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Modeling Pedestrian Priority at Unsignalized Crossings Using Machine Learning: A Review

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Abstract

Pedestrian safety at unsignalized crossings is a critical concern in urban transport, where priority negotiation often depends on informal interactions rather than strict regulatory control. Over the past two decades, researchers have employed diverse methods to model pedestrian priority, ranging from gap-acceptance theory and statistical regression to simulation-based approaches. However, these methods have struggled to capture the complexity and variability of pedestrian–vehicle interactions across different contexts. Recent advances in machine learning (ML) offer new possibilities by enabling the integration of large-scale, high-resolution datasets and the identification of latent behavioral patterns with greater predictive accuracy. This article presents a literature review of the conceptual, methodological, and policy-oriented research on modeling pedestrian priority at unsignalized crossings. It synthesizes contributions from traditional traffic engineering approaches and highlights the emergence of ML-based methods, including supervised learning, deep learning, and hybrid models. Contextual determinants such as infrastructure design, pedestrian and driver characteristics, and multimodal interactions are also reviewed to frame the broader applicability of predictive modeling. The review identifies critical gaps in data availability, model interpretability, and policy translation, calling for future work on explainable, context-aware ML frameworks and interdisciplinary collaboration. By systematically mapping the state of the art, this literature review underscores the potential of ML-driven insights to inform evidence-based transport policy, enhance pedestrian safety, and support the development of inclusive and sustainable mobility systems.

Keywords

pedestrian priority, unsignalized crossings, machine learning, road safety, modeling, prediction models

1 Introduction

The increasing emphasis on sustainable and equitable urban mobility has brought pedestrian safety and accessibility to the forefront of transportation research and policy (Levulytė et al., 2017; Ceder, 2021). Pedestrians, as the most vulnerable road users, face elevated risks at unsignalized crossings, where priority negotiation depends largely on informal interactions between drivers and pedestrians rather than explicit regulatory control (Ezzati Amini et al., 2019; Sarker et al., 2024). These crossing environments present unique challenges for transport planners: balancing vehicular efficiency with pedestrian rights, ensuring compliance with road safety principles, and aligning with broader objectives of livable and inclusive cities (Al-Mahamid et al., 2025; Doi et al., 2016; Ghadi and Török, 2021; Rui and Othengrafen, 2023; Xu et al., 2020). Yet, despite significant progress in traffic engineering and behavioral studies, pedestrian priority at unsignalized crossings remains inconsistently understood and inadequately modeled in policy frameworks (Nassereddine, 2025).

Traditional approaches to examining pedestrian–vehicle interactions have largely relied on descriptive statistics, gap-acceptance models, and traffic conflict techniques (Kadali et al., 2015). While these methods provide valuable insights, they often fall short of capturing the complexity and stochastic nature of crossing dynamics, particularly when heterogeneous road users, contextual factors, and cultural norms interact. In contrast, the growing application of

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machine learning (ML) and data-driven models offers new opportunities to advance both methodological rigor and practical relevance. By leveraging naturalistic trajectory data, video analytics, and multimodal transport datasets, ML-based frameworks can model latent behavioral patterns, predict priority negotiations, and quantify the safety implications of policy interventions with greater accuracy (Hamdan and Sipos, 2025a; Mobini Seraji et al., 2025; Yang et al., 2024).

The literature is fragmented across transportation engineering, computer science, and behavioral psychology, with few integrative reviews that systematically examine the state of knowledge on ML applications in modeling pedestrian priority at unsignalized crossings. Addressing this gap is essential not only for advancing scientific understanding but also for guiding policy innovations that ensure safe and equitable urban mobility systems.

In this literature review, we aim to synthesize the emerging body of research at the intersection of pedestrian safety, priority modeling, and machine learning applications. Specifically, we address the following guiding questions:

1. Conceptualization of Priority: How has pedestrian priority at unsignalized crossings been conceptualized, operationalized, and measured across empirical studies?
2. Methodological Advances: What machine learning approaches have been applied to model pedestrian–vehicle interactions, and how do they compare with traditional statistical frameworks in terms of accuracy, interpretability, and policy relevance?
3. Data and Contextual Factors: What types of datasets (e.g., video analytics, trajectory data, naturalistic observations) and contextual variables (e.g., traffic volume, infrastructure design, cultural norms) have been integrated into ML models of pedestrian priority?
4. Research Gaps and Future Directions: What are the key limitations of current studies, and how can future research better integrate ML methodologies with transport policy frameworks?

By systematically addressing these questions, this article contributes to bridging the methodological and policy domains, thereby advancing the potential of ML-driven pedestrian priority modeling as a cornerstone of data-driven transport policy solutions.

The search engines implemented were ScienceDirect (Elsevier, online-a), Scopus (Elsevier, online-b), and IEEE Xplore (IEEE, online). Additional articles were identified analyzing the citations referenced in other articles. Search terms included unsignalized crossing, accident, pedestrian priority, prediction models, pedestrian–vehicle interactions and machine learning. These search terms were based on what is commonly found in the literature. This review of pedestrian-focused studies at unsignalized crossings encompasses research published between 2013 and 2025, totaling 45 studies. Of these, 18 studies employed traditional statistical and observational methods, including gap acceptance analyses, behavioral surveys, and direct video-based observations, primarily quantifying pedestrian decision-making and risk exposure. 15 studies utilized modeling and simulation approaches, including agent-based, game-theoretic, fuzzy logic, and psychophysics-based models, to provide detailed mechanistic insights into pedestrian-vehicle interactions and crossing decision-making processes. The remaining 12 studies applied machine learning and artificial intelligence techniques, including supervised and unsupervised learning, interpretable ML, and deep learning frameworks, to predict pedestrian crossing behavior, vehicle yielding, and safety outcomes under complex traffic conditions. This categorization highlights the methodological evolution in pedestrian research at unsignalized crossings, demonstrating a clear progression from classical observational studies toward advanced computational and predictive modeling frameworks that enhance both understanding and evidence-based interventions for improving pedestrian safety.

2 Conceptualizing pedestrian priority at unsignalized crossings

Priority at unsignalized crossings is complex, as it is situated at the intersection of legal prescriptions, human behavior, and socio-cultural expectations. Unlike signalized intersections where control devices explicitly dictate movement rights, unsignalized crossings often depend on negotiated interactions between drivers and pedestrians. Priority in such contexts is not only a matter of traffic law but also a behavioral construct shaped by perception, trust, and implicit communication cues such as eye contact, speed adjustments, and body posture (Amado et al., 2020).

2.1 Definitions and theoretical underpinnings

In traffic law, priority typically denotes the legal right-of-way granted to one road user over another (Zhang et al., 2025). However, the translation of legal right into observable behavior is rarely straightforward. Drivers may not always yield even when obligated, and pedestrians may choose not to assert their legal rights if they perceive risks or ambiguities in driver intentions (Hell et al., 2021).

Theoretical frameworks such as gap-acceptance theory have historically been employed to conceptualize pedestrian decision-making, where individuals evaluate traffic gaps as acceptable or unacceptable for crossing (Tian et al., 2022). However, gap-acceptance models assume rational, utility-maximizing behavior, whereas contemporary behavioral evidence suggests that pedestrians often rely on heuristics, social cues, and adaptive strategies (Tian et al., 2025).

2.2 Behavioral and psychological perspectives

Understanding priority at unsignalized crossings requires close attention to human factors. Pedestrian decisions are influenced by perceived safety, personal risk tolerance, and confidence in driver compliance. Eye contact and mutual acknowledgment are often cited as mechanisms for establishing informal right-of-way, though their effectiveness varies across contexts (Kalam et al., 2025; Sahani et al., 2018). From the driver's perspective, yielding behavior may be influenced by perceived pedestrian vulnerability (e.g., children, older adults), vehicle speed, or situational urgency (Ahmed et al., 2024; Krizsik and Sipos, 2024).

Behavioral psychology also underscores the role of social norms in shaping yielding practices. In regions where pedestrian priority is culturally reinforced, drivers tend to comply more frequently, whereas in settings with weaker enforcement or inconsistent norms, pedestrians may be reluctant to claim their legal rights (Nordfjærn and Şimşekoğlu, 2013). This divergence has implications for cross-country comparability of priority models and raises challenges for the transferability of machine learning models trained on localized data. Table 1 presents a summary of key studies examining pedestrian behavior and safety at unsignalized crossings. The included studies investigate factors such as gap acceptance, crossing speed, distraction, cognitive load, traffic interactions, infrastructural interventions, and modeling approaches. This overview highlights the research context, methodological approach, and main findings, providing a foundation for understanding pedestrian priority and informing predictive and safety-oriented models at unsignalized crossings.

3 Traditional approaches to modeling pedestrian priority

Research on pedestrian priority at unsignalized crossings has historically relied on conventional traffic engineering and behavioral modeling techniques. These approaches, while foundational, reveal important limitations when applied to the inherently stochastic and interactive nature of pedestrian–vehicle encounters. Many studies employed manual observation and video-based conflict analysis to quantify yielding rates, waiting times, and pedestrian gap acceptance (Habibovic et al., 2013; Sheykhfard and Haghighi, 2020; Singh and Kathuria, 2021). Furthermore, Gap-acceptance models, logistic regression, and survival analysis became the dominant analytical frameworks for explaining pedestrian crossing decisions (Rella Riccardi et al., 2023; Sogbe, 2024; Tian et al., 2024). Later, Microsimulation and agent-based models extended analytical methods by enabling the replication of complex traffic environments and heterogeneous actors (Gracian et al., 2024; Lakmali et al., 2024). Game-theoretic models, for example, conceptualized crossings as negotiation processes where pedestrians and drivers act as rational players with competing objectives (Amini et al., 2021; Ezzati Amini et al., 2024). Despite their theoretical appeal, these models often relied on strong assumptions regarding rationality, perfect information, or parameter calibration, which constrained their predictive realism.

Overall, traditional approaches provided valuable descriptive and inferential insights but exhibited limited scalability and predictive robustness. Their deterministic or parameter-driven nature restricted their applicability in heterogeneous, high-density, or culturally diverse contexts. These limitations have created space for data-driven and machine learning methods, which are capable of handling complex, high-dimensional datasets and capturing latent behavioral patterns beyond the reach of classical models.

4 Emergence of machine learning in pedestrian priority research

Recent years have witnessed a marked shift from classical modeling techniques toward machine learning (ML)-driven approaches for predicting pedestrian priority at unsignalized crossings (Hamdan and Sipos, 2025b; Usman and Khattak, 2026). ML models offer the capacity to analyze large-scale, high-dimensional datasets, capture non-linear and context-dependent behaviors, and provide predictive insights with potential policy relevance (Hamdan and Sipos, 2025c). This section synthesizes existing research along three dimensions: data sources, ML methodologies, and evaluation of model performance.

4.1 Data sources and collection techniques

The quality and granularity of input data are critical for ML-based modeling. Studies increasingly leverage:

- Video-based observations and computer vision outputs: Automated extraction of pedestrian trajectories, vehicle

Table 1 Summary of key studies on pedestrian behavior, safety, and crossing characteristics at unsignalized crossings

Study	Country of the dataset	Description	Key findings
Ivanović et al. (2022)	Serbia	Behavioral analysis at 4 urban unsignalized crossings using a multiphase model integrating DEA, fuzzy DEA, FUCOM, PIPRECIA, MARCOS to assess crossing efficiency	Shorter accepted gaps associated with women and individual pedestrians; some risky behavior observed
Komarova (2022)	Poland	Observed pedestrian and vehicle flows to determine intersection capacity and critical headways for safe unsignalized crossing	Actual pedestrian headways shorter than required; increasing pedestrian volume reduces lane capacity; unsignalized crosswalks on high-volume roads can significantly reduce traffic efficiency
Yang et al. (2022)	China	Evaluated upstream detection (UD) strategy at mid-block crosswalks serving pedestrians and non-motor users using VISSIM simulations	UD strategy reduces pedestrian delays even in mixed traffic; higher non-motor presence increases overall delays; effective for enhancing unsignalized crossing efficiency
Perra et al. (2022)	Greece	Observed 554 pedestrians at unsignalized crossings using Bayesian regression to study distraction by mobile phone	Distraction increases exposure duration; carrying objects or crossing with companions extends crossing time ; provides data for predictive models for unsignalized crossing safety
Farooq et al. (2024)	Pakistan	Peak-hour video observations at unsignalized intersection; analysis of pedestrian and vehicle violations, traffic patterns, and road infrastructure	Illegal pedestrian crossings and parking were main congestion factors; countermeasures include signage, enforcement, awareness, and infrastructure modifications
Pawlak et al. (2025)	Poland	Assessed active pedestrian crossing system (sensors and warning signals) under high pedestrian flow and limited visibility	High pedestrian detection accuracy; false activations minimal; low driver yielding (27.8%); highlights need for system calibration and driver awareness campaigns
Otković et al. (2025)	Croatia	36 parameters analyzed across 11 unsignalized school-zone crosswalks; neural networks used to determine dominant influences on children's crossing speed	Traffic and infrastructure most influential; children's behavior and risky actions significant when dominant correlations excluded; high predictive accuracy for crossing speed models

speeds, and spatial interactions (Banerjee et al., 2023; Pavel et al., 2022; Tahir and Haque, 2024).

- Naturalistic driving data: Instrumented vehicles and GPS-based recordings capturing driver responses in real-world (Carsten et al., 2013; Ziakopoulos et al., 2020).
- Sensor fusion datasets: LiDAR, radar, and smart-city sensor networks enabling multi-modal detection and tracking (Syamal et al., 2024).
- Crowdsourced or connected mobility data: Mobile apps and connected vehicles providing large-scale behavioral datasets (Mahrez et al., 2022; Shamroukh et al., 2025).

These datasets allow ML models to move beyond pre-defined explanatory variables, enabling detection of subtle patterns in pedestrian–vehicle interactions that were previously inaccessible.

4.2 Machine learning approaches

A wide spectrum of ML techniques has been applied, ranging from classical supervised methods to deep learning architectures. A first line of inquiry has concentrated on predicting pedestrian decision-making at the crossing interface. Singh et al. (2024) and Sakib et al. (2024) both employed supervised classifiers to forecast crossing choices and crosswalk usage, respectively, finding that ensemble tree-based methods, particularly Random Forest (RF) consistently outperformed econometric and other ML baselines. Their findings emphasize that behavioral variables such as pedestrian delay, arrival order, and walking speed, together with infrastructural attributes including crosswalk suitability, median guard rails, and lighting, critically shape pedestrian compliance and priority. Extending this line, Zhang et al. (2023) demonstrated, through simulator experiments, that neural network architectures significantly improve the prediction of crossing initiation time and duration over logistic and linear regression models, thus advancing micro-level behavioral prediction.

A complementary body of work has focused on driver yielding and pedestrian–vehicle interaction dynamics. Fu et al. (2022) integrated a Distance–Velocity conceptual framework with ML algorithms, showing that RF and logistic regression outperform traditional gap-acceptance models, with predictive accuracy surpassing 90% for pedestrians and 80% for drivers. Datta and Kadali (2025) expanded this perspective to semi-urban Indian arterials, employing advanced variants such as Bayesian neural networks, permutation-invariant SVM, and distributional autoreplicative RF to model yielding drivers' dilemma-zone behavior. Similarly, Wang et al. (2023) employed drone-derived trajectories combined with RF and SHAP analysis, concluding that vehicle–pedestrian distance dominates yielding decisions, while simultaneously demonstrating the value of interpretability in operational deployment. Collectively, these works underscore the capacity of ML to model reciprocal agent interactions that are both dynamic and contextually contingent.

Recent advances also highlight the integration of environmental and visual data into pedestrian safety modeling. Barquilla and Lee (2025) used street-view imagery from over 36,000 crosswalks in Seoul to diagnose risk factors, revealing through SHAP-enhanced RF models that lower sky openness and higher building density increase crash likelihood, while sidewalk coverage and traffic control measures mitigate risks. Their study exemplifies the scalability of computer vision combined with interpretable ML for urban diagnostics. Parallel efforts in smart city contexts, such as Kim and Chan (2025), have harnessed video analytics (YOLO-based detection) to provide real-time pedestrian crossing alerts to drivers, demonstrating strong potential for embedded safety systems in dense traffic environments.

Finally, beyond predictive modeling, decision-analytic and cross-domain applications have contributed valuable complementary insights. Fattah et al. (2025) applied multi-criteria decision-making models to classify risky crossing behaviors in Khulna, identifying group crossings, mobile-phone use, and perpendicular patterns as particularly hazardous. While not strictly ML-driven, their approach underscores the importance of structured behavioral prioritization. In parallel, Bustamante Orellana et al. (2025) explored ML prediction of driver automation usage, finding workload to be the most decisive factor. Although centered on automated driving rather than pedestrian safety, their findings reinforce the generalizability of ML for human decision prediction in safety-critical contexts.

Taken together, these contributions mark a methodological maturation in pedestrian priority research. Ensemble methods, particularly Random Forest and its derivatives, have emerged as dominant tools, consistently outperforming both classical statistical baselines and alternative ML algorithms. Neural networks add precision in temporal prediction, while SHAP-based interpretability advances ensure that models are not only predictive but also actionable for policy and infrastructure design. A unifying trend across the literature is the coupling of behavioral, infrastructural, and contextual data sources to produce more holistic and operationally relevant models. This trajectory suggests that the next phase of research should focus on integrating multi-source data pipelines, advancing explainable ML, and embedding predictive systems within adaptive traffic management and smart city infrastructures to enhance pedestrian safety at scale.

5 Research gaps and future directions

Despite the growing body of literature on machine learning (ML) applications in modeling pedestrian priority at unsignalized crossings, several critical gaps remain. Addressing these gaps is essential to enhance predictive accuracy, methodological rigor, and policy impact.

Current studies are often constrained by limited data diversity, focusing on single cities or homogeneous traffic environments (Reyes-Norambuena et al., 2024). Such limitations reduce model generalizability and hinder the transferability of findings across regions with differing infrastructure, traffic laws, and cultural norms.

Based on the literature synthesis, the following avenues are recommended:

5. Interdisciplinary approaches: Combining transportation engineering, behavioral science, and AI to capture both micro-level decision-making and macro-level traffic patterns.
6. Context-aware modeling: Developing models that incorporate urban morphology, cultural norms, and multimodal interactions to improve generalizability.
7. Explainable ML frameworks: Emphasizing transparency, interpretability, and uncertainty quantification to enhance policy relevance.
8. Simulation–ML hybrids: Integrating physics-informed or agent-based simulations with ML for predictive robustness under diverse scenarios.
9. Evaluation of interventions: Longitudinal studies and pilot projects assessing the impact of ML-informed infrastructure or policy changes on pedestrian safety metrics.

By systematically addressing these research gaps, future studies can advance the dual objectives of scientific rigor and practical policy impact, supporting the development of safer, more inclusive urban mobility systems.

6 Conclusion

This review synthesizes the state of knowledge on modeling pedestrian priority at unsignalized crossings, with a particular focus on the emerging role of machine learning (ML) methodologies. Traditional approaches, including gap-acceptance models, statistical regression, and simulation-based frameworks have provided foundational insights but remain limited in capturing the stochastic, context-dependent nature of pedestrian–vehicle interactions. ML approaches, leveraging high-resolution trajectory data, computer vision, and sensor fusion, offer enhanced predictive capability, enabling the identification of latent behavioral patterns and context-specific risk factors. The integration of contextual determinants such as roadway design, pedestrian and driver characteristics, cultural norms, and multimodal interactions into ML frameworks is critical for both model robustness and policy relevance. By translating predictive insights into actionable outputs, such as risk maps, compliance metrics, and infrastructure evaluations, ML has the potential to inform evidence-based, inclusive, and sustainable transport policies. Despite these advancements, challenges persist in terms of data availability, model interpretability, and policy translation. Future research should prioritize interdisciplinary collaboration, context-aware modeling, and explainable ML frameworks to ensure that predictive insights are both scientifically rigorous and operationally meaningful. Moreover, longitudinal evaluation of ML-informed interventions will be essential to validate their real-world effectiveness and scalability.

In conclusion, modeling pedestrian priority using ML represents a promising avenue for advancing urban road safety. By bridging predictive analytics and transport policy, data-driven approaches can support safer, more equitable, and sustainable mobility systems, ultimately contributing to the global agenda of protecting vulnerable road users and promoting livable cities.

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