Modern Transportation Volume 12 Issue 1 (2023) doi: 10.18686/mt.v12i1.9199

Original Research Article

Surrogate safety evaluation of curve sections on an interurban highway under heterogeneous traffic conditions in India

Satbir Singh Puwar[1], **Mohan Rao Amudapuram**[2,*], **Velmurugan Senathipathi**[2]

[1] *Gawar Construction Ltd, Gurgaon 122018, India*

[2] *AcSIR Faculty, CSIR-Central Road Research Institute, New Delhi 110025, India*

*** Corresponding author:** Mohan Rao Amudapuram, amrao_crri@yahoo.co.in

Abstract: Road traffic safety is a global concern. Conventionally, road safety evaluation is carried out by analyzing historical crash data, which is a reactive approach to safety analysis. The safety analyst has to wait for sufficient time to accumulate crash data before taking up any safety analysis as a sample of substantial crashes is required for analysis. But in safety analysis with a proactive approach no crash data is required, which is replaced with surrogate "conflicts", which can be obtained from the new techniques of traffic conflict technique and surrogate safety parameters. Other approaches can be applied in traffic safety evaluation in anticipation of the crash occurrence. The advent of traffic conflict techniques, i.e., use of traffic conflicts in place of crashes and microsimulation methods like modeling of the traffic flow and pattern in traffic streams on a road network, started to apply as a method of analyzing microscopic simulation models and traffic conflict techniques to determine the safety issues in traffic systems and correlate them to the probable incidences of collisions. In this regard, surrogate safety parameters have been used to determine the level of safety on the typical curve sections of an interurban highway namely, Faridabad-Gurgaon four-lane divided highway in Haryana, India. This is accomplished by the use of vehicle trajectory data extracted through microscopic simulation in Verkher in Staedten Simulation (VISSIM) and analysis in Surrogate Safety Assessment Model (SSAM) for the above-referred corridor. Further, efforts have been made to present the intensity of traffic conflicts happening at the curved sections. The surrogate safety measures time to collision (TTC), deceleration rate (DR), and change in velocity (ΔV), as well as conflicting vehicle speed (Max S), are obtained by analysis from the SSAM model for all the curve sections and are validated using the reported crash data on the curve sections of the candidate corridor for 3 years. With the help of statistical elaboration, the critical threshold for TTC with the heterogeneous traffic movement is found 1.6 s, meaning any conflict occurring less than this time would invariably lead to a fatal crash. Similarly, the critical deceleration rate is observed as 0.569 m/s^2, implying that any conflict with more than this value may lead to a fatal crash. Further, the Delta$V$ values deduced for the study corridor on interurban curve sections catering to heterogeneous traffic movement is 4.1 m/s. Again, any conflict more than this value can turn into a potential crash.

Keywords: surrogate safety; interurban curve sections; time to collision; microscopic simulation; the intensity of traffic conflicts

1. Introduction and background

The negative externality for the expansion of highway networks and the increase in vehicle population is the increase in road fatalities. As per World Health Organization (WHO)[1] statistics in their publication titled, "Global status report on road safety 2018", 1.35 million fatalities and 50 million grievous injuries globally occur annually due to road crashes, and many are disabled for life as a result. On Indian roads, more than 150,000 people lose their lives and more than 450,000 are seriously injured in road crashes annually, accounting for about 11% of the total fatalities across the globe. The high proportion of fatalities could be attributed to the heterogeneous traffic conditions that include high-speed traffic (which invariably resorts to

Received: 3 July 2023 Accepted: 14 September 2023 Available online: 3 January 2024

speeding), sharing the road space with vulnerable road users (VRUs), as well as speeding and unsafe road infrastructure, and poor upkeep of the vehicles (incredibly few of the motorized two-wheelers and heavy vehicles plying in the periphery of the cities) contribute to the high fatality rates[2]. Therefore, it is pertinent to devise innovative ways the evaluate the safety situation of a road or road facility by a proactive approach which can be performed quickly without waiting for the collection of past crash data for analysis.

2. Literature review

The 'surrogate' word means 'substitute' or 'replacement.' Therefore, applying surrogate measures to observe traffic safety, we mean to replace the requirement for crash records with another factor representing traffic safety. The surrogate safety measures are developed with the help of identification, classification, and evaluation of traffic conflicts. In general, safety evaluations of road facilities are performed by the use of historical crash data. It is performed with the help of statistical methods, mainly by comparison of observed data and prediction with conventional predictive models. Fundamentally, the degree of safety on the road and the number of road crashes that occur there have a direct correlation. However, road crash data is an accurate representation of safety. However, its use in safety evaluation has many drawbacks. The major disadvantage in analyzing the traffic safety aspect of a new facility is that one has to wait until a sufficient number of crashes occur, which is unethical also. The data collected as such have many subjectivities. Alternatively, other approaches can be applied in traffic safety evaluation in anticipation of the crash occurrence. These techniques are called traffic surrogate safety models. Surrogate Safety Assessment Model (SSAM, Version 3.0) (U.S. Department of Transportation, Federal Highway Administration) is a software application prepared to apply statistical analysis of vehicle trajectory data imported from microscopic simulation models. The software application determines the number of surrogate safety measures for each conflict identified in the trajectory data and then calculates and summarizes (mean, max, etc.) each surrogate measure. The vehicle trajectory data file is extracted from the simulation software Verkher in Staedten Simulation (VISSIM, version 7.0, PTV Group, Germany).

Amundsen and Hyden[3], defined the conflict in a normal way, as an observed situation in which two or more road users approach each other on a collision course, and wherein the incidence of a road crash is imminent if neither of them takes evasive action. From the above definition, it is evident that some traffic events may convert to crashes. Considering the increasing trend in road crashes across the globe, it is essential to develop safety indicators that could be allowed in preventive safety analysis without waiting for a crash to occur. The use of surrogate safety measures which are not based on the observation of actual crashes but are related to crash likelihood has proven to be viable solutions as per the various reported works. The focus of this study is on singling out suitable surrogate safety measures applicable for typical curve sections of an interurban highway utilizing a microsimulation approach. There are several surrogate safety measures in literature, out of which some are compatible with microsimulation possibilities. Astarita et al.[4] studied surrogate safety indicator from the vehicle trajectories, in their study they considered road-side objects. The parameters are validated using the crash data at different intersections. Yang et al.[5] applied microsimulation in their study for evaluating safety performance of a novice drivers and developed an Intelligent Driver Model (IDM) by incorporating human physiological factors and surrogate safety measures.

The aspects considered for conflict analysis and the use of microscopic simulation for safety analysis are presented in the succeeding paragraph in the review of the associated literature and a discussion on the study's motivation and approach.

2.1. Literature on conflict analysis

Each crash can occur due to one or a multitude of factors including vehicle conditions, road conditions, emotional states of the drivers, traffic situations, etc. The measures representing near crashes such as traffic conflicts are commonly considered proximal measures of safety, or simply surrogate safety measures. Migletz et al.[6] in their research has established that the quantity and severity of such near-crash events have a close statistical relationship with crashes rather in some cases, have proved to be better predictors of the expected number of crashes than past crash data. Considering the above scenario, the Surrogate Safety Assessment Model (SSAM) can be deployed to assess the dangers of traffic events in a meaningful way. Accordingly, SSAMs are otherwise called proximal indicators. Generally, there are two categories of proximal indicators, e.g., temporal and non-temporal proximal indicators. In this regard, one temporal-based indicator is time to collision (TTC) which is analyzed in this study. In addition, the non-temporal indicators considered are deceleration rate (DR), conflicting vehicle maximum speed (Max S), and relative speed (Maximum Delta$V$). All these parameters are derived from the conflicts between two vehicles in which one vehicle may have to encounter other vehicles (s) in the traffic stream to avoid a road crash.

2.2. Literature on safety analysis using microscopic simulation

Microsimulation is a computerized scientific tool that comprehensively computes activities like highway traffic flowing through a road network. The potentiality of microscopic simulation concerning traffic safety and traffic conflict analysis has been appreciated in the research domain during the four decades by Darzentas et al.[7], Sayed et al.[8] and Cunto[9]. In this regard, Cunto[9] inferred that the ability of microscopic simulation to assess safety depends on the ability of these models to capture complex behavioral relationships that can lead to crashes and to establish a relationship between simulated safety measures and crash risk. Deepak and Vedagiri[10] inferred that the prediction of road crashes based on past crash data has its inherent drawbacks due to the quality and coverage of crash data recording especially in developing economies like India and hence it is concluded that assessment of the level of traffic safety by using surrogate safety measures like TTC is the most suitable. Chin et al.[11] devised an objective way of defining conflicts along with two conflict measures, one related to TTC and the other to deceleration. Instead of making conflict counts, they deployed the probability distribution of conflict measures to derive the probability of a serious conflict. Weibull distribution was found most appropriate for probability distribution in this case. Al-Fawzan[12] studied various ways targeted at the estimation of Weibull parameters, e.g., shape parameter (β) and scale parameter (η) as Weibull distribution is a useful distribution, especially for carrying out reliability and maintainability analysis during microscopic simulation. Laureshyn et al.[13] have shown the theoretical framework by using Delta-V as a measure for traffic conflict severity analysis based on site-based observations. Huang et al.[14] developed a traffic safety evaluation method based on simulated conflicts at signalized intersections. The simulated trajectory file is imported to SSAM for analysis by the Surrogate Safety Assessment Model (SSAM) to derive simulated conflicts. Siddharth and Gitakrishnan[15] introduced a method of use in the automatic calibration of the VISSIM model by sensitivity analysis of an intersection in Chennai. The VISSIM parameters, which affect driving behavior in Indian heterogeneous traffic conditions, were found using sensitivity analysis. Zhao P and Lee[16] use surrogate safety measures for predicting rear-end collision risk in the matter of a car with heavy vehicle heterogeneous traffic on a freeway. The result revealed that TTC and Post Encroachment Time (PET) are high for heavy vehicles to car and less for cars with cars. Sohel et al.[17] focused on developing and applying proximal surrogate safety indicators. Thirty-eight types of major proximal parameters are identified. These identified indicators are divided into two major groups, such as temporal and non-temporal. According to measuring attributes, such as distance, deceleration, and others, the non-temporal measures are further sub-classified into three categories. Durrani et al.[18] estimated the driving behaviour variables for cars and heavy vehicles for the Wiedemann 99 vehicle-following model. They revealed that heavy vehicles used to keep large gaps in space and time with the vehicle in front and are less sensitive to the leading car's behaviour. They use less acceleration at the time of starting from a stationary position in comparison to cars.

2.3. Research objective and gap

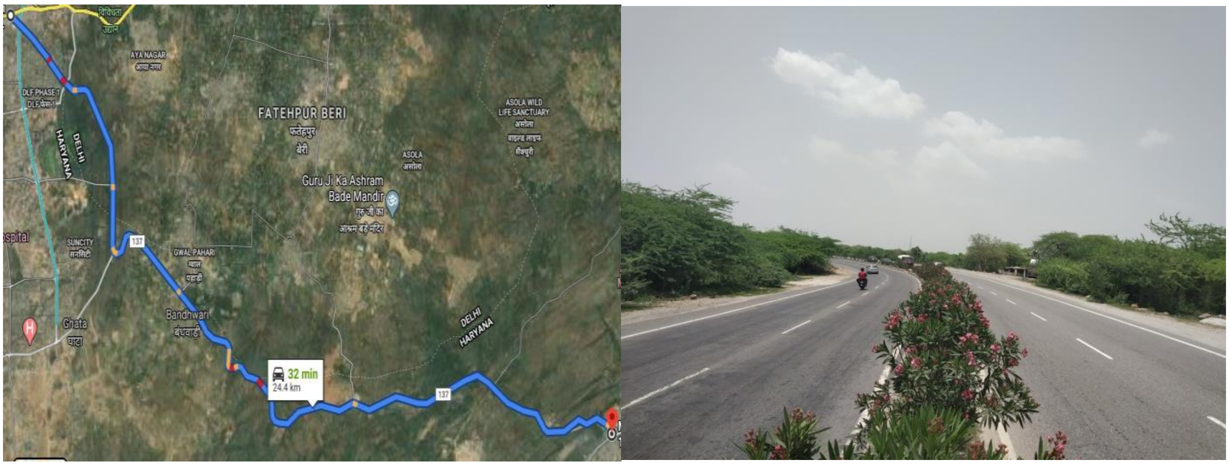
The objective of this study is to determine surrogate safety measures with the application of microsimulation and SSAM and find how they are related to the safety on the curve sections of an interurban road and to find out the most probable locations for crash occurrence. From the reviewed literature it is found that devising the Surrogate Safety Assessment Methods based on the conduct of microsimulation is an area that is not explored adequately under mixed traffic conditions prevailing on Indian roads. Very few studies were found on curved sections of the road, because of this research gap, a need was felt to quantify the traffic conflicts occurring on a typical interurban road corridor in the state of Haryana, India. While performing the above analysis for the candidate road corridor, this paper considers only the curve sections falling in the above-referred study section aimed at the analysis of conflicts and surrogate safety measures. This is because the conflict assessment and its comparison with actual crash data for the entire corridor need a different outlook for the midblock and intersections which are not dealt with in this paper. In this regard, the microscopic evaluation of traffic safety of the curve sections is conducted and this is followed by the application of surrogate safety assessment parameters. Further, validation of the proposed surrogate safety parameters is performed with the past crash data reports between 1 January 2015 and 31 December 2017 on the curve locations of the study corridor.

3. Study area and data collection

3.1. Study area

This study was carried out on Gurgaon to Faridabad Road, which is a major district road and is an interurban road situated on the urban periphery of the National Capital Territory (NCT) of Delhi joining the above two major cities with a direct and shortest route, bypassing Delhi. From the perusal of crash reports recorded by the concessionaire, it is revealed that the rate of crashes happening per kilometer per year on this road is substantially high in comparison to the national average of crashes happening elsewhere. This corridor has a total length of 24.31 km. It is four lanes divided interurban corridor having a 7.0 m wide carriageway, 1.5 m paved shoulder, 2 m wide median, and 0.25 m kerb shyness having an earthen shoulder width of 1.5 m on either side. It is a fact that the safety performance of any road corridor is greatly dependent on the geometric parameters of the road and traffic conditions. The study corridor comprises seven major intersections and out of which 5 are signalized and 2 are un-signalized coupled with the corridor traversing through 15 horizontal curves and 10 midblock.

Surrogate measures of safety that can be proposed for this road corridor will be different for different sections of the road like mid-blocks, curves, and intersections. To study the behavior of vehicles at various sections of the road, each surrogate safety measure has to be analyzed separately for mid-blocks, curves, and intersections. As cited in the above paras, this paper deals with only the estimation of potential crash locations with the help of surrogate safety parameters by considering curve sections only. The minimum and maximum length of the curve section varies between 200 m to 2500 m and the radius of the curve varies from 90 m to 800 m respectively. It may be further noted that the small stretches of straight lengths, as well as mild curves having radii above 800 m and the associated tangent lengths, are treated as part of straight reaches and hence not considered in this study. This is because the vehicles negotiating the above road stretches do not face potential crash proneness due to the presence of such mild curves coupled with negligible speed changes due to the above geometrics. The study area is shown in **Figure 1**.



(a) **(b)**

Figure 1. Gurgaon to Faridabad study corridor, **(a)** key plan of Gurgaon-Faridabad road corridor; **(b)** typical view of curve section of Gurgaon-Faridabad.

3.2. Data collection

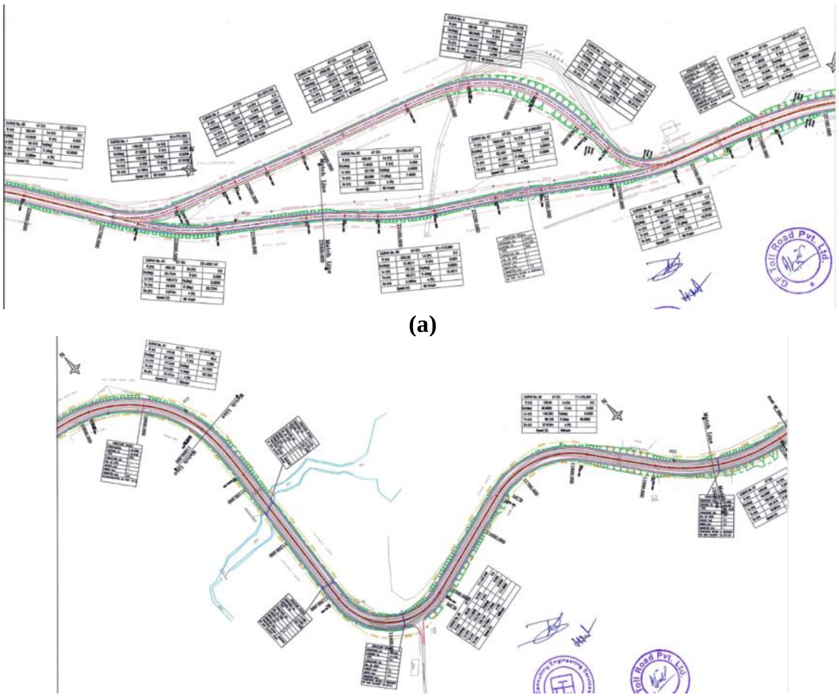
To collect traffic count data and spot speeds classified traffic volume survey with videography and a spot speed survey with a laser speed gun were conducted in each curve section at the appropriate place. The location of data collection was selected at each curve stretch keeping the view that the sample drawn is a representative one. For obtaining speed profile and acceleration/deceleration of various vehicles at every 1 m as well as centerline deviations, gradient, and geometric details performance box was used on all the curved sections. This data is given as input to VISSIM software used for performing the simulation of the curve sections of the study corridor. The 15 curve locations on the study corridor are simulated using VISSIM software and calibrated heuristically using the data stated above. The methodology proposed includes a depiction of vehicles, geometry, and traffic, then a selection of calibration variables by multi-parameter sensitivity analysis, defining their ranges heuristically, and identifying the parameter values by an optimization model. First, default values are used for the calibration of the simulation and the results are compared to real-world values. If these values have minor errors, then the model can be accepted with default values, and there is no need for further calibration. On the contrary, if the error is significant, the calibration will be done by changing the driving behavior parameters. The calibration can be done with vehicle representation, e.g., vehicle type and class (bike, three-wheeler, car, LCV, bus, truck), geometric representation, traffic representation, selection of parameters and their ranges and measures of effectiveness, and parameters optimization. As explained by Mathew et al.[19], the driving behavior parameters are tuned by conducting sensitivity analysis. The parameter values are changed with a small margin, and their impact is determined if the effect is not substantial; the parameter values are not further changed. In this way, by reiteration, the model has been calibrated.

As mentioned earlier, the past crash record data for the period from 1 January 2015 to 31 December 2017 was obtained from the concessionaire, who is carrying out the Operation and Maintenance (O&M) of the road. The various details available in the above data are the chainage details, cause, and type of each road crash that eventually helped in the segregation of many road crashes occurring at mid-blocks, curves, and intersections as per their occurrence. **Table 1** presents the number and locations of the road crashes that have taken place during the last 3 years on the curve section along with their share in total road crashes on the entire corridor.

It is evident from **Table 1** that the share of road crashes at curve sections of the study corridor is substantially high, which varies between 77 to 81 percent. **Figure 2** shows the typical curve section with curvature details.

Table 1. Details of road crashes from 2015 to 2017 on the curve sections.

S. No.	**Curve ID**	**Chainage of horizontal curve**	**Length (m)**	**Radius (m)**	**Vertical gradient (%)**	**Super elevation (%)**	**Number of road crashes**			
							2015	**2016**	**2017**	**Grand total**
1	C 1	Km 2.25–3.00	750	160	5.538	7	8	2	4	14
2	C 2	Km 3.30–3.50	200	800	2.992	2.5	2	1	0	3
3	C 3	Km 4.20–4.4	200	240	5.471	2.5	3	2	4	9
4	C 4	Km 5.97–6.30	330	155	0.195	2.5	7	9	6	22
5	C 5	Km 6.50–9.00	2500	120	4.387	7	54	21	16	91
6	C 6	Km 9.20–9.50	300	800	1.83	2.5	3	1	3	7
7	C 7	Km 9.50–11.00	1500	175	2.315	7	22	15	12	49
8	C 8	Km 11.30–12.10	800	90	4.986	7	42	34	28	104
9	C 9	Km 12.80–14.33	1530	160	0.94	7	17	22	15	54
10	C 10	Km 14.80–15.85	1050	180	0.18	7	21	18	15	54
11	C 11	Km 16.05–16.50	450	180	4.99	7	13	14	13	40
12	C 12	Km 16.92–18.29	1370	240	1.316	7	15	8	4	27
13	C 13	Km 19.69–20.20	510	160	1.838	7	19	8	14	41
14	C 14	Km 20.40–20.94	540	500	4.288	5	2	0	3	5
15	C 15	Km 21.34–23.89	2460	90	4.957	7	22	23	9	54
Total crashes at the curve locations							250	178	146	574
Total crashes on the entire corridor							325	221	186	732
Share of crashes on the curve locations (% age)							76.92	80.5	78.5	78.4



(a)

(b)

Figure 2. (a) typical curve section on study corridor Km 22.50 of GF road; **(b)** typical curve section on study corridor Km 11.50 of GF road.

4. Methodology adapted for the study

Microscopic simulation has been performed for the curve sections present on the study corridor using VISSIM version 7.0. Each of the curve sections present on the study corridor has been simulated for 2 h in which the first-hour simulation was for warm-up and balancing whereas the results for the second hour are considered for extracting trajectory files and validated using VISISM software. VISSIM software is commercially available in the market and has good compatibility with SSAM software. The present study used the Wiedemann-99 model of car-following which is compatible to inter-urban motorways it allows the calibration of the model as per study corridor traffic conditions. The default parameters available in the model tested weather they are giving proper results, the study observed the default values are not sufficient, hence they are calibrated using the field data such as traffic volume, speed (spot speed, entire corridor speed), travel time, lateral placement of vehicles, error tolerance is used 5 percent. Same model is used for all the curve sections entire corridor is simulated at a time. The Surrogate Safety Assessment Model (SSAM) is used to determine the classification, and evaluation of traffic conflicts from the imported vehicle trajectory output from microscopic traffic simulation models. This software is capable of computing many surrogate measures of safety for each conflict that is identified in the trajectory file. This computes and summarizes mean max and other associated statistics for each of the surrogate measures. The surrogate safety measures such as TTC, Max S, and DeltaV are extracted for each of the curve sections independently. Aggregate data, i.e., by adding all the individual curve sections is used for the identification of threshold values in SSA. The severity analysis of the crash aimed at the identification of the intensity of the crash (as fatal, serious injury, minor injury, and property damage only) was done using the disaggregated crash data for various chainages of curve sections. Using the above, the developed severity zones and the threshold values have been compared for the identified curve sections on the study corridor. In this way, the validation of the threshold values and severity zones was performed with the use of the individual SSA parameter for each curve and the recorded crash data over three years. The brief method for surrogate safety analysis of curve sections is discussed in detail in the forthcoming section.

5. Findings of the study

In this research, a vehicle trajectory data file is built for each of the curve sections in simulation through VISSIM, and then vehicle trajectory files are imported to SSAM to determine the surrogate safety measures. Therefore, the vehicle-to-vehicle conflict data are derived from SSAM.

Geometric design standards of study corridor: The study corridor is designed for 100 Kmph and the operating speed/speed limit on the corridor is 80 Kmph. As per IRC:73-1980[20] and IRC:SP-84-2019[21] the minimum desirable radius of horizontal curves for plain and rolling terrain is 400 m and absolute minimum radius is 250 m and the vertical grade change is not allowed within 150 m for the ruling gradient of 2.5 percent. The safe stopping sight distance (SSD) is 120 m when the operating speed is 80 Kmph which requires the time headway of 5.4 s say 5 s to be considered for the study section. Keeping it in view, the maximum TTC threshold value used is 5 s whereas the PET threshold is considered as 9.5 s for the identification of serious conflicts being a limitation in SSAM on the study corridor.

5.1. Analysis of TTC

Hayward 1971 defined the time to collision as the expected time of a collision between two vehicles if they remain at their present speed and on the same path. As discussed in the above paras, the TTC is an important spatial parameter to measure surrogate safety and hence can be used as an important warning criterion in automobile collision avoidance systems (ACAS) and driver assistance systems. At the same time, it is to be borne in mind that if the severity increases the TTC values decrease, this shows that they are inversely proportional. Considering the above, the use of the reciprocal of the TTC values is useful to find the distribution in place of the direct values of TTC. Various mathematical functions have been tested to fit in the Probability Density Function (PDF) for the values of 1/TTC measure, and hence the PDF function considered is given in Equation (1):

$$g(s) = \left[\frac{k}{w}\right]\left(\frac{s}{w}\right)^{k-1} \exp\left[-\left(\frac{s}{w}\right)^{k}\right] \tag{1}$$

where, 'k' and 'w' are shape and scale parameters.

A brief discussion of the applicability of Weibull distribution and performing statistical tests is given in the subsequent section.

TTC distribution obtained at the curve sections

The analysis of TTC has been done for all the curve sections (both simple and compound curves) present on the study corridor. The PDF and cumulative distribution function derived for the various curve sections are presented in **Figure 3**. As explained above, trajectories of vehicles are extracted through VISSIM, and from the imported trajectory files surrogates such as TTC values for each conflict are thoroughly analyzed using SSAM. The analysis of TTC was performed for the entire set of curve sections, i.e., 15 numbers in the study corridor, combined as well as for each curve section independently. Goodness-of-fit statistics is judged with the Kolmogorov-Smirnov (K-S) test. This test is applied to find the goodness of fit of the distribution. The null hypothesis assumes that the data follows a specified distribution at 95% confidence level for the critical value of p which is 0.296 for the 50 and above number of observations. The null hypothesis is accepted if the calculated D-statistic value is less than the critical value of p. Since, the D-statistic estimated from the distribution is less than the critical value of 0.296, the PDF fitted with Weibull distribution function of reciprocal of TTC is accepted. The results presented in **Figure 3** indicate that the data fit well with the Weibull distribution for the curve sections considered in this study. Further, the goodness of fit statistics for all the curve sections is presented in **Table 2** and it is evident from the above results that TTC is 1.58 s say 1.6 s. This implies that if the derived value of TTC is less than the above threshold value of 1.6 s at any candidate curve section, the conflict is considered serious.

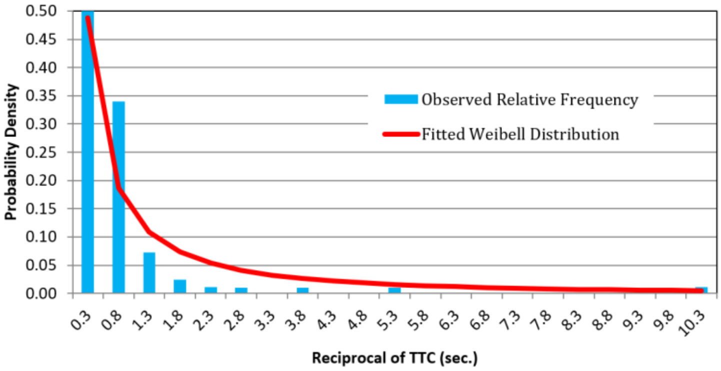


Figure 3. Distribution of TTC for curve sections.

Table 2. PDF of 1/TTC for curve section.

Limit	Frequency	Observed relative frequency	Fitted Weibull distribution	Cumulative dist. function CDF (1)	Cumulative dist. function CDF (2)	D-statistic
0.3	162,960	0.51	0.49	0.51	0.54	0.03
0.8	108,699	0.34	0.19	0.85	0.69	0.16
1.3	23,067	0.07	0.11	0.92	0.76	0.17
1.8	7689	0.02	0.07	0.95	0.80	0.15
2.3	3520	0.01	0.05	0.96	0.83	0.12
2.8	3272	0.01	0.04	0.97	0.86	0.11
3.3	0	0.00	0.03	0.97	0.87	0.09
3.8	3364	0.01	0.03	0.98	0.89	0.09
4.3	0	0.00	0.02	0.98	0.90	0.08
4.8	0	0.00	0.02	0.98	0.91	0.07
5.3	3307	0.01	0.02	0.99	0.92	0.07
5.8	0	0.00	0.01	0.99	0.93	0.06

5.2. Analysis of deceleration rate (DR)

Like the reciprocal of TTC, the variation of deceleration rate (DR) is quite similar. When the conflicts are more serious, the variation in DR can be high. In comparison to the inverse of TTC, the variation of DR is considered a better predictor for crash severity when the deceleration rate values are higher. The deduced deceleration rate for the curve sections is found to range from 0.01 m/s^2 to 8.34 m/s^2. The Probability Distribution Function (PDF) and Cumulative Distribution Function (CDF) in terms of DR were calculated for each of the curve sections and the same are presented in **Figure 4**. Goodness-of-fit statistics were carried out using the K-S test and it is found to be satisfactory. The mean deceleration rate for curve sections is found to be 0.569 m/s^2.

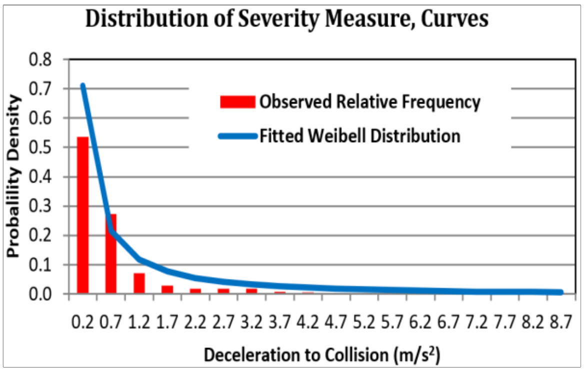
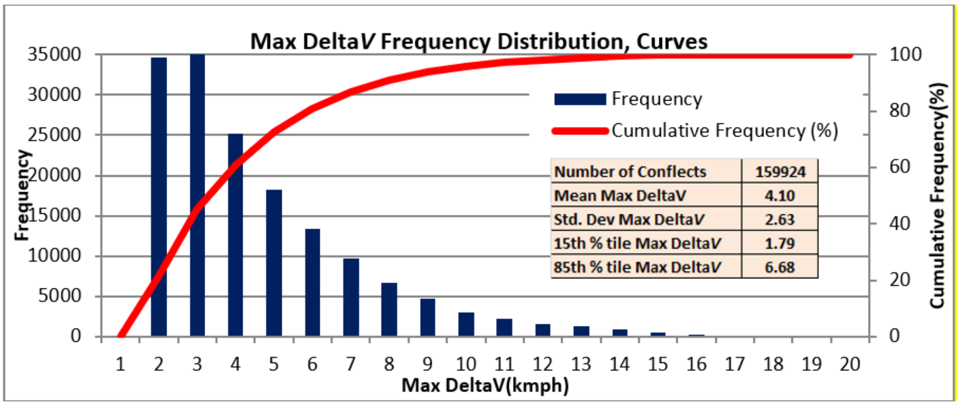


Figure 4. Probability distribution of DR for curve sections.

5.3. Analysis of Max Delta*V*

Because Max Delta*V* coupled with First Delta*V* and Second Delta*V* are other important components of SSAM, the same has been deduced by assuming a hypothetical collision of vehicles faced with the conflict for the candidate curve sections on the study corridor. In this regard, Max Delta*V* is assumed as the maximum variation of the velocity of the vehicles involved in the conflict, however, First Delta*V* and Second Delta*V* are the difference in velocity between conflict velocity and the post-collision velocity respectively. The frequency distribution of Max Delta*V* for the whole curve sections is applied along with 15th percentile and 85th percentile values and the same are shown in **Figure 5**. When the value of Max Delta*V* increases, the seriousness of conflict also increases. The mean value of Max Delta*V* determined for curve sections is 4.1 m/s, i.e., 14.76 Kmph which is taken as the threshold value for identifying the critical section[11]. When the value of Max Delta*V* is higher than the above threshold value, the incidence of any conflict is considered under a serious category wherein the likelihood of any type of crash is expected.



Number of Conflicts	159924
Mean Max DeltaV	4.10
Std. Dev Max Delta*V*	2.63
15th % tile Max Delta*V*	1.79
85th % tile Max Delta*V*	6.68

Figure 5. Max Delta*V* frequency distribution plots for curve sections.

5.4. Analysis of conflict severity

The severity of each conflict is determined by assessing the severity score for every conflict based on the above-derived values of TTC, Max Delta*V*, and Max *S* values for the candidate curve sections considered in the study corridor. The Hyden severity zones illustrated in **Figure 6** have been deployed by plotting the Max *S* versus TTC derived on the study corridor.

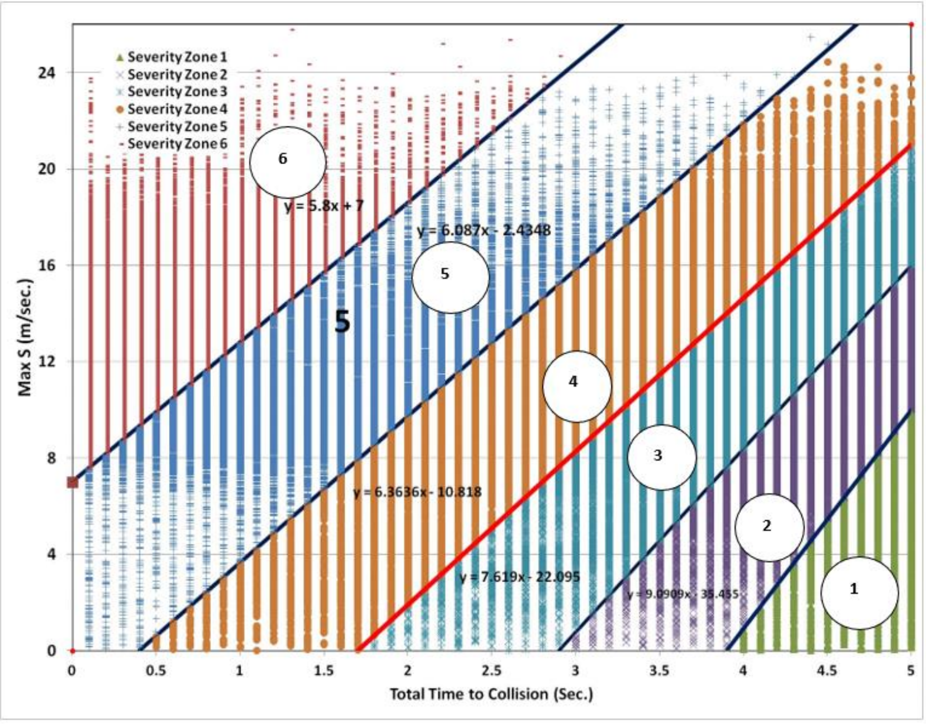


Figure 6. Max *S* versus TTC conflict severity zones for different curve sections on the study corridor.

5.4.1. Severity analysis

In this study, conforming to Ministry of Road Transport and Highways[22] the crashes based on their severity are classified as fatal, seriously injured, minor injury, and property damage. The basis for this classification is the quantum of damage caused to the person and the vehicle. The classification of the severity of the crash concerning traffic conflict has a bearing on the procedure based on the parameter selected. The severe conflicts indicate the proximity or how close these conflicts are to the crash. In SSAM generally, the classification of the severity of a crash is based on the following parameters of traffic conflicts.

- Crash severity based on Max *S* values.
- Crash severity based on TTC values.
- Crash severity based on Max *S* and TTC values.
- Crash severity based on Delta*V* values.

5.4.2. Crash severity based on Max *S* values

As discussed earlier, Max *S* is the maximum speed of the vehicle observed, involved in the conflicts occurring at the curve sections and hence Max *S* is assumed as the most suitable indicator for defining the severity of crash. Accordingly, a Max *S* versus TTC plot has been drawn for the candidate curve sections with the scattering of the data in the plot which is characterized under 6 severity zones (**Figure 6**). In this way, severity lines are plotted with the mean TTC value derived from the TTC distribution curve and the mean Max *S* value obtained from the conflict data of the curve sections.

A total of 323,104 potential conflicts on different curve sections of the study corridor are plotted in **Figure 6**. The severity line joining with the TTC value is less than 1.6 s and the Max *S* value is more than 23 m/s which shows that the conflicts occurring at the study corridor are split into a 50:50 ratio approximately. This thick red line is termed as Uniform Severity Line[23] as depicted in **Figure 6**. The conflicts related to the curve are divided into uniform severity zones and the same are plotted with different colors/textures to identify the range of severity as illustrated in **Figure 7**. Further, **Table 3** presents the severity zones, the criteria of TTC Max *S*, and the number of curve sections placed in each severity zone.

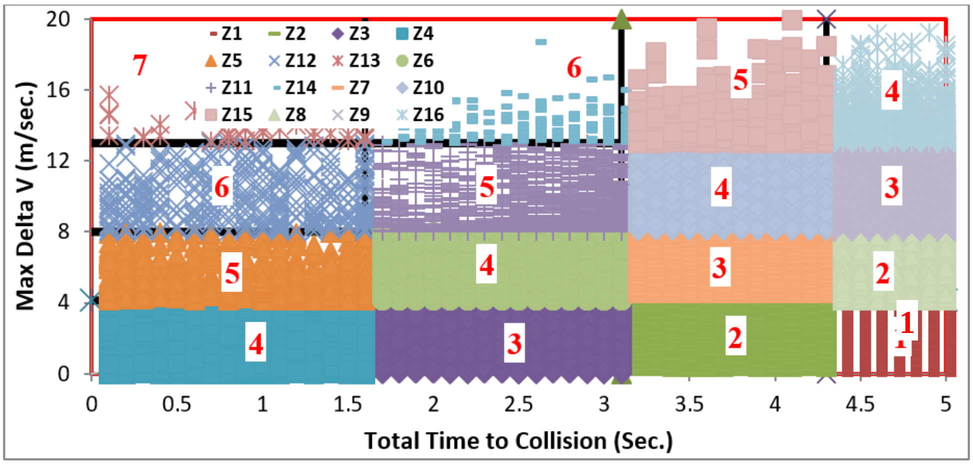


Figure 7. Max Δ*V* versus TTC plot for severity score in curve sections.

Table 3. Severity zones based on TTC.

Severity zone	Criteria (TTC)	Criteria Max *S*	Number of curve sections (in %)
1	3.9	10	4.88
2	2.9	16	22.55
3	1.6	23	21.84
4	0.2	30	21.66
5	0	36	20.96
6	0	>36	8.11

5.4.3. Crash severity based on TTC values

The surrogates TTC and DR are direct indicators of the severity of the conflict. As established by Sayed et al.[8], the lower TTC value indicates a higher probability of a crash based on the TTC values computed for the severity of the crash. From the analysis, the mean/critical value of TTC for curve sections of the study corridor is 1.6 s, and the conflicts with a critical value less than this TTC value fall in the severity zones 3, 4, and 5 whereas conflicts with TTC $\geq$ 1.60 s fall in severity zones 1, 2 and 3 conforming to the Hyden severity zone concept (refer **Figure 7**).

On application of the above analogy, it is seen that approximately 20.4 percent of the curve locations fell below the critical range of 1.6 of TTC. Assuming the above phenomenon, the TTC ranges are selected by splitting the conflicts uniformly under various severity zones for the different curve sections falling on the study corridor. Accordingly, the conflicts with TTC less than or equal to 1.6 s have been assigned a risk of collision (ROC) score of 4, because it is the more extreme condition. Similarly, conflicts with TTC higher than 4.3 s have been given a score of 1 because these conflicts have low propensity levels. **Table 4** presents the ROC score derived based on various TTC ranges by considering the curve sections and the associated collision propensity level on the study corridor.

Table 4. Assigned ROC scores based on TTC scores.

TTC values ROC score	TTC range (seconds)	Number of curve sections (in %)	Collision propensity level
1	TTC > 4.3	27.93	Low
2	3.10 < TTC $\leq$ 4.3	27.32	Moderate
3	1.60 < TTC $\leq$ 3.10	24.32	High
4	TTC $\leq$ 1.60	20.43	Extreme

5.4.4. Analysis of crash severity based on DeltaV

Delta$V$ (DV) is the variation in velocity before and after the hypothetical collision. Delta$V$ values are determined from vehicle trajectory data and are used for identifying the severity of the conflict. TTC values and Delta$V$ values are further employed to identify the characteristics of each potential conflict through segregation based on the type of severity zones as shown in **Figure 8**. TTC value of 1.6 s is the critical value obtained from the probability distribution and the mean value of DeltaV is 4.1 m/s.

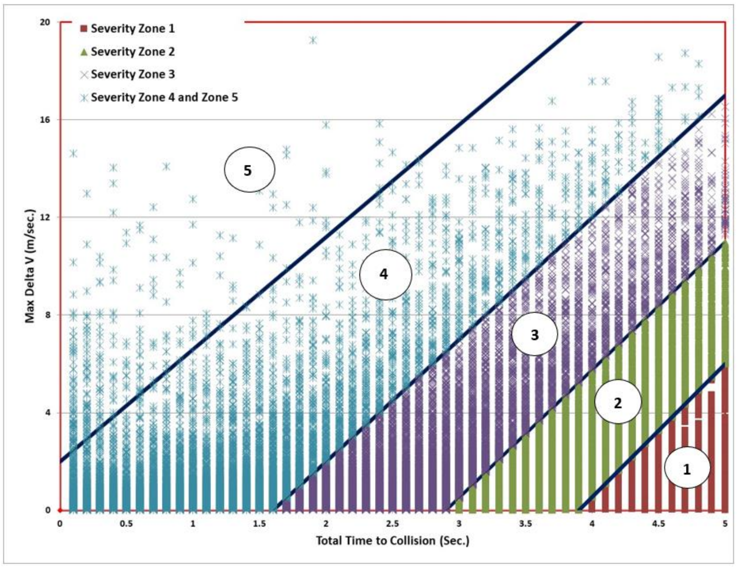


Figure 8. Delta$V$ versus TTC conflict severity zone for curve sections of the study corridor.

ROC score based on Max Delta*V* is assigned to each conflict. **Table 5** shows the ROC scores and ranges of Delta*V* and collision propensity level for the study corridor which typically exhibits traffic heterogeneity prevailing on Indian highways.

Moreover, the ranges of the TTC and Delta*V* values derived through the severity score graph are plotted for the possible conflicts covering all the curve sections. In **Figure 7** different severity scores based on the TTC and Delta*V* are presented. For ease of appreciation, various colors and legends/textures are assigned for separate zone values.

Table 5. Assigned ROC concerning Max Δ*V*.

Max DeltaV ROC score	Max Δ*V* range (m/s)	Number of curve sections (in %)	Collision propensity level	Number of conflicts	Percentage of conflicts
1	Max $\Delta V \leq 4.13$	88,465 (62.26)	Low	88,465	62.26
2	$4.13 <$ Max $\Delta V \geq 6.72$	32,299 (22.73)	Moderate	32,299	22.73
3	$6.72 <$ Max $\Delta V \geq 10$	15,277 (10.75)	High	15,277	10.75
4	Max $\Delta V > 10$	6057 (4.26)	Extreme	6057	4.26

Further, the overview of **Figure 8** which presents the potential conflicts on the various curve sections of the study corridor reveals that each of the conflict zones is presented in a different color/legend for easy identification. In **Table 6** the modified values of TTC and Delta*V* with the number of curve sections are presented. **Table 6** also contains the contour lines and their equations where line # 1 is the lower contour line and in the same way, other contour lines are placed following their ROC scores.

Table 6. Changes from initial to modified overall severity score.

Overall, ROC score	Criteria		Number of curve sections (%)	Line number	Equation (Max Δ*V*)	Collision propensity level
	TTC	Delta*V*				
1	>3.9	6	81,109 (25.10)	1	$5.454x - 21.27$	Low
2	2.9	11	77,866 (24.10)	2	$5.238x - 15.19$	Property damage
3	1.6	17	84,061 (26.02)	3	$5x - 8$	Serious
4	<1.6	>25	80,068 (24.78)	4	$4.6x + 2$	Fatal

5.5. Crash potential versus crash history

As briefed above, the 15 curve sections existing on the study corridor have been simulated using VISSIM. Surrogate Safety Assessment Model software is used to extract the surrogate safety measures, e.g., TTC, Max *S*, and Delta*V*. The above deduced surrogate safety measures are found for each of the individual curve sections by defining the severity zone plot and the type of severity zone. Accordingly, **Figure 8** presents the individual curve sections and the severity zones to which they belong.

The crash data which was collected for the study corridor for the 3 years along with the type of crashes is presented in **Table 7**. This data has been applied to validate the potentiality of each curve section by comparing it with surrogate parameter values. The **Figure 9** represents the TTC, Max Delta*V* and number of severity zones same as the study out come as mentioned in **Figure 8**. TTC and Delta*V* values of each individual curve sections are calculated, the red dots in the **Figure 9** represents each individual curve section which are plotted using respective curve section values. Each curve section location in severity zone is validated with the actual observed total crashes and their type of crashes (refer **Table 7**). The inferences have been drawn based on a comparison of SSAM results (refer **Figure 9**) and crash data (refer **Table 7**) from the reported crashes:

- On the entire study corridor, the number of road crashes occurring on the curve sections is of the order of 78% during the 3 years. In this regard, curve sections namely, C11 and C13 accounted for 3 numbers of fatal crashes whereas C8 and C15 accounted for 2 numbers of fatal crashes. In addition, these four curve sections accounted for a sizable number of other types of road crashes as well and hence these sections fall under zone 5 or at the periphery of zone 5 as per SSAM. On the other hand, on the curve sections C1, C5, C7, C9, and C10, one fatal crash took place coupled with a sizable proportion of other types of crashes as well and hence classified under zone-4 through SSAM. Hence it can be inferred that SSAM presented the true representations of the ground realities concerning the radius of the curve, vertical gradient, and superelevation (road geometrics).
- Further, curve sections namely, C4, C6, C12, and C14 fall under zone 3 as per the results of SSAM which represents serious injury and that truly represents the ground conditions following the road geometrics. Similarly, C12 also accounts for a sizable proportion of grievous and minor crashes as per results of SSAM which is again aptly reflected (vide **Figure 9**) as this curve section is falling on the periphery of zone 3.
- In line with the pattern of reported road crashes in sections, C2 and C3 which fall under zone 2 near the periphery of zone 2 as per SSAM results and thus account for the dominant share of minor injury and property-damage related crashes.

Table 7. Number and severity type of crashes on the candidate road curve section.

S. No.	Section No.	Number of fatal crashes	Number of grievous injury crashes	Number of minor crashes	Number of non-injury crashes
1	C1	1	2	4	5
2	C2	Nil	0	1	1
3	C3	Nil	1	5	2
4	C4	Nil	6	2	11
5	C5	1	23	15	44
6	C6	Nil	2	0	4
7	C7	1	17	17	13
8	C8	2	27	33	37
9	C9	1	18	14	19
10	C10	1	19	18	19
11	C11	3	14	10	13
12	C12	1	7	6	11
13	C13	3	15	12	13
14	C14	Nil	3	0	1
15	C15	2	15	9	27

Note: C1 to C15 indicate the curve sections on the study corridor.

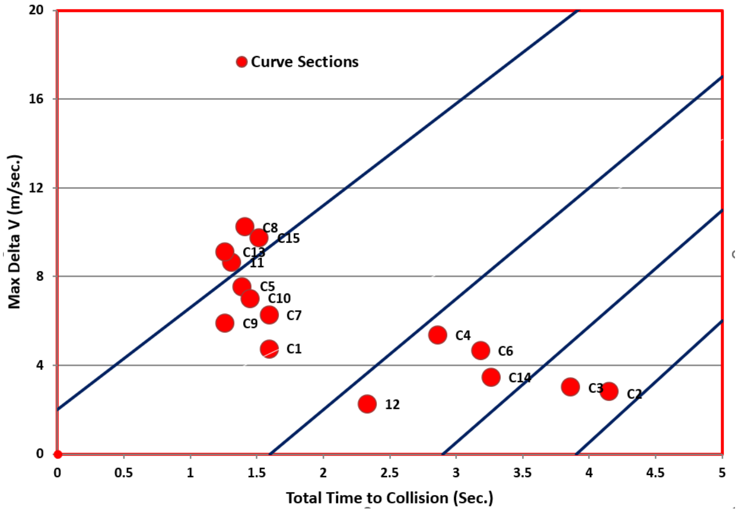


Figure 9. Individual curve sections in developed crash severity zone.

6. Discussion and conclusions

This study has been carried out on an interurban 4-lane road corridor having a length of 24.31 km comprising 15 typical curve sections between two adjacent straight mid-blocks to deduce the surrogate safety parameters and to understand their behavior. The curve sections are simulated using VISSIM software. Calibrating and satisfactory validation were done with field data collected from the study area. Thereafter, the vehicle trajectories are built for all curve sections and imported to SSAM for analysis to determine surrogate safety parameters using this SSAM software. Further, the various surrogate safety measures have been thoroughly evaluated to determine the threshold values of surrogate parameters. Different severity zones have been plotted based on threshold values to assess the potential crash locations and to find a type of crash likely to occur, i.e., severity of a crash.

In this study, it is revealed that TTC and DR follow the Weibull distribution. Further, the critical TTC on interurban curve sections catering to heterogeneous traffic movement is 1.6 s implying thereby that any conflict with less than this time would invariably lead to a fatal crash. In the same way, the rate of critical deceleration observed is 0.569 m/s which again infers that any conflict with more than this value will lead to a fatal crash having the scenario of traffic heterogeneity. Further, the Delta$V$ values deduced for the study corridor on interurban curve sections catering to heterogeneous traffic movement is 4.1 m/s which again implies that the likelihood of conflict more than this value can turn to be a potential crash.

The surrogate safety measures values determined from the above analysis are validated with the real-world crash data collected on the study corridor over 3 years. In a nutshell, the methodology deduced in this work can be replicated to identify probable potential crash-prone locations for any interurban highway exhibiting similar terrain, geometry, and traffic heterogeneity. Moreover, the determined threshold values can be used to identify the intensity of severity on the curve location.

7. Future research

Though this study has successfully developed the surrogate safety measures on the curve sections of the interurban corridor and has suggested the probable crash locations, this study has not considered variables like axle configuration, the environment, and the quality of the road pavement, which may influence the accuracy of the results. Moreover, in the analysis of trajectory files in SSAM, the number of conflicts and their type are only determined, which is only a proxy of the crashes.

To address the above issues, future studies can be taken up by considering the missed variables like axle configuration, the environment, and the quality of the road pavement. Further, the conflicts derived from the analysis be converted into crashes and should be compared with the actual crashes on the curve sections to validate the study.

Author contributions

Conceptualization, SSP, MRA and VS; methodology, SSP, MRA and VS; software, SSP and MRA; validation, SSP, MRA and VS; formal analysis, SSP and MRA; investigation, MRA; resources SSP; data curation, SSP; writing—original draft preparation, SSP and MRA; writing—review and editing, MRA; visualization, SSP and MRA; supervision, MRA and VS; project administration, MRA and VS; funding acquisition, SSP. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

The authors wish to place on record their gratitude to all the field staff and postgraduate students involved in data collection as well as in preliminary analysis. Further, the authors express their heartfelt gratitude to M. Parida, Director, CSIR-Central Road Research Institute, New Delhi, India for giving his permission to publish this paper.

Conflict of interest

The authors declare no conflict of interest.

References

1. WHO. *Global Status Report on Road Safety 2018.* WHO; 2018.
2. Pirdvani A, Brijs T, Bellemans T, Wets G. Evaluation of traffic safety at un-signalized intersections using microsimulation: A utilization of proximal safety indicators. *Advances in Transportation Studies Journal Section A* 2010; 22(22): 43–50.
3. Amundsen F, Hyden C. *Proceeding: First of Workshop on Traffic Conflicts*. Institute of Transport Economics; 1977. p. 143.
4. Astarita V, Guido G, Vitale A, Giofre V. A new microsimulation model for the evaluation of traffic safety performances. *European Transport* 2012.
5. Yang H, Wu Y, Xiao H, Zhao Y. Simulation study of rear-end crash evaluation considering driver experience heterogeneity in the framework of three-phase traffic theory. *Journal of Advanced Transportation* 2021; 2021: 1–13. doi: 10.1155/2021/5533722.
6. Migletz J, Glauz WD, Bauer KM. *Relationships Between Traffic Conflicts and Accidents.* U.S. Department of Transportation Federal Highway Administration; 1985.
7. Darzentas J, Cooper DF, Storr PA, McDowell MRC. Simulation of road traffic conflicts at T-junctions. *Simulation* 1980; 34(5): 155–164. doi: 10.1177/003754978003400505.
8. Sayed T, Brown G, Navin F. Simulation of Traffic Conflicts at Unsignalized Intersections with TSC-Sim. *Accident Analysis and Prevention* 1994; 26(5): 593–607. doi: https://doi.org/10.1016/0001-4575(94)90021-3.
9. Al-Fawzan MA. *Methods for Estimating the Parameters of the Weibull Distribution*. King Abdul-Aziz City for Science and Technology; 2000.
10. Chin CC, Quek ST. Measurement of traffic conflicts. *Safety Science* 1997; 26(3): 169–185. doi: 10.1016/S0925-7535(97)00041-6
11. Cunto F, Saccomanno FF. Calibration and validation of simulated vehicle safety performance at signalized intersections. *Accident Analysis and Prevention* 2008; 40(3): 1171–1179. doi: 10.1016/j.aap.2008.01.003
12. Killi DV, Vedagiri P. Proactive evaluation of traffic safety at an unsignalized intersection using micro-simulation. *Journal of Traffic and Logistics Engineering* 2014; 2(2): 140–145. doi: 10.12720/jtle.2.2.140-145.
13. Laureshyn A, De Ceunynck T, Karlsson C, et al. In search of the severity dimension of traffic events: Extended Delta-Vas a traffic conflict indicator. *Accident Analysis and Prevention* 2017; 98: 46–56. doi: 10.1016/j.aap.2016.09.026.

14. Huang F, Liu P, Yu H, Wang W. Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. *Accident Analysis and Prevention* 2013; 50: 1014–1024. doi: 10.1016/j.aap.2012.08.018.
15. Siddharth SMP, Ramadurai G. Calibration of VISSIM for Indian heterogeneous traffic conditions. *Procedia-Social and Behavioral Science* 2013; 104: 380–389. doi: 10.1016/j.sbspro.2013.11.131.
16. Zhao P, Lee C. Assessing rear collision risk of cars and heavy vehicles on freeways using surrogate safety measures. *Accident Analysis and Prevention* 2018; 113: 149–158. doi: 10.1016/j.aap.2018.01.033.
17. Mahmud SMS, Ferreira L, Hoque MS, Tavassoli A. Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs. *IATSS Research* 2017; 41(4): 153–163. doi: https://doi.org/10.1016/j.iatssr.2017.02.001
18. Durrani U, Lee C, Maoh H. Calibrating the Wiedemann’s vehicle-following model using mixed vehicle-pair interactions. *Transportation Research Part C: Emerging Technologies* 2016; 67: 227–242. doi: 10.1016/j.trc.2016.02.012.
19. Mathew TV, Radhakrishnan P. Calibration of Microsimulation Models for non- Lane based Heterogeneous Traffic at Signalized Intersection. *Journal of Urban Planning & Development* 2010; 136(1). doi: 10.1061/(ASCE)0733-9488(2010)136:1(59)
20. The Indian Roads Congress. *IRC: 73-1980. Geometric Design Standards for Rural (Non-Urban) Highways*. Indian Roads Congress; 1980.
21. The Indian Roads Congress. *IRC: SP: 84-2019. Manual of Specifications and Standards for Four Laning of Highways through Public Private Partnership.* The Indian Roads Congress; 2019.
22. MoRT&H. *Road Accidents in India.* Government of India Ministry of Road Transport and Highways Transport Research Wing (MoRT&H); 2018.
23. Hydén C. *The Development of A Method for Traffic Safety Evaluation: The Swedish Traffic Conflict Technique* [PhD thesis]. Lund University; 1987.