending vehicle. The largest percentage of conflicts is seen in high-risk conflicts for the scenario without speed bumps, which is 52.91% in Composition 3 with Volume 3, which also had a higher number of MTW vehicles. In contrast, under the scenario with speed bumps, it is observed that the highest percentage of risk conflicts is seen under medium-risk conflicts (52.55%) for Composition 3 with Volume 3 having a higher MTW proportion.

6.3.2 Identification of risk of conflicts using conflicting speed based on simulation

Similar to the field observations, a box plot was created to determine the per-

Table 6. Volume and Composition for Simulation Modelling.

Volume			Composition				
Volume	Major Road (veh/hr)	Minor Road (veh/hr)	Composition	MTW (%)	LMV (%)	MThW (%)	HMV (%)
I	1000	250	I	45	34	17	4
II	2000	500	II	55	24	17	4
III	3000	750	III	65	14	17	4

Table 7. Details of variation in positive and negative PET using simulation.

Volume	Composition	Without a speed bump (%)		With a speed bump (%)	
		Positive PET	Negative PET	Positive PET	Negative PET
Volume I	Composition I	56.23	43.77	31.00	69.00
Volume II		64.35	35.65	35.24	64.76
Volume III		76.25	23.75	39.35	60.65
Volume I	Composition II	54.23	45.77	41.95	58.05
Volume II		70.1	29.9	38.99	61.01
Volume III		72.12	27.88	41.43	58.57
Volume I	Composition III	50.23	49.77	41.28	58.72
Volume II		65.25	34.75	42.7	57.3
Volume III		78.25	21.75	44.56	55.44

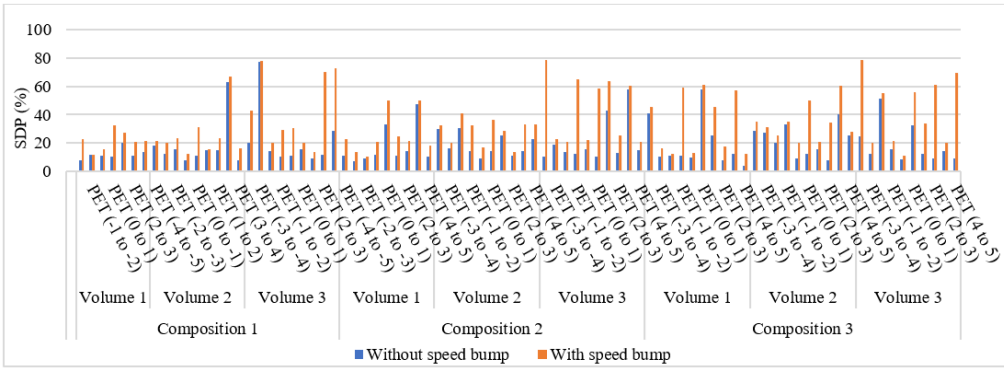


Fig. 16. Simulated SDP variation across PET ranges for the scenarios without and with the speed bump.

centages of high, medium, and low-risk conflicts. This involved calculating and combining the average conflicting speed for each conflict across both scenarios: with and without speed bumps. Fig. 16 below shows the boxplot obtained for three risk-conflicting speed categories.

Fig. 17 illustrates the quartiles of conflicts into three distinct speed ranges based on risk levels and conflicting speeds resulting from the offending vehicle's forced entry: Lower quartile (10-23 km/h), Intermediate quartile (23-52 km/h), and Upper quartile (52-65 km/h). Table 9 presents the number and percentage of low, medium, and high-risk conflicts in comparison to the total conflicts in both scenarios. Table 9 shows that intersections with speed bumps on minor roads had a lower percentage of high-risk conflicts than those without speed bumps, and this was consistent across all three volume levels. This is due to the fact that the presence of speed bumps on minor roads helps in the reduction of forced gap behaviour of offending vehicles.

Table 8. Number and Percentage of conflicts based on PET across scenarios based on simulation.

Scenario	Volume	Composition	Total Number of observed conflicts	Number of low-risk conflicts (i.e, PET value between ±2.5 and ±5 sec)	Number of medium-risk conflicts (i.e, PET value between ±1.5 and ±2.5 sec)	Number of high-risk conflicts (i.e, PET value between 0 and ±1.5 sec)
Without a speed bump	Volume 1	Composition 1	615	103 (16.68%)	205 (33.30%)	308 (50.03%)
	Volume 2		817	138 (16.87%)	266 (32.51%)	414 (50.62%)
	Volume 3		1050	178 (16.91%)	340 (32.37%)	533 (50.73%)
	Volume 1	Composition 2	566	92 (16.27%)	198 (34.91%)	276 (48.82%)
	Volume 2		1077	177 (16.47%)	368 (34.13%)	532 (49.40%)
	Volume 3		1128	189 (16.73%)	373 (33.06%)	566 (50.20%)
	Volume 1	Composition 3	513	88 (17.20%)	160 (31.20%)	265 (51.60%)
	Volume 2		1169	191 (16.33%)	405 (34.69%)	573 (48.99%)
	Volume 3		1320	233 (17.64%)	389 (29.45%)	698 (52.91%)
With a speed bump	Volume 1	Composition 1	605	103 (16.99%)	308 (50.96%)	194 (32.05%)
	Volume 2		1125	191 (17.00%)	574 (51.00%)	360 (32.00%)
	Volume 3		1257	217 (17.26%)	651 (51.79%)	389 (30.95%)
	Volume 1	Composition 2	546	93 (16.97%)	278 (50.92%)	175 (32.10%)
	Volume 2		889	148 (16.66%)	444 (49.99%)	296 (33.35%)
	Volume 3		1079	191 (17.70%)	573 (53.10%)	315 (29.19%)
	Volume 1	Composition 3	651	111 (17.04%)	333 (51.12%)	207 (31.84%)
	Volume 2		778	129 (16.58%)	387 (49.73%)	262 (33.69%)
	Volume 3		1005	176 (17.52%)	528 (52.55%)	301 (29.94%)

Table 9. Number and percentage of conflicts based on conflicting speed across scenarios using simulation.

Scenario	Volume	Composition	Total No. of observed conflicts	Number of low-risk conflicts based on conflicting speed	Number of medium-risk conflicts based on conflicting speed	Number of high-risk conflicts based on conflicting speed
Without speed bump	Volume 1	Composition 1	615	129 (21.02%)	121 (19.74%)	364 (59.23%)
	Volume 2		817	157 (19.22%)	165 (20.20%)	495 (60.59%)
	Volume 3		1050	289 (27.54%)	190 (18.12%)	571 (54.35%)
	Volume 1	Composition 2	566	156 (27.49%)	103 (18.13%)	308 (54.38%)
	Volume 2		1077	293 (27.16%)	196 (18.21%)	588 (54.63%)
	Volume 3		1128	224 (19.83%)	226 (20.04%)	678 (60.13%)
	Volume 1	Composition 3	513	140 (27.35%)	93 (18.16%)	280 (54.48%)
	Volume 2		1169	231 (19.80%)	234 (20.05%)	703 (60.15%)
	Volume 3		1320	321 (24.33%)	250 (18.92%)	749 (56.75%)
With speed bump	Volume 1	Composition 1	605	137 (22.57%)	351 (58.07%)	117 (19.36%)
	Volume 2		1125	261 (23.22%)	648 (57.58%)	216 (19.19%)
	Volume 3		1257	289 (23.00%)	726 (57.75%)	242 (19.25%)
	Volume 1	Composition 2	546	119 (21.88%)	320 (58.59%)	107 (19.53%)
	Volume 2		889	244 (27.44%)	484 (54.42%)	161 (18.14%)
	Volume 3		1079	265 (24.59%)	610 (56.56%)	203 (18.85%)
	Volume 1	Composition 3	651	156 (24.02%)	371 (56.99%)	124 (19.00%)
	Volume 2		778	198 (25.45%)	435 (55.91%)	145 (18.64%)
	Volume 3		1005	273 (27.15%)	549 (54.64%)	183 (18.21%)

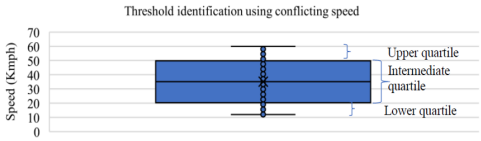


Fig. 17. Box plot for conflicting speed across scenarios based on simulation.

6.3.3 Identification of risk of conflicts using SDP based on simulation

Similar to the field observations, a box plot was created to determine the percentages of high, medium, and low-risk conflicts. This involved calculating and combining the average SDP for each conflict type across both scenarios: with and without speed bumps. Fig. 18 shows the boxplot obtained for three risk-SDP categories.

Fig. 18 shows conflict quartiles categorised into three ranges based on risk levels and SDP resulting from forced entries by the offending vehicles: Lower quartile (3-21%), Intermediate quartile (21-60%), and Upper quartile (60-80%). Table 10 below presents the number and percentage of low, medium, and high-risk conflicts observed under scenarios of with and without speed bumps for varying volumes and compositions. Table 10 demonstrates that the percentages of high-risk conflicts identified based on SDP thresholds are higher in scenarios without speed bumps at all volume levels.

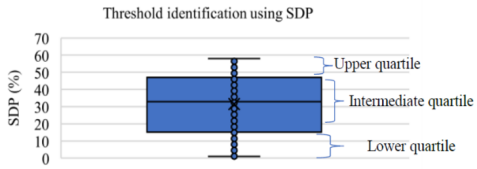


Fig. 18. Box plot for conflicting speed across scenarios based on simulation.

7. Results and Discussion

The present study quantified the impact of speed bumps and associated changes in forced gap behaviour at a three-legged unsignalised intersection in Thiruvananthapuram city in Kerala, India. Based on the field observations and simulation studies, this study concludes the following.

- After implementing speed bumps on minor roads, a reduction in forced gap behaviour among minor road vehicles was observed. The reduction was evident from the increase in the proportion of negative PET values from 36.57% to 55.72% when compared to the scenario without a speed bump. ANOVA showed much greater within-group variation (6919.42) than between-group variation (1.24), indicating significant variation in PET values.

- In the scenario without a speed bump, HMV exhibited an average occupancy time of 13.28 seconds within the PET range of 0 to 1 seconds, which increased to 44.66 seconds with the presence of a speed bump. The highest shift in average occupancy time for HMV can be attributed to the speed bump installation on the minor road, which effectively reduced forced entries.

- When MTW acted as both conflicting and offending vehicles, the highest speed increase on the major road was observed within the PET range of -3 to -2 seconds. The speeds were increased from 10 kmph to 20.67 kmph after the installation of the speed bump. This indicated that reduced forced entries of offending vehicles onto the major road increased the speed of major road vehicles.

- It is found that while comparing with and without speed bump scenarios, the highest SDP variation of 6.5% is observed at lower volume levels for the PET range of -1 to -2 seconds. This also indicated that the installation of a speed bump led to an increase in SDP values across all PET ranges due to a reduction in forced entries of minor road vehicles after the implementation of a speed bump.

- With the implementation of speed bumps on minor roads, it is observed that there was a lower percentage of high-risk conflicts based on surrogate safety indicators than those without

Table 10. Number and percentage of conflicts based on SDP across scenarios using simulation.

Scenario	Volume	Composition	Total Number of observed conflicts	Number of low-risk conflicts based on SDP	Number of medium-risk conflicts based on SDP	Number of high-risk conflicts based on SDP
Without a speed bump	Volume 1	Composition 1	615	167 (27.09%)	112 (18.23%)	336 (54.69%)
	Volume 2		817	226 (27.67%)	148 (18.08%)	443 (54.25%)
	Volume 3		1050	300 (28.60%)	187 (17.85%)	562 (53.55%)
	Volume 1	Composition 2	566	148 (26.20%)	104 (18.45%)	313 (55.35%)
	Volume 2		1077	296 (27.50%)	195 (18.12%)	586 (54.37%)
	Volume 3		1128	288 (25.55%)	210 (18.61%)	630 (55.84%)
	Volume 1	Composition 3	513	130 (25.27%)	96 (18.68%)	288 (56.05%)
	Volume 2		1169	321 (27.49%)	212 (18.13%)	636 (54.38%)
	Volume 3		1320	336 (25.43%)	246 (18.64%)	738 (55.93%)
With a speed bump	Volume 1	Composition 1	605	164 (27.09%)	331 (54.68%)	110 (18.23%)
	Volume 2		1125	307 (27.31%)	613 (54.52%)	204 (18.17%)
	Volume 3		1257	321 (25.56%)	702 (55.83%)	234 (18.61%)
	Volume 1	Composition 2	546	137 (25.04%)	307 (56.22%)	102 (18.74%)
	Volume 2		889	229 (25.70%)	495 (55.72%)	165 (18.57%)
	Volume 3		1079	295 (27.38%)	588 (54.46%)	196 (18.15%)
	Volume 1	Composition 3	651	184 (28.30%)	350 (53.78%)	117 (17.93%)
	Volume 2		778	200 (25.74%)	433 (55.69%)	144 (18.56%)
	Volume 3		1005	258 (25.72%)	560 (55.71%)	187 (18.57%)

speed bumps, and this was consistent across all three volume levels. The reason for this can be attributed to the reduction in the forced gap behaviour of the offending vehicles due to the presence of speed bumps.

- It is observed from simulation that at higher volume levels with higher MTW composition, the proportion of positive PET values was 78.25% for the scenario without a speed bump, indicating higher forced gap behaviour. The highest proportion of negative PET values was observed at 69% at lower volume levels, with higher LMV composition for the scenario with a speed bump, indicating reduced forced gap behaviour.

- It is observed from simulation that for the scenario without a speed bump, the percentage of high-risk conflicts is highest (56.05%) under low volume levels with higher MTW composition. This suggests that forced gap behaviour exhibited is higher under low volume levels when MTW proportion is higher. In contrast, for the scenario with speed bump, the percentage of medium risk conflicts is highest (56.22%) under moderate volume levels with high LMV composition. This suggests that the presence of a speed bump reduces the severity of conflicts from high to medium risk due to the reduction in forced gap behaviour.

8. Conclusions

This research shows that installing speed bumps on minor roads can reduce forced-gap behaviour and improve safety at unsignalised intersections. After installation, negative PET values increased from 36.57% to 55.72%, while high-risk conflicts were generally lower across all three traffic-volume levels. Also, the proportion of high-risk conflicts was about 28 to 32% lower when a speed bump was provided on the minor road compared with when no speed bump was present. The simulation results also showed that the proportion of high-risk conflicts increased by 37% at higher traffic volumes when there was no speed bump.

However, the present study primarily

focuses on the safety implications of forced-gap behaviour under the presence of speed bumps based on various surrogate safety indicators. The associated operational and environmental effects of speed bumps, such as changes in weather conditions, lighting conditions, off-peak hours, minor-road delay, queue length, fuel consumption, emissions, and noise, were not explored. The potential effects on rear-end crash risk also remain outside the scope of the present study. Future research could therefore examine these aspects alongside safety performance to provide a more comprehensive assessment of the overall impacts of speed-bump installation under heterogeneous traffic conditions.

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