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Surrogate Safety Assessment of Unsignalized Intersections Under Heterogeneous Traffic Conditions in India: A Review of Pet, Speed-Based Criticality And Vehicle-Class Effects

Prof. Nimit Palasanawala[1], Prof. Neha B. Kagra[2], Prof. Chirakumar. S. Modhiya[3], Prof. Kinnari Pratik Shah[4]

[1,2,3,4]Department of Civil Engineering, Government Engineering College Bharuch, India

ABSTRACT:
Road safety assessment at unsignalized intersections in India is complicated by heterogeneous vehicle composition, weak lane discipline, non-compliance with priority rules, aggressive gap acceptance, pedestrian interactions and incomplete crash records. Surrogate safety measures (SSMs), particularly post-encroachment time (PET) and time to collision (TTC), have therefore become important proactive tools. This review critically analyses studies covering Indian unsignalized T-intersections, four-legged intersections, pedestrian-vehicle interactions, mixed-traffic facilities and broader methodological developments in surrogate safety assessment. The reviewed studies show a progression from microsimulation and conventional PET analysis toward speed-enhanced criticality, vehicle-class analysis, trajectory-based interaction analysis, forceful-gap behaviour, conflict-severity indices, extreme-value modelling and systematic synthesis. Across the studies, motorized two-wheelers (M2W/MTW), autorickshaws (M3W), cars and light vehicles repeatedly emerge as important contributors to critical interactions, while pedestrian movements and forced gap creation introduce additional sources of conflict. Intersection geometry, traffic volume, traffic composition, speed, gap acceptance and time of day influence conflict occurrence and severity. However, the literature continues to face limitations associated with fixed thresholds, site-specific data, manual or semi-automated extraction, limited crash validation and incomplete integration of vehicle dynamics and behavioural heterogeneity. Reaction time, braking capability, vehicle mass, conflict angle, speeds of both interacting road users, pedestrian behaviour, weather and site-level heterogeneity are not yet integrated consistently into a unified Indian model. Based on the synthesis, this review proposes a vehicle-class-specific, reaction-time-aware and severity-oriented surrogate safety framework calibrated for Indian mixed traffic and validated against independent intersections and crash records.

KEYWORDS: Surrogate safety measures; PET; TTC; mixed traffic; unsignalized intersections; motorized two-wheelers; autorickshaws; pedestrian safety; traffic conflicts; conflict severity; India

1. INTRODUCTION

Road intersections are critical components of an urban transportation network because several traffic

streams converge, diverge and cross within a restricted area. The safety problem becomes more complex in India because traffic is heterogeneous and commonly includes motorized two-wheelers, three-wheelers, cars, buses, light commercial vehicles and heavy vehicles operating with limited lane discipline. The reviewed Indian studies describe simultaneous longitudinal and lateral interactions, non-yielding behaviours, forced gap creation, abrupt speed changes and pedestrian-vehicle interactions as important characteristics of unsignalized traffic [1], [2], [4], [6], [7], [9]–[12]. The problem is particularly relevant at unsignalized T-intersections, where right-turning and through movements compete for the same conflict area. Crash-based safety assessment is reactive and depends on reliable historical crash records. Surrogate safety assessment provides a proactive alternative because conflicts occur much more frequently than crashes and can be observed from comparatively short observation periods. PET is generally useful for crossing conflicts, while TTC is useful for longitudinal interactions; however, the reviewed evidence indicates that a single time-based threshold cannot fully represent conflict severity in heterogeneous traffic [5], [9].

The literature reviewed here shows a methodological evolution. Early studies used microsimulation and PET to compare safety under alternative traffic conditions [1], [13]. Subsequent Indian studies introduced field video observations, vehicle-type classification, speed-based proximal indicators and PET threshold analysis [2]–[6], [9]. Further work considered pedestrian-vehicle interaction patterns, forceful gap behaviour and vehicle-class effects [10]–[12]. More recent research incorporated conflict-severity indices based on time and expected kinetic-energy loss, bivariate extreme-value methods, and systematic mapping of surrogate safety assessment

[14]. The resulting literature indicates a shift from simple conflict counting toward context-sensitive modelling of conflict probability and severity.

The purpose of this review is therefore not merely to summarize, but to analyse methodologies, variables, findings and limitations collectively and identify a defensible research gap. Particular attention is given to five dimensions: (i) surrogate indicators, (ii) vehicle-class and road-user effects, (iii) traffic, behavioural and geometric variables,

(iv) statistical modelling and crash validation, and (v) threshold and severity-index selection. The final outcome is a proposed research framework for a vehicle-class-specific Indian conflict model that retains the practical advantages of PET/TTC while incorporating speed, braking, interaction severity, behaviour and geometric context.

2. EVOLUTION OF SURROGATE SAFETY RESEARCH IN INDIAN MIXED TRAFFIC

Vedagiri and Killi [3] established a practical methodology for evaluating an uncontrolled intersection using surrogate safety measures and microsimulation under mixed traffic conditions. PET, together with microsimulation, was used to investigate the effects of traffic conditions and alternative management measures. The study demonstrated the value of proactive safety assessment and showed that increasing traffic volume reduced mean PET, indicating deteriorating safety. It also examined measures such as speed control and geometric improvements.

Paul and Ghosh [5] subsequently addressed an important weakness of conventional PET analysis: PET indicates temporal proximity but does not directly represent the severity associated with the speed of the through vehicle. Using four unsignalized intersections in the National Capital Region, the study proposed a methodology combining PET with the conflicting speed of through-moving vehicles. This speed-enhanced approach demonstrated why a predetermined PET threshold alone can be misleading when

different vehicle categories operate at different speeds. Paul and Ghosh [5] subsequently developed a speed-based proximal indicator for right-turn-related crashes and connected the indicator with crash information, strengthening the argument for incorporating vehicle speed into conflict criticality.

Patel and Gundaliya [6], [10] extended proactive safety evaluation to multilane and urban unsignalized intersections and developed proximal safety indicators using field observations. Their studies reinforce the practical value of video-derived surrogate measures while also highlighting the site-specific nature of thresholds and the need to account for local traffic and geometric conditions. Goyani et al. [12] further extended the analysis to vehicle type and intersection geometry at four Indian unsignalized T-intersections. Their findings showed that powered two-wheelers and light vehicles exhibited important differences in crossing-conflict patterns relative to heavier vehicles, demonstrating that the same PET value can have different safety implications for different vehicle combinations.

Paul et al. [13] explicitly quantified the effects of motorized two-wheelers and autorickshaws on crossing conflicts at eight urban unsignalized T-intersections. Truncated Negative Binomial regression was used for critical and non-critical crossing-conflict counts. This transformed vehicle composition from a descriptive characteristic into an explanatory variable in a conflict-frequency model. Goyani et al.

[12] developed crossing-conflict models under heterogeneous traffic using Poisson-Tweedie regression and included traffic volume, composition, geometry and time of day. These studies collectively show that aggregate traffic volume alone may not adequately represent exposure in Indian mixed traffic because the composition of the interacting streams changes the conflict environment.

The additional studies broaden the behavioural and methodological scope. Advani et al. [8] defined forceful gap behaviour at unsignalized intersections using speed reductions of major-road vehicles and examined its effect on critical gap acceptance. This is relevant because a conflict can arise not only from an insufficient nominal gap but also from the interaction between entering vehicles and the forced response of priority-stream vehicles. Kathuria and Vedagiri [9] used semi-automated trajectory data at three unsignalized intersections and analysed pedestrian-vehicle interaction patterns using speed, TTC, PET and gap-time profiles. Their study classified responsive and non-responsive interaction patterns and demonstrated that both TTC and PET can contribute to severity classification. Shah and Vedagiri [7] similarly used PET and Support Vector Machine-based thresholds to classify pedestrian-vehicle conflict severity by vehicle type and approach speed. These studies indicate that road-user behaviour and vulnerable-road-user interactions should be included in a comprehensive framework.

Caliendo and Guida [1] demonstrated the potential of microsimulation-based critical conflicts for predicting crashes at unsignalized intersections. Their calibrated simulation used TTC and PET thresholds to identify critical conflicts, and the resulting critical-conflict measures showed a statistically significant relationship with observed crashes. Paul and Ghosh [13] advanced the severity perspective by developing a Conflict Severity Index (CSI) using PET, Δt and expected loss in kinetic energy. Their sensitivity analysis showed that speed, vehicle mass difference and conflict angle influence CSI, and the proposed index was examined against observed severe crash types. Gastaldi et al. [14] applied bivariate extreme-value approaches to unsignalized-intersection safety, showing that correlated surrogate measures or conflict points can be modelled jointly rather than independently.

3. COMPARATIVE ANALYSIS OF THE REVIEWED STUDIES

Table 1. Comparative summary

Study	Sites / Setting	Main SSM / Method	Key contribution	Main limitation / opportunity
Vedagiri & Killi (2015)	Uncontrolled intersection; mixed traffic; microsimulation	PET; microsimulation	Proactive safety evaluation; management alternatives	Simulation/field transferability; limited vehicle-specific modelling
Paul & Ghosh (2018)	4 NCR unsignalized intersections	PET + conflicting speed; critical speed	Speed-enhanced criticality ; crash linkage	Small site sample; braking/reaction assumptions
Patel & Gundaliya (2018)	Multilane unsignalized intersection	SSM; field evaluation	Proactive safety assessment	Site-specific application
Patel & Gundaliya (2020)	Surat urban unsignalized intersection	Proximal safety indicators	Development of field-based indicators	Transferability of thresholds
Paul & Ghosh (2020)	Intercity highway unsignalized intersections	PET threshold analysis	Crash-related PET threshold identification	Threshold dependence; mixed traffic variability
Goyan i et al. (2021)	4 Indian unsignalized T-intersections	PET; GEV; vehicle-type analysis	Vehicle combinations and geometry effects	Limited sites; PET remains central
Paul & Ghosh (2017)	4 NCR uncontrolled intersections	PET + conflicting speed	Speed-enhanced proximal safety indicator	Limited sites; vehicle dynamics simplified
Shah & Vedagiri (2018)	Indian unsignalized intersection; pedestrians	PET; SVM	Vehicle type/speed-specific pedestrian conflict severity	Single-site application
Advan i et al. (2020)	Indian unsignalized intersections; mixed traffic	Gap acceptance; speed reduction	Definition of forceful gap behaviour	Behaviour-specific and site-dependent
Kathuria & Vedagiri (2020)	3 Indian unsignalized intersections; pedestrians	Trajectory data; TTC; PET; IVM	Behaviour-based pedestrian-vehicle severity classification	Limited sites; trajectory extraction effort

Calien do & Guida (2012)	Urban unsignalized intersections, Salerno, Italy	Microsimulation; TTC; PET	Critical conflicts linked statistically with crashes	Different traffic context from India
Paul & Ghosh (2021)	10 unsignalized intersections on intercity highways	PET; Δt; ΔKE; CSI	Conflict severity including expected kinetic consequences	Requires assumptions on collision mechanics
Gastal di et al. (2021)	Three-leg unsignalized intersection	Bivariate EVT	Joint modelling of correlated surrogate extremes	Method/data requirements ; non-Indian context
Arun et al. (2021)	Systematic literature mapping	SSM review/framework	Identifies crash-conflict and injury-severity research needs	Review-level evidence; not site-specific
Tarko (2012)	General road-safety modelling	Crash surrogates; exceedance statistics	Crash-precursor modelling framework	General framework rather than Indian intersection study

3.1 Surrogate safety indicators

PET is the dominant indicator for crossing conflicts in the reviewed studies because it is comparatively simple to obtain from video and does not require estimating the future trajectory of vehicles [1]–[9]. However, Paul and Ghosh [13] demonstrated that PET alone may be misleading when conflicting-vehicle speed differs substantially between events. TTC is useful for rear-end and longitudinal interactions because it incorporates relative speed and spacing, while Kathuria and Vedagiri [9] showed that TTC and PET can jointly characterize pedestrian-vehicle interaction patterns. Paul and Ghosh [11] further demonstrated that time-based indicators can be combined with expected kinetic-energy loss to represent consequences as well as proximity. Gastaldi et al. [14] showed that multiple surrogate measures can also be modelled jointly using bivariate extreme-value methods.

The evidence therefore supports a multi-dimensional interpretation: PET can represent temporal proximity, speed can represent kinetic severity, TTC can represent closing risk in longitudinal interactions, and energy-based terms can represent potential collision consequences [9], [12], [14], [15]. Arun et al. [15] also identified the development of stronger crash-conflict relationships and injury-severity estimation as important future needs. Future Indian models should therefore avoid treating one fixed threshold as a complete representation of safety and should instead estimate a continuous or probabilistic conflict-severity function.

3.2 Vehicle-class effects

Vehicle heterogeneity is one of the clearest recurring findings. The Indian studies show substantial proportions of two-wheelers and three-wheelers in the traffic stream. Paul et al. [13] reported that M2W

and M3W proportions in conflicting and offending streams influenced critical and non-critical crossing-conflict counts, while Goyani et al. [12] demonstrated vehicle-type and traffic-composition effects. Shah and Vedagiri [7] further showed that vehicle type and approach speed influence pedestrian-vehicle conflict severity. Vehicle class matters not only because of frequency but because different classes have different dimensions, acceleration/deceleration capabilities, maneuverability, operating speeds and mass [6], [10], [14]. Consequently, vehicle-class effects should enter both conflict-generation and conflict-severity models.

Vehicle-pair interaction is also important. The conflict-severity framework of Paul and Ghosh [13] indicates that vehicle mass difference, speed and conflict angle influence expected severity. The forceful-gap study of Advani et al. [8] demonstrates that the response of a major-road vehicle to an entering vehicle can alter the effective interaction. Therefore, models that aggregate all conflicts into one class may conceal meaningful differences among M2W–M2W, M2W–car, M3W–car, car–HV and other combinations.

3.3 Traffic volume and composition

Traffic volume is consistently important, but its relationship with conflict frequency is not necessarily monotonic. The Poisson-Tweedie analysis [8] indicates that increasing offending and conflicting volumes can change critical-conflict frequency, while the behavioural evidence from forceful-gap research [11] shows that demand and gap acceptance can alter the speed response of priority-stream vehicles. Caliendo and Guida [1] also found that peak-period traffic conditions were important in their microsimulation/crash-prediction application. These findings imply that volume should not be treated only as an exposure variable; it also changes the interaction environment and gap-acceptance behaviour.

3.4 Intersection geometry and control

Traffic composition modifies this exposure effect. A model based only on PCU or total vehicles per hour may hide important differences between a stream dominated by two-wheelers and one dominated by cars or heavy vehicles [6]–[8]. A more appropriate Indian model should include vehicle-class proportions and, where possible, vehicle-pair combinations, accepted-gap characteristics and approach speeds [7], [11]. Intersection geometry and control influence the opportunity for crossing and turning conflicts. The Indian studies identify differences associated with intersection type, central islands and conflict-zone characteristics [3], [4], [6], [8]. However, geometry is often represented through categorical variables rather than continuous descriptors such as sight distance, turning radius, entry angle, channelization, conflict-zone dimensions and effective crossing width. A more transferable model should explicitly measure these characteristics.

The evidence base is predominantly observational and site-specific. The methodological contribution of Caliendo and Guida [1] shows that microsimulation can extend the range of traffic conditions considered, while Gastaldi et al. [14] demonstrate that extreme-value models can use surrogate observations to estimate safety without requiring long crash histories. The combined evidence suggests that geometry should be represented consistently in both field-based and simulation-based safety models.

3.5 Time of day and operating conditions

Peak/off-peak conditions appear in several studies and are relevant because demand, speed and traffic composition vary over time [8], [13]. However, a binary peak/off-peak variable is only a proxy for more fundamental operating conditions such as speed variance, density, queue length, gap distribution and driver behaviour. Forceful-gap behaviour [11] and pedestrian interaction patterns [12] further demonstrate that behavioural responses can change the safety meaning of the same traffic demand level.

The reviewed studies also largely rely on daytime observations and selected sites. Pedestrian interactions

are explicitly considered by Shah and Vedagiri [7] and Kathuria and Vedagiri [9], but weather, night-time visibility, wet pavement and other environmental conditions are not consistently represented across the literature. This remains a limitation for a general Indian model.

3.6 Statistical modelling

The reviewed research employs microsimulation, empirical distributions, machine-learning classification, extreme-value methods, generalized linear models, truncated negative-binomial regression, Poisson-Tweedie regression and trajectory-based behavioural analysis [1], [7], [8], [10]–[15]. This methodological diversity is valuable because conflict observations can be discrete, over-dispersed, correlated and heterogeneous. Gastaldi et al. [14] demonstrated the value of bivariate EVT when surrogate datasets are correlated, while Tarko [2] provided a framework for modelling crash precursor events. Arun et al. [15] highlighted the need for stronger links between surrogate events and actual crashes.

Nevertheless, most models still aggregate interactions by time interval, conflict type or critical/non-critical category. Such aggregation can conceal the interaction-level mechanism that produces the conflict. A hierarchical or mixed-effects framework could explicitly represent intersection-level, vehicle-level and road-user-level heterogeneity. A Bayesian or probabilistic approach could also quantify uncertainty in site transferability and threshold estimation. The literature supports combining count models for conflict frequency with interaction-level severity models rather than relying on one indicator or one statistical formulation.

4. CRITICAL SYNTHESIS OF LIMITATIONS

The review identifies six connected limitations. First, fixed PET thresholds remain common. Predetermined thresholds are convenient but may not be transferable across vehicle classes, speeds and intersection environments [1], [9], [10]. Second, vehicle classes are often aggregated despite evidence that individual classes and vehicle-pair combinations behave differently [6]–[8], [14]. Third, reaction time and braking response are rarely measured directly, even though critical-speed and stopping-distance concepts depend on these factors [2], [9]. Fourth, speed is not consistently incorporated for both interacting vehicles, while conflict-severity work indicates that speed and conflict angle can affect potential collision consequences [14]. Fifth, manual or semi-automated trajectory extraction and relatively small site samples limit generalizability [6], [10], [12]. Sixth, validation against crash data is not consistently performed. Caliendo and Guida [1] and Paul and Ghosh [11] provide examples of connecting surrogate measures with crash information, while Arun et al. [15] identify the crash-conflict relationship as a continuing research need.

A further limitation is the treatment of behavioural mechanisms. Advani et al. [8] show that forceful gap creation can alter the speed response of major-road vehicles and critical gap acceptance. Shah and Vedagiri [7] and Kathuria and Vedagiri [9] show that pedestrian-vehicle interactions require behavioural and trajectory information in addition to a single temporal indicator. The combined implication is that the next generation of Indian research should move from a fixed-threshold, site-specific conflict count toward a vehicle-class-specific probabilistic severity model using interaction-level trajectory information, behavioural response, reaction time, speed, vehicle characteristics and geometric context.

The literature also indicates that severity should be separated from frequency. Count models can explain how traffic volume, composition and geometry influence the number of conflicts [7], [8], whereas severity models such as the CSI [14], SVM-based pedestrian thresholds [10] and bivariate EVT [15] address the extremity or consequences of interactions. A unified framework should therefore model both processes

and validate them independently.

The combined implication is that future Indian studies should integrate PET/TTC with speed, conflict angle, vehicle mass, braking response, behavioural response and geometric context. Crash linkage should be used wherever sufficiently reliable records are available, and independent-site validation should be treated as an essential step for demonstrating transferability.

5. IDENTIFIED RESEARCH GAP

Based on the expanded literature, the key research gap is the lack of an integrated Indian framework that simultaneously accounts for vehicle class, vehicle-pair interaction, reaction time, speed, braking capability, pedestrian behaviour, forceful gap acceptance, intersection geometry and traffic exposure when determining conflict severity. Existing studies have established the usefulness of PET/TTC, speed-based indicators, vehicle-class analysis, trajectory-based interaction measures, conflict-severity indices and extreme-value methods [6]–[15], but these approaches are generally developed separately.

The gap can therefore be stated as follows: existing Indian studies have established that surrogate conflicts are influenced by traffic composition, traffic volume, intersection geometry, speed, gap acceptance and road- user behaviour, while broader methodological studies demonstrate the value of severity indices, multivariate extreme-value modelling and crash-precursor frameworks [9]–[15]. However, a generalized vehicle-class-specific conflict-severity model that simultaneously distinguishes vehicle-pair combinations, measures behavioural response and braking characteristics, incorporates both interacting speeds and geometric context, and is validated across independent Indian intersections remains insufficiently developed in the literature reviewed.

This gap is suitable for further doctoral research because it extends, rather than replaces, the established PET/TTC framework. The proposed extension is to introduce measurable behavioural, vehicle-specific and kinetic parameters, compare alternative statistical formulations, and test whether the resulting model transfers across sites and traffic conditions.

Table 2. Research-gap synthesis and proposed direction.

Dimension	What the reviewed papers establish	Remaining gap	Proposed PhD direction
PET/TTC	PET is practical for crossing; TTC for rear-end/longitudinal interactions	Thresholds vary with context and road user	Develop data-driven, context-specific risk curves
Vehicle class	M2W/M3W/car s materially affect conflicts	Vehicle-pair effects not fully integrated into severity model	Model vehicle-pair-specific risk
Pedestrian s	PET/TTC and behaviour classify pedestrian-vehicle severity	Pedestrian response not integrated with vehicle conflict model	Include pedestrian trajectory and evasive response
Speed	Higher conflicting speed changes criticality	Both interacting speeds not consistently modelled	Use both speeds and speed difference

Reaction time	Stopping-distance logic depends on reaction time	Usually assumed rather than measured	Estimate empirical class-specific reaction time
Braking / energy	CSI shows mass, speed, angle and energy consequences	Standard assumptions may limit transferability	Estimate class/condition -specific deceleration and energy terms
Gap behaviour	Forceful gap entry changes major-road vehicle response	Behaviour rarely integrated into SSM models	Model forced-entry and accepted-gap mechanisms
Geometry	Intersection type and geometric features influence conflicts	Often categorical/site -specific	Use continuous geometry and conflict-zone variables
Statistical modelling	NB, TNB, Poisson-Tweedie, EVT, SVM and microsimulation are useful	Different models address different components	Compare frequency + severity + extreme-value frameworks
Validation	Some studies link conflicts with crashes	Independent-site validation remains limited	Multi-site external validation + crash linkage
Crash-conflict link	Crash surrogates provide a precursor framework	Relationship remains a major research need	Calibrate surrogate-to-crash probability

6. CONCLUSIONS

The reviewed literature establishes a substantial foundation for surrogate safety assessment at unsignalized intersections. PET is consistently useful for crossing conflicts, while TTC is valuable for rear-end and longitudinal interactions [1], [5], [12]. Speed-based indicators demonstrate that temporal proximity should be interpreted together with operating speed [2], [9]. Vehicle-class and composition studies show that Indian mixed traffic cannot be represented adequately by a single homogeneous vehicle category [6]–[8]. Pedestrian studies further demonstrate the need to consider vulnerable-road-user behaviour and trajectory patterns [10], [12].

The methodological development from microsimulation and conventional PET to speed-based criticality, vehicle-type modelling, behavioural trajectory analysis, forceful-gap characterization, conflict-severity indices and extreme-value modelling demonstrates a progression toward more context-sensitive safety assessment [9]–[15]. At the same time, fixed thresholds, limited site coverage, manual or semi-automated extraction, incomplete behavioural variables and inconsistent crash validation remain important limitations. The systematic mapping review by Arun et al. [15] reinforce the need for stronger crash-conflict relationships and context-specific SSM selection.

The principal research opportunity is therefore a vehicle-class-specific and reaction-time-aware surrogate safety framework for Indian mixed traffic. Such a framework should retain the practical advantages of PET/TTC while incorporating speed, braking, expected kinetic consequences, vehicle-pair interactions, pedestrian behaviour, forceful gap acceptance and geometric context. Validation across independent sites and, wherever possible, crash records would strengthen its practical applicability for proactive safety assessment at heterogeneous unsignalized intersections.

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