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

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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.

Objectives

- This study presents 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.
- The paper 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.
- Lastly, a **consolidated framework** is introduced to facilitate the comparison of indicators in terms of their definition, applicability, and thresholds.

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.
- **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.
- 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/s², 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/s³), is also used to capture sudden changes in motion that may indicate critical interactions.

Time-based indicators

- Time-based measures describe how close in time a **potential conflict or collision may occur**. Key indicators include Time to Collision (TTC), Post Encroachment Time (PET), Time Advantage (TAdv), and Time to Accident (TA). These metrics are widely used to identify and classify conflict severity, with lower values generally indicating higher risk. They are particularly effective for analyzing dynamic interactions using trajectory data.

Distance-based indicators

- Distance-based indicators focus on the **spatial proximity between vehicles and pedestrians**. Measures such as Minimum Distance (MD), Relative Distance (RD), and Passing Distance (PD) quantify how close the two road users come during an interaction. Smaller distances indicate increased collision risk, making these indicators useful for assessing safety in confined or low-speed environments.

Speed-based indicators

- Speed-based indicators capture the **intensity of vehicle movements and evasive actions**. Metrics such as Deceleration Rate (DR), Deceleration to Safety Time (DST), jerk, and DeltaV reflect how abruptly a driver reacts to avoid a conflict. These indicators are primarily used to assess the severity of interactions rather than their occurrence.

Combined indicators

- Combined indicators integrate **time, distance, and speed components** to better represent the complexity of vehicle–pedestrian interactions. These approaches provide a more comprehensive assessment of both collision likelihood and severity, addressing the limitations of single indicators and supporting more robust safety analysis.

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.

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

Authors	Location				Indicator				Thresholds
	Signalized	Unsignalized	Mid-blockCrossing	Jaywalking	Time-based	Distance-based	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, PETs≤5s and S<40km/h, PET>5s:no risk
[8]			√	√	√				PETs≤3s, PET<1s, RTTC <3s, RTTC <1s
[10]	√				√				TTC≤1.5s
[12]		√			√				PETs1.5s:dangerous
[13]				√	√				TTC≤3.6s:pedestrian at high risk
[17]			√				√		DR<3.0m/s², DR<4.5m/s², DR<6m/s², DR>6m/s² / 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 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/s²,TA_{Ped}<0.88s and DST_{veh}<-1.68 m/s²
[22]			√		√				TAdv <2-3s
[23]			√		√				PPF→Safe:PET>3.3s,TTC>4s & DST<1.5m/s², Slight conflict: 1s<PETs3.3s, 2s<TTCs4s & DST<1.5m/s²,Serious conflict: PETs1s,TTCs2s & DST≥1 m/s² VPF→ Safe: PET>2s and TTC>3s, Slight conflict: 1s<PETs2.5s and 1s<TTCs3s, Serious conflict: PETs1s and TTCs2s
[25]	√				√				PETs2s,PETs5.5s, PET>5.5s
[26]		√			√		√		High risk: PETs 1.5s and Speed 48≥km/h Moderate-risk:1.5sPET s3s, 32km/hsSpeeds48km/h Low-risk: 3sPETs5s and 16km/hsSpeeds32km/h Safe: PET≥5s and Speeds16km/h
[27]		√			√				Evasive action by one of the agents : TTC<1.5s, TTC<3s, TTC>3s 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
[30]		√			√				PETs1s: critical
[31]			√		√				3.6≤TTCs4.3s
[33]		√			√	√	√		PPF→ TTCs5s, TTCs8s and TTC>8s, VPF → TTC s-2s safe interaction and TTC >-2s short time gap DRs 2m/s2 (light), DR≤3.45m/s2 (medium), DRs5m/s2 (heavy) and DR>5m/s2 (emergency) - DC s12m, DC s30m and DC>30m
[34]		√						√	Risk indicator (RI) <2.26s , RI< 2.94s , RI< 3.97s, RI>3.97s
[36]	√		√				√	√	Pedestrian step frequency<0.7steps/s², jerk<-8m/s²
[38]			√		√				TAdv <10s for considering conflicts
[39]	√				√		√		TTC<2s, Jerk<-8m/s²
[40]			√		√				LPETs1s, LPETs3s, L PET>3s
[42]							√		DSTs0m/s², DST<1m/s², DST<2m/s², DST <4m/s², DST <6m/s², DST ≥6m/s²

- 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.
- 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.
- At the same time, the **variability in reported threshold values** highlights the absence of universally accepted standards, reinforcing the need for context-sensitive or adaptive evaluation frameworks.

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/s²	Severity of evasive action	All	>3 m/s²
DST	Required deceleration to avoid collision	m/s²	Safety evaluation	All	Context-dependent
Jerk	Rate of change of acceleration	m/s³	Abrupt maneuver detection	All	< -8 m/s³

Conclusions

- 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.
- 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.
- Based on these findings, **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.
- Overall, this review contributes not only by organizing existing knowledge but also by **identifying critical directions** for advancing the assessment of vehicle–pedestrian interaction safety.