# Assessing Traffic Safety of Vehicle-Pedestrian Interaction at Intersections, Mid-Block Crossings and Jaywalking

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**Abstract.** Pedestrians consist a large part of vulnerable road users in transportation networks with unpredictable behaviour and different motion profiles and patterns. Their interaction with vehicular traffic is a major pillar in the field of transportation and it is vital to maintain high safety levels in any type of interaction due to pedestrians' high vulnerability. Numerous studies have dealt with these issues and been focused on evaluating traffic safety levels at the encounter points using different indicators and surrogate safety measures (SSMs). Scope of this work is to present the findings of an extensive literature review summarizing the different indicators used for assessing the risk levels of these interactions. The review includes interactions at intersections, mid-block crosswalks and jaywalking using real time collected data, virtual experiments and driving simulators. Apart from these issues, the review revealed critical values of these indicators for categorizing the safety levels of the interactions as well for identifying the thresholds the pedestrians perceive for deciding to cross the road segment. The results showed that time-, distance- and speed based indicators are the main categories of parameters used for describing interactions and assessing their safety levels.

**Keywords:** pedestrians, surrogate safety measures, crosswalks, jaywalking, automated vehicles.

## 1 Introduction

Pedestrians' interaction with vehicles at signalized or unsignalized intersections and mid-block crosswalks consist a major pilar of traffic safety due to their unpredictable behaviour as they can easily change their speed, direction of moving or perform a risky road crossing forcing the vehicle to harsh braking or fully stop to avoid a potential conflict. Additionally, pedestrians tend very often to cross the road at any possible unmarked and undesignated location (jaywalking) deteriorating safety levels of their interaction with the vehicles as the driver or the machine (in case of highly or fully automated vehicles), should be ready for immediate and prompt reaction.

This paper aims to present the findings of an extensive literature review concerning the different indicators used for assessing the risk levels of these interactions. The review includes interactions at intersections, mid-block crosswalks and jaywalking using real time collected data, simulation tools or virtual experiments and driving simulators. Finally, critical values of these indicators for categorizing the safety levels of the interactions are also presented.

In addition to compiling existing studies, this review aims to provide a more structured and analytical synthesis of surrogate safety indicators. To this end, the manuscript adopts an improved narrative approach in presenting the literature, where references are discussed in context by explicitly referring to the contributing authors rather than solely relying on numerical citations. A consolidated framework is introduced to facilitate the comparison of indicators in terms of definition, applicability and thresholds.

## 2 Definitions

To improve clarity and facilitate comparison among the various surrogate safety measures discussed in this study, the main indicators are briefly defined below along with their interpretation, units, and applicability.

Time-based indicators are among the most widely used measures for assessing vehicle–pedestrian interactions, as they capture the temporal proximity between road users. Time to Collision (TTC) represents the time remaining until a collision would occur if both the vehicle and the pedestrian continue with their current speed and trajectory. It is typically expressed as $TTC = d / v_{(rel)}$, where $d$ is the distance between the two road users (in meters) and $v_{(rel)}$ is their relative speed (in m/s), resulting in TTC values expressed in seconds. Lower TTC values indicate more critical situations. Post Encroachment Time (PET) is defined as the time difference between the moment one road user leaves a conflict point and another arrives at the same point; it is also measured in seconds, with smaller values indicating higher risk. Time Advantage (TAdv) expresses the temporal priority between interacting users, reflecting who passes first through a potential conflict area, while Time to Accident (TA) is conceptually similar to TTC but is typically used within specific conflict analysis frameworks to describe the severity of an encounter. These indicators are particularly suitable for dynamic analyses where trajectories and speeds are available (video-based observations or simulation studies).

Distance-based indicators describe the spatial proximity between pedestrians and vehicles and are typically expressed in meters. Minimum Distance (MD) refers to the smallest separation distance observed during an interaction, while Relative Distance (RD) represents the instantaneous distance between the two road users. Passing Distance (PD) is used to characterize how closely a vehicle passes relative to a pedestrian during an interaction. In all cases, smaller distance values correspond to higher collision risk. Distance-based indicators are particularly useful in low-speed environments or when spatial relationships are more relevant than temporal dynamics.

Speed-based indicators focus on the kinematic aspects of interactions and the intensity of evasive maneuvers. Deceleration Rate (DR) quantifies the rate at which a vehicle reduces its speed, typically expressed in $m/s^2$, and is often used as an indicator of conflict severity, with higher values corresponding to more abrupt and potentially unsafe maneuvers. Deceleration to Safety Time (DST) extends this concept by estimating the deceleration required for a vehicle to avoid a collision within a given time frame. Jerk, defined as the rate of change of acceleration ($m/s^3$), is also used to capture sudden changes in motion that may indicate critical interactions. These indicators are especially relevant for assessing the severity of conflicts rather than their occurrence.

# 3 Indicators for Describing and Assessing the Safety Levels of Vehicles – Pedestrians Interactions

## 3.1 Time – based indicators

One of the most popular and widely used indicator is Time to Collision (TTC) firstly introduced by Hayward [1]. Thresholds for TTC are established at the early 80s, when [2] set the value of 1.5s, a threshold adopted also in other research studies [3, 4] while other studies resulted in higher critical values [5-7]. Variations of TTC introduced in the literature can be found in Laureshyn et al. [8].

Post Encroachment Time (PET) is another popular surrogate safety measure for assessing safety levels of pedestrian – vehicle interactions [9]. Lord [10] used the threshold of 3s for defining traffic conflicts at signalized intersections while a lower threshold value equal to 1.5s was established by Fu et al. [11] for dangerous conflicts, specifically. PET thresholds have been established for analyzing encounters inside and outside crosswalks, proving that illegal crossing is riskier [12] and at signalized intersection taking into consideration the approaching vehicle type [13].

A lower value of PET of 1s for defining critical conflicts was obtained by Paul & Ghosh [14] when studying crossing conflicts and right turn crash data at intersections located on highways instead of urban or rural environments. A combination of PET and vehicle approaching speed were employed in Chaudhari et al. [15] for clustering vehicle – pedestrian conflicts severity at urban midblock crossings. In case of more than one lane, an alternative indicator named Lane based PET (LPET) has been defined for evaluating and classifying conflicts between vehicles and pedestrians considering each full lane as a conflict zone [16, 17].

Concerning zebra crossing, specifically, Time-To-Zebra$_{arrive}$ (TTZ$_{arr}$) has been established for classifying deriver-pedestrian interaction introduced by [18] who defined critical thresholds of 1s and 4s. Higher threshold values were found in Schneemann & Gohl [19] and Bella & Silvestri [20]. Another time – based indicator for describing pedestrian – vehicle conflicts is Time Advantage (TAdv) defined by Zaki et al. [21] who established a threshold of 10s for distinguishing conflicts from normal encounters. Time to Accident (TA) was firstly proposed by [16] for defining the severity of a conflict according to the Swedish Traffic Conflict Technique. Based on video observations he concluded that a value of TA below 1.5s indicated a serious conflict while TA higher than 3s corresponds to normal encounters.

## 3.2 Distance – based indicators

The spatial proximity of the two agents and the potentiality and severity of their collision can be expressed by distance – based indicators established and being applied either solely or with other time-based indicators. Olszewski et al. [22] used the passing distance for classifying encounters as dangerous when the vehicle either passes in front of the pedestrian or immediately after him. A distance-based indicator is also mentioned in Pascucci [23] where he indicates that if the relative distance between a vehicle and a pedestrian is below 1.5m, there is a high probability of collision occurrence.

Amini et al. [24] developed a model for assessing the conflict risk of interactions between pedestrians and light vehicles and made a combination of time-, space- and speed – based indicators for evaluating the severity levels of these interactions. In their study, they define a conflict as critical if conflict speed exceeds 1m/s, the minimum distance (MD) is below 1.5m; similar as in Pascucci [23] and the arrival time to the minimum distance (TMD) below 1.5s; similarly to the threshold set by Navarro et al. [25] for TTC.

### 3.3 Speed – based indicators

Hupfer [26] introduced Deceleration to Safety Time (DST), as a more efficient and reliable indicator than the widely-used TTC and PET for evaluating traffic situations when vehicles and pedestrians are interacting, establishing six thresholds for indicating severity and the magnitude of the evasive action the driver has to perform. The same indicator and thresholds were applied by Johnsson et al. [27] in cases where the vehicle decelerates or stops giving priority to the pedestrian. Apart from DST, Deceleration Rates (DR) have also been adopted as speed -based indicators for evaluating safety and proved to be a valid safety indicator [28].

Zhang et al. [29] proposed evasive actions – based parameters for identifying severe encounters based on pedestrian actions and vehicle jerk for detecting pedestrian conflicts a unsignalized intersections. The same jerk threshold ($-8m/s^2$) was also combined jerk profiles with TTC values for detecting critical traffic events.

## 4 Discussion

The conducted literature review revealed various indicators used for describing the interaction between vehicles and pedestrians as well as thresholds established for classifying different interaction severity levels. Time -, distance- and speed – based indicators have been established aiming to assess interactions' safety levels at different meeting location types more accurately and precisely. The review also highlighted that the combination of time – and speed - based indicators is very popular and proved to be reliable for assessing the safety levels of pedestrian – vehicle interactions. The sole use of temporal, or any other type, indicators may be proved to be insufficient in detecting all the critical conditions or misinterpreting a situation as unsafe and critical.

To improve clarity and facilitate comparison among the various surrogate safety indicators identified in the literature, a consolidated summary is provided in Table 2. Table 2 presents the main indicators along with their definition, unit of measurement, primary purpose, applicable interaction context, and indicative threshold values reported in previous studies. This structured overview supports a more comprehensive understanding of the similarities, differences, and applicability of each indicator.

The improved presentation of the literature, combining narrative-based citations and structured comparison of indicators, reveals important patterns that are not immediately evident in isolated studies. In particular, it becomes clear that while early research primarily relied on single time-based indicators such as TTC and PET, more recent studies increasingly adopt combined approaches integrating temporal, spatial, and kinematic variables. This shift reflects the growing recognition that no single indicator can fully capture the complexity of vehicle–pedestrian interactions.

**Table 1.** Indicators for describing and evaluating vehicle – pedestrian interactions

| | **Location** | | | | **Indicator** | | | | **Thresholds** |
|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Signalized** | **Unsignalized** | **Mid-block-Crossing** | **Jaywalking** | **Time-based** | **Distance-** | **Speed-based** | **Other** | |
| [1] | | √ | | | √ | | | | LPET≤1s, LPET≤5s, L PET>5s |
| [2] | | | | √ | √ | √ | √ | | CS > 1m/s, MD <1.5m, TMD<1.5s |
| [3] | | | √ | | √ | | | | $TTZ_{arr}$<2.5s, $TTZ_{arr}$<3.5s, $TTZ_{arr}$<4.5s, $TTZ_{arr}$>4.5s |
| [4] | | | | √ | √ | | | | TTC<2.5s, TTC<3.5s, TTC<4.5s, TTC>4.5s |
| [5] | | | √ | | √ | | | | $TTZ_{arr}$<3s, $TTZ_{arr}$<5s, $TTZ_{arr}$>5s |
| [7] | | | √ | | √ | | √ | | PET≤1.5s and S>40km/h, PET≤5s and S<40km/h, PET>5s:no risk |
| [8] | | | √ | √ | √ | | | | PET≤3s, PET<1s, RTTC <3s, RTTC <1s |
| [10] | √ | | | | √ | | | | TTC≤1.5s |
| [12] | | √ | | | √ | | | | PET≤1.5s:dangerous |
| [13] | | | | √ | √ | | | | TTC≤3.6s:pedestrian at high risk |
| [17] | | | √ | | | | √ | | DR<3.0m/s$^2$, DR<4.5m/s$^2$, DR<6m/s$^2$, DR>6m/s$^2$ / TA<2s, TA<1.8s, TA<1.6s |
| [19] | | √ | | | √ | | | | Evasive action by one of the agents: TTC<1.5s,TTC<2.5s, TTC>2.5s<br>No evasive action TTC<1.3s and PET<1s, TTC >2.3s and PET >2.6s |
| [20] | √ | | | | √ | | √ | | PET<2.32s,$TA_{veh}$<1.12s,$DST_{ped}$<-2.74m/s$^2$,$TA_{Ped}$<0.88s and $DST_{veh}$<-1.68 m/s$^2$ |
| [22] | | | √ | | √ | | | | TAdv <2-3s |
| [23] | | | √ | | √ | | | √ | PPF→Safe:PET>3.3s,TTC>4s & DST<1.5m/s$^2$, Slight conflict: 1s<PET≤3.3s, 2s<TTC≤4s & DST<1.5m/s$^2$,Serious conflict: PET≤1s,TTC≤2s & DST≥1 m/s$^2$<br>VPF→ Safe: PET>2s and TTC>3s, Slight conflict: 1s<PET≤2.5s and 1s<TTC≤3s, Serious conflict: PET≤1s and TTC≤2s |
| [25] | √ | | | | √ | | | | PET≤2s,PET≤5.5s, PET>5.5s |
| [26] | | √ | | | √ | | √ | | High risk: PET≤ 1.5s and Speed 48≥km/h<br>Moderate-risk:1.5s≤PET ≤3s, 32km/h≤Speed≤48km/h<br>Low-risk: 3s≤PET≤5s and 16km/h≤Speed≤32km/h<br>Safe: PET≥5s and Speed≤16km/h |
| [27] | | √ | | | √ | | | | Evasive action by one of the agents : TTC<1.5s, TTC<3s, TTC>3s<br>No evasive action: PET<1s, PET<3s, PET>3s |
| [28] | | √ | | | | √ | √ | | PPF: Hupfer et al. (1998), VPF: PD<1.7m, speed >8m/s |
| [29] | | | | √ | √ | √ | | | RD<1.5m, TTC<5s : conflict, PET≤1s: critical |

**PPF: pedestrian passes first, VPF: vehicle passes first*

**Table 2.** Summary of key surrogate safety indicators for vehicle–pedestrian interactions

| **Indicator** | **Definition** | **Unit** | **Purpose** | **Interaction Type** | **Typical Thresholds** |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| TTC (Time to Collision) | Time until collision if trajectories remain unchanged | s | Collision imminence | All | 1–3 s |
| PET (Post Encroachment Time) | Time difference at conflict point | s | Conflict detection | Intersections, crossings | 1–3 s |
| TAdv (Time Advantage) | Temporal priority between users | s | Interaction characterization | Crossings | <2–10 s |
| TA (Time to Accident) | Time to potential accident in conflict analysis | s | Severity classification | General | <1.5–3 s |
| MD (Minimum Distance) | Minimum separation distance | m | Spatial risk | All | <1.5 m |
| RD (Relative Distance) | Instantaneous distance between users | m | Collision likelihood | All | <1.5 m |
| PD (Passing Distance) | Distance during passing maneuver | m | Interaction proximity | Crossings | <1.5–2 m |
| DR (Deceleration Rate) | Rate of speed reduction | $m/s^2$ | Severity of evasive action | All | >3 $m/s^2$ |
| DST | Required deceleration to avoid collision | $m/s^2$ | Safety evaluation | All | Context-dependent |
| Jerk | Rate of change of acceleration | $m/s^3$ | Abrupt maneuver detection | All | < -8 $m/s^3$ |

# 5 Conclusions

This study presented a comprehensive review of surrogate safety indicators used to assess vehicle–pedestrian interactions across intersections, mid-block crossings, and jaywalking conditions. While a wide range of time-, distance-, and speed-based indicators has been identified, the analysis reveals several important trends, limitations, and research needs that extend beyond a simple summary of the literature.

The methodological approach of this review combines systematic literature organization with enhanced interpretative synthesis, aiming to bridge the gap between descriptive reporting and analytical insight. A key finding is the lack of consistency in threshold values across studies, even for widely used indicators such as TTC and PET. This variability limits the comparability of results and suggests that many thresholds remain context-dependent, influenced by factors such as traffic composition, infrastructure design, and local behavioral patterns.

Another important insight is the increasing shift toward combined indicators that integrate temporal, spatial, and kinematic variables. These approaches appear more robust in capturing the complexity of pedestrian–vehicle interactions compared to single-indicator methods. However, their practical applicability is often constrained by data requirements and computational complexity.

The review also indicates a growing trend toward the use of advanced data collection techniques, such as video-based trajectory extraction and simulation environments. Despite this progress, there remains a gap in the validation of surrogate safety measures against real-world crash data, particularly in diverse traffic environments and under emerging conditions such as automated and connected mobility systems.

Furthermore, limited attention has been given to behavioral heterogeneity, including differences in pedestrian decision-making, risk perception, and interaction with automated vehicles. Addressing these aspects is essential for developing more realistic and human-centered safety assessment frameworks. Future research should focus on: (i) establishing harmonized or adaptable threshold frameworks, (ii) validating surrogate indicators across different contexts and datasets, (iii) integrating behavioral and environmental factors into safety models, and (iv) exploring the implications of emerging mobility technologies on pedestrian safety.

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