

Multi-Agent Simulation Modeling and Optimization Strategies for Pedestrian – Vehicle Conflict Behavior at Intersections

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Abstract

Amidst the increasing complexity of urban traffic networks and the frequent pedestrian-vehicle conflicts at intersections, this study addresses the challenges inherent in conventional methodologies, which often fail to accurately capture dynamic decision-making processes and are heavily reliant on empirical data. We propose an innovative simulation framework that synergistically integrates multi-agent behavioral modeling with dynamic non-cooperative game theory. This framework enables precise representation of pedestrian and vehicle behavioral strategies, conflict evolution, and spatial distribution patterns, complemented by conflict density mapping for enhanced visual risk assessment. Empirical results demonstrate the model's capability to accurately identify high-risk zones and to substantially mitigate conflict frequency and severity through the modulation of vehicle yielding probabilities and the regulation of pedestrian behavior. By transcending the limitations of traditional static-rule-based approaches, the proposed framework offers a robust and theoretically grounded tool for traffic safety risk evaluation, thereby furnishing valuable insights for intersection safety management and the design of intelligent transportation systems.

1. Introduction

In the course of modern urban development, transportation networks have continuously expanded and become increasingly complex. As critical nodes within urban traffic systems, intersections have become the most frequent sites of interaction between pedestrians and vehicles, and also the most conflict-prone areas. Studies have indicated that a significant proportion of traffic accidents worldwide occur at intersections. In China as well, urban intersections are recognized as high-risk zones that pose serious threats to pedestrian and vehicular safety. Furthermore, under conditions of poor signal control or high traffic density, frequent conflicts between pedestrians and vehicles not only increase traffic safety risks but also significantly reduce traffic efficiency, leading to congestion and delays.

In recent years, to better understand and address the complexity of interactions among traffic participants at intersections, numerous researchers have introduced game theory models and multi-agent modeling approaches to more accurately simulate decision-making processes and interactive behaviors. For example, a non-cooperative dynamic game model was proposed to analyze the strategic choices of drivers and pedestrians under varying speeds and levels of risk perception, providing a theoretical foundation for understanding traffic behavior (Rui et al., 2023). Game theory has also been integrated with cellular automata to simulate dynamic pedestrian-vehicle interactions, demonstrating the advantages of this approach in modeling complex traffic systems (Wu et al., 2019). The “Intend–Wait–Cross” model was developed to capture pedestrians' crossing decisions in greater detail, thereby improving the realism of pedestrian behavior simulations (Rasouli and Kotseruba, 2022). In the field of multi-agent modeling, predictive mechanisms have been introduced into social force models to enhance their ability to handle potential conflicts, further improving the applicability of these models in intersection simulations (Wang

et al., 2025). Chinese researchers have also made notable contributions. For example, based on projects at Beijing Jiaotong University, a multi-layer integrated model was constructed to incorporate social behavioral factors into intersection design, enabling in-depth analysis and quantitative simulation of interaction mechanisms at intersections (Zhang et al., 2021).

Despite these advancements in modeling precision and behavioral simulation, several critical challenges remain. From a methodological perspective, traditional rule-based or social force models still struggle to accurately capture the dynamic decision-making processes of pedestrians and drivers at intersections, especially under the influence of belief, risk perception, and time pressure. Moreover, most existing models rely heavily on large amounts of trajectory data for training and validation. In real-world applications, however, the collection of such data is often hindered by high acquisition costs and privacy concerns, severely limiting the applicability of these models. Regarding conflict detection, many studies continue to employ simple geometric or temporal thresholds, which fail to account for the cognitive evolution and bounded rationality inherent in game-based behavior, leading to insufficiently accurate or comprehensive conflict assessments.

In light of these challenges, there is an urgent need for a new method capable of accurately characterizing behavioral strategies, conflict evolution, and spatial distribution between pedestrians and vehicles at intersections, even in the absence of real-world trajectory data. This study proposes a simulation framework for intersection behavior based on multi-agent behavioral modeling and dynamic non-cooperative game theory. Additionally, a conflict density map is innovatively introduced for visualized identification and risk assessment, aiming to provide a solid theoretical basis for improving intersection safety and enhancing the efficiency of urban traffic systems.

2. Research area and data sources

2.1 Research area

The study selects the intersection of Gaoliangqiao Road and Beizhan North Street in Xicheng District, Beijing, China, as the core research area, as shown in Figure 1. This location lies within the Xizhimen transportation hub, connecting Gaoliangqiao Road and Beizhan North Street. Its unique geographical position, adjacent to Beijing North Railway Station and surrounded by key commercial facilities, residential areas, and urban rail transit stations, makes it an extremely important node within Beijing’s transportation network, bearing substantial traffic pressure.

Due to this special locational characteristic, the intersection experiences a high density of pedestrian and vehicular flow, with a large number of pedestrians, non-motorized vehicles, and various motor vehicles converging daily. The traffic volume is enormous, particularly during the morning and evening peak hours when instantaneous flow reaches its maximum. This high volume results in complex traffic behavior patterns, including multi-directional and multi-path crossings among pedestrians, non-motorized vehicles, and motor vehicles. Behaviors such as vehicle lane changes, pedestrian crossings, and non-motorized vehicle weaving are intertwined, and irregular operations by some traffic participants further contribute to the highly dynamic and uncertain nature of the traffic flow.

This intersection thus exhibits typical and representative characteristics, making it well-suited for modeling pedestrian–vehicle interactions and analyzing conflict evolution.

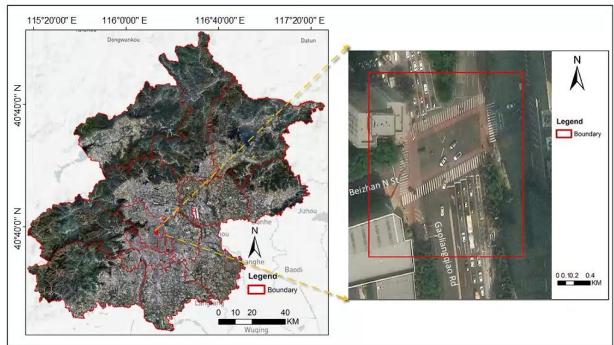


Figure 1. Research Area.

2.2 Data Sources

This study employs multi-source heterogeneous geospatial datasets to ensure a comprehensive and accurate representation of traffic conditions at the intersection of Gaoliangqiao Road and Beizhan North Street. Key spatial information including roadway configuration, lane demarcations, pedestrian sidewalk boundaries, and other critical topological features were extracted from Google Maps (<https://www.google.com/maps>). These data constitute the foundational physical environment for the simulation model, providing precise spatial boundary conditions essential for subsequent pedestrian – vehicle interaction simulations. The data collection was conducted in 2025.

To authentically capture pedestrian flow characteristics at the intersection, empirical data were obtained via on-site field surveys. Pedestrian volumes were quantified through manual counts and video analyses at all entry and exit points of the intersection across varying temporal intervals and directional

flows. These data offer crucial empirical foundations for pedestrian behavior modeling. The survey period spanned from March 21 to March 22, 2025.

Vehicular flow and speed data were sourced from the Amap Open Platform (<https://lbs.amap.com>), which delivers high-frequency, high-resolution dynamic traffic information, including real-time traffic volumes, average speeds, and congestion indices. Such data reflect the macroscopic operational dynamics of vehicular traffic, providing indispensable support for simulating both macroscopic traffic flow evolution and microscopic driving behaviors. Traffic state data for March 2025 were utilized in this study.

Furthermore, the traffic signal timing plans and control logic—integral to replicating the operational characteristics of the intersection—were principally derived from standards and signal timing guidelines issued by local traffic management authorities. A detailed analysis of these official documents enabled accurate reconstruction of signal cycles, phase sequences, green ratios, and other pertinent parameters, ensuring that the simulation outcomes faithfully represent actual signal control mechanisms.

By integrating these multi-source datasets, this research aims to develop a high-precision, high-fidelity traffic simulation framework, facilitating an in-depth examination of pedestrian–vehicle interactions and conflict evolution at the Gaoliangqiao Road and Beizhan North Street intersection.

Data Type	Data Source	Data Acquisition Period
Geospatial Data	Google Maps	Year 2025
Pedestrian Flow Data	Survey	March 21 – 22, 2025
Vehicle Flow and Speed Data	Amap Open Platform	March 2025 Traffic Condition Data

Table 1. Data Description

3. Methodology

When modeling complex traffic systems, it is common to integrate multiple approaches to capture the distinct behaviors of heterogeneous agents as well as their intricate dynamic interactions. The following section provides a detailed overview of pedestrian and vehicle behavior modeling and elucidates how, within the intersection context, these agents engage in strategic interactions through dynamic non-cooperative game-theoretic models.

3.1 Multi-Agent Systems, MAS

In complex traffic environments, multi-agent systems (MAS) provide a robust framework for simulating and understanding the dynamic behaviors of pedestrians and vehicles. The core of this approach lies in treating each traffic participant as an independent agent, each governed by a set of behavioral rules, capable of perceiving the environment and interacting with other agents, thereby generating emergent macroscopic traffic flow patterns.

Pedestrian behavior modeling is fundamental to understanding urban space utilization and traffic efficiency. The model employed here integrates the advantages of the Social Force Model and Rule-Based Models, enabling a more realistic representation of pedestrian movement decisions in complex environments. The Social Force Model decomposes the forces

acting on pedestrians into several components that collectively determine their trajectories: (1) Driving Force: the primary motivation for pedestrians to pursue their individual goals, propelling them toward their desired direction and velocity. Mathematically, this is typically represented as an adjustment of the current velocity toward the desired velocity. (2) Social Repulsive Force: an instinctive force that causes pedestrians to avoid collisions by maintaining personal space, which intensifies as the distance between pedestrians decreases, simulating mutual avoidance behavior. (3) Environmental Obstacle Force: pedestrians also avoid fixed environmental obstacles such as walls, poles, and trees. This force pushes pedestrians away from obstacles, ensuring no penetration or collision occurs. The overall pedestrian motion can be summarized as:

$$m_i \frac{dv_i}{dt} = f_i^{desire} + \sum_{j \neq i} f_{ij}^{social} + \sum_w f_{iw}^{wall}, \quad (1)$$

where f_i^{desire} = Driving Force
 f_{ij}^{social} = Social Force
 f_{iw}^{wall} = Environmental Force

Vehicle behavior modeling focuses on the decision-making processes of individual vehicles operating within traffic flows, particularly under complex conditions. The Krauss microscopic traffic flow model is employed, which assumes that drivers consistently strive to accelerate at their maximum achievable rates while decelerating as necessary to prevent collisions with preceding vehicles (Mecheva et al., 2022). This model ensures safety by considering safe following distances and driver reaction times. The decision-making process encompasses: (1) Car-following behavior: vehicles adjust their speeds based on the gap and relative velocity with the preceding vehicle to maintain a safe following distance. When the distance falls below the safety threshold, vehicles decelerate; otherwise, they accelerate. (2) Acceleration and deceleration decisions: acceleration is determined by multiple factors including the vehicle's desired acceleration, relative distance and velocity to the vehicle ahead, and the maximum possible braking capacity. The model computes a "safe speed" — the maximum speed at which the vehicle can safely travel given the current gap to the preceding vehicle — and adjusts acceleration accordingly. (3) Lane-changing decisions: although the Krauss model primarily addresses longitudinal movements, lateral maneuvers such as lane changes are incorporated in simulation through lane-changing rules, enabling vehicles to seek faster lanes or prepare for turns. (4) Stochastic perturbations: random disturbances are introduced to capture driver behavior variability such as attention lapses and reaction time differences, thereby enhancing the realism of the simulation. The fundamental dynamic equations governing vehicle motion are as follows:

$$v(t + \Delta t) = \min(v_{safe}, v(t) + a \cdot \Delta t, v_{max}), \quad (2)$$

where v_{safe} = safe velocity
 v_{max} = maximum velocity

3.2 Dynamic Non-Cooperative Game

The simulation system constructed for the intersection employs a multi-agent system to model the spatial position changes and path choices of pedestrians and vehicles. On this basis, a dynamic non-cooperative game module is introduced to handle

localized pedestrian-vehicle conflict decision-making. The coupling process consists of four steps: perception, judgment, feedback, and execution. When a pedestrian or vehicle approaches a conflict zone or when predicted trajectories intersect, the system triggers the game module. Based on variables such as position, velocity, distance, and signal status, it determines whether to enter the game scenario. The computed optimal strategy is then fed back into the multi-agent system to control individual parameters such as acceleration and passing state, thereby driving behavioral adjustments.

The dynamic non-cooperative game model is specifically designed to describe the trade-off decision-making behaviors between pedestrians and vehicles in the intersection environment. The model assumes that both pedestrians and vehicles possess independent decision-making capabilities before entering the potential conflict zone, with their strategy sets consisting of two fundamental options: "pass" and "wait." Once the game triggering conditions are met — such as the distance falling below a threshold, trajectory overlap, or signal phase transitions — the system immediately initiates a local game process. During decision-making, the system constructs the following payoff functions for each agent to quantify the benefits and costs associated with adopting a particular strategy. An example of such a payoff function is presented as follows:

$$\frac{dx_i}{dt} = x_i(f_i - \bar{f}), \quad (3)$$

where x_i = Frequency of the i th strategy
 $\bar{f}$ = Payoff

The payoff function drives strategy selection through risk penalties and time costs, thereby achieving an optimal balance between safety and efficiency.

Regarding strategy solution, this study employs the best response iteration method to compute the equilibrium strategies. Specifically, the system first enumerates all payoff values for both parties under the two strategy combinations of "pass" and "wait," constructing a local game matrix. It then seeks a stable strategy profile — i.e., a Nash equilibrium — where neither party can increase their payoff by unilaterally changing their strategy. Upon completion of the game calculation, the resulting strategy is fed back into the multi-agent system: if the outcome dictates that the vehicle waits and the pedestrian passes, the vehicle agent automatically executes deceleration or stopping maneuvers; if the pedestrian chooses to wait, their speed is set to zero while awaiting the signal change or clearing of the path. This "perception – game – feedback" closed-loop mechanism effectively enhances the model's capability to simulate pedestrian-vehicle interaction decisions and conflict evolution in complex traffic environments, providing a theoretical foundation for traffic safety assessment and optimization at intersections. The bidirectional coupling of "local game decision-making + multi-agent behavior evolution" establishes a behavior simulation framework with a perception – game – feedback closed loop, significantly improving the model's ability to characterize conflict dynamics in high-density, multi-interaction traffic scenarios.

4. Experiment

This study utilizes the AnyLogic modeling platform to develop a traffic simulation system, modeling a typical urban four-way intersection scenario with both signalized and unsignalized controls. The system dynamically captures pedestrian and

vehicle interactions and conflict processes under varying strategy constraints. Figure 2 illustrates a partial snapshot from the simulation, visually presenting dynamic trajectories of pedestrians and vehicles alongside representative interaction scenarios. The arrowed trajectory lines represent individual movement paths, with red indicating pedestrians and blue indicating vehicles. The figure highlights typical conflict situations at the intersection where pedestrian crossings interact with oncoming traffic. Arrows denote movement direction, and denser trajectory areas suggest potential conflict zones.

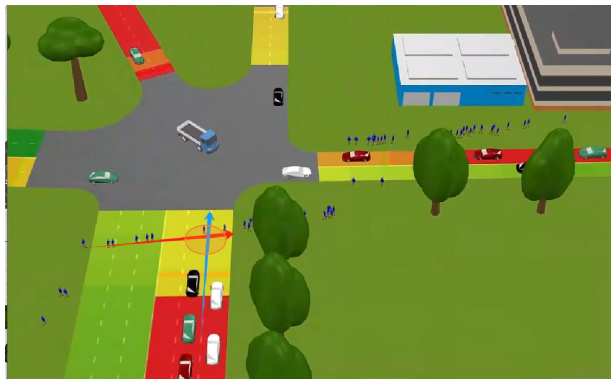


Figure 2. Simulation Illustration.

4.1 Spatial Distribution Analysis of Conflicts

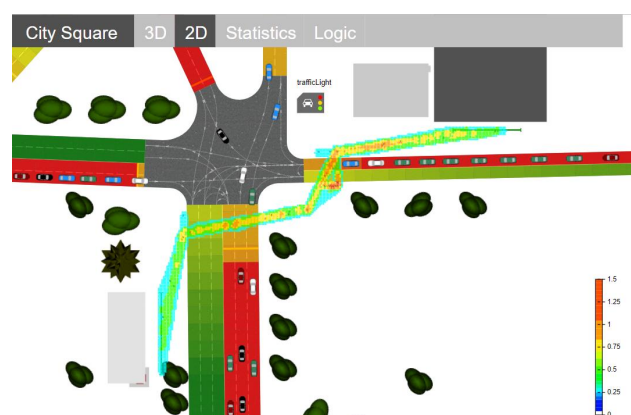
In traffic simulation, analyzing the spatial distribution of conflicts is a crucial step for assessing intersection safety and identifying high-risk areas. By visualizing simulation results as heatmaps, the clustering characteristics of conflict events within the intersection can be intuitively revealed, thereby providing valuable data support for subsequent traffic design optimization and safety management.

4.1.1 Spatial Characteristics of Conflicts under Signalized Control: Based on the analysis of conflict heatmap data generated from simulation experiments, as shown in Figure 3, high-conflict areas at the intersection exhibit significant spatial clustering, primarily concentrated in the following two typical locations.

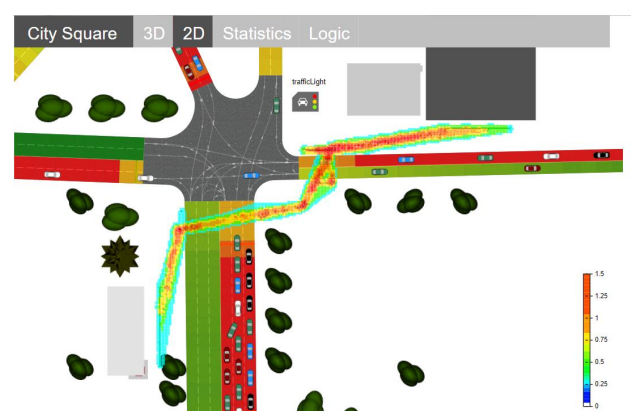
As the main pedestrian crossing route, the central area of the crosswalk experiences frequent conflicts due to multiple compounded factors. From the perspective of behavioral interaction, there is an inherent conflict between pedestrians' urgent desire to cross quickly and vehicles' goal of efficient passage. When signal timing is unclear or pedestrian flow reaches peak levels, a contention for right-of-way frequently arises in this area. The uncertainty in pedestrian movement characteristics further exacerbates the risk of conflict; fluctuations in pedestrian walking speed and path deviations significantly increase the difficulty for vehicles to make avoidance decisions. Drivers approaching the intersection must simultaneously process multi-directional traffic flows, signal statuses, and pedestrian dynamics, which can disperse their attention and lead to potential lapses in perceiving pedestrians on the crosswalk. Visual obstructions caused by surrounding buildings, parked vehicles, or large motor vehicles create blind spots in the central crosswalk area, reducing mutual perception capabilities among traffic participants. Additionally, some pedestrians have cognitive biases regarding crosswalk priority and may enter the vehicle lane prematurely without confirming safety. If drivers fail to decelerate timely due to improper speed

control or delayed judgment, the likelihood of conflict increases directly.

The high incidence of conflicts at the right-turn lane entry essentially results from the coupling of right-turning vehicles and pedestrians crossing straight ahead. Traffic regulations allowing right-turning vehicles to proceed without stopping under safe conditions potentially conflict with pedestrians' right-of-way on the crosswalk. Drivers entering the right-turn lane at relatively high speeds are prone to overlook pedestrians due to insufficient observation. During the right-turn maneuver, especially for large passenger or freight vehicles, the A-pillar structure or vehicle body layout can create blind spots, limiting the driver's perception of pedestrians in the front-right and side-rear areas. Pedestrians often focus more on the dynamics of straight-moving vehicles and underestimate the trajectories of side-turning vehicles, resulting in delayed evasive reactions. If the intersection signal timing does not include dedicated right-turn phases or independent pedestrian crossing periods, the temporal and spatial overlap between right-turn vehicle flows and pedestrian flows intensifies. Moreover, some drivers, driven by the desire to maintain traffic efficiency, may engage in aggressive right-turn behaviors when pedestrians are about to or are currently crossing, further exacerbating the right-of-way conflict.



(a) Off-peak Period



(b) Peak Period

Figure 3. Conflict Heatmap under Signal Control.

4.1.2 Conflict Spatial Characteristics under Unsignalized Control: At unsignalized intersections, traffic order primarily relies on real-time perception and autonomous decision-making by traffic participants, in the absence of unified external control mechanisms. Motor vehicles typically assess the risk of lateral conflicts by perceiving traffic elements within reachable distances ahead and decide whether to decelerate or change

trajectories accordingly to yield; pedestrians and non-motorized vehicles select crossing opportunities based on observed traffic gaps. This “local perception — autonomous response” operational mechanism replaces the centralized priority instructions of signal control systems and directly shapes the spatial evolution characteristics of traffic conflicts within the intersection.

Simulation results indicate that conflicts at such intersections are not evenly distributed throughout the space but exhibit significant spatial clustering in specific areas. As shown in the conflict heatmap (Figure 4), red zones represent locations with high conflict frequency, mainly concentrated in vehicle deceleration segments before entering the intersection, the multi-directional traffic convergence area at the intersection center, and perception blind spots at the intersection edges and corners. These areas are typical zones where traffic flow aggregates, transitions, and strategic interactions occur, resulting in elevated perceptual pressure and operational complexity. Specifically, vehicles approaching the intersection must simultaneously recognize multi-directional traffic information and select paths within a limited decision window, concentrating driver workload and increasing the likelihood of delayed reactions leading to conflicts. In the intersection center, lacking clear priority rules, motor vehicles rely on strategic judgment and dynamic yielding, causing a notable rise in conflict density. Additionally, the intersection’s corner zones, often occluded by vehicle structures and limited sightlines, create localized blind spots that raise the probability of spatial overlap among traffic participants.

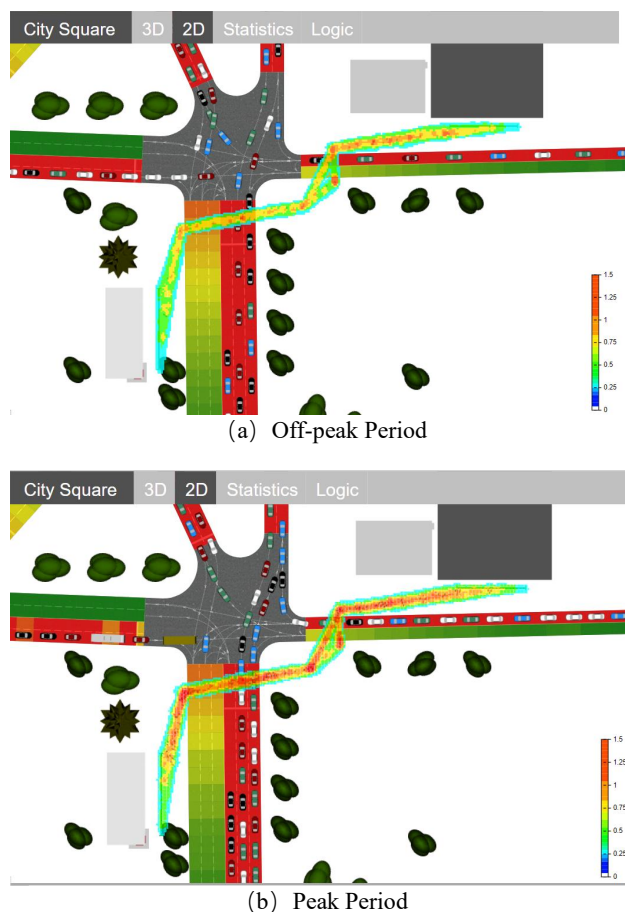


Figure 4. Conflict Heatmap under Unsignalized Control.

Although the heatmap primarily depicts conflict distribution among motor vehicles, combining actual traffic operation characteristics suggests that areas where pedestrian and non-motorized vehicle crossing paths intersect with motor vehicle trajectories also face elevated conflict risks. Under unsignalized conditions, slow-moving traffic often initiates crossing before fully entering motor vehicle perception zones, easily triggering abrupt braking or evasive maneuvers, thereby increasing system instability and intensifying localized conflicts.

4.2 Analysis of the Impact of Strategies on Conflict Probability

The study leverages a high-fidelity simulation platform to compare the impacts of different pedestrian–vehicle behavioral strategies on conflict risk at signalized and unsignalized intersections. The analysis focuses on two key behavioral parameters: first, the probability of motor vehicles yielding in potential conflict situations; second, the degree of pedestrian aggressiveness during crossing. By constructing systematic combinations of these parameters, the study examines how individual strategy variations modulate intersection safety performance, revealing heterogeneous effects under different traffic control regimes.

Results indicate that under unsignalized conditions, where traffic order primarily depends on individual local perception and autonomous decision-making, conflict potential is more sensitive to fluctuations in individual behavior. In this context, increasing the vehicle yielding probability significantly reduces both overall and localized conflict rates, particularly within densely mixed pedestrian–vehicle interaction zones, thereby demonstrating notable safety improvements. Concurrently, suppressing pedestrian aggressiveness effectively decreases conflict hotspot density. The synergistic regulation of these behaviors — characterized by a “high yielding — low aggressiveness” combination — substantially enhances the fluidity of pedestrian–vehicle interactions and overall system stability.

Under signalized conditions, since right-of-way is governed by signal phases, the system inherently imposes some order constraints, resulting in a lower baseline conflict rate. Nevertheless, during signal transition periods or at intersections of right-turning vehicles and crossing pedestrians, regulatory gaps still exist, rendering individual behavioral adjustments relevant. Simulation results show that although the marginal safety improvement from increasing vehicle yielding probability is less pronounced than in unsignalized scenarios, it still provides a clear buffering effect in local conflict zones. Likewise, reducing pedestrian aggressiveness contributes to mitigating critical conflicts during signal phase boundaries.

Across both control mechanisms, the “high yielding — low aggressiveness” behavioral strategy combination consistently exhibits a synergistic effect in suppressing conflicts, with stronger and more sensitive outcomes observed in unsignalized environments. These findings suggest that the marginal impact of individual behavioral regulation varies significantly depending on the traffic control context. Therefore, policy formulation should consider the practical boundary conditions of control mechanisms to tailor behavioral guidance and risk intervention strategies accordingly.

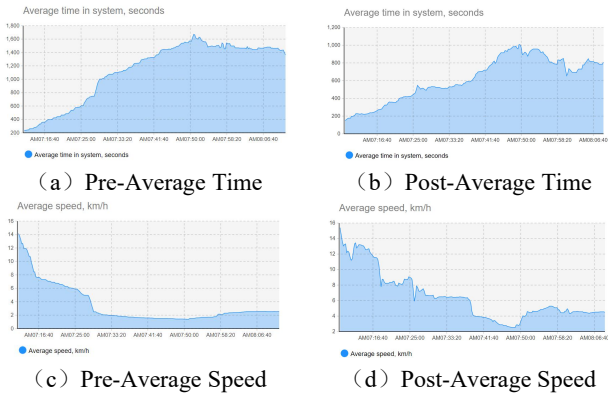


Figure 5. Comparative Data.

4.3 Temporal Indicator Analysis

To systematically characterize the impact of different control conditions and behavioral strategy combinations on intersection traffic safety, this study introduces three types of microscopic safety indicators with temporal dimensions — Post Encroachment Time (PET), Time to Collision (TTC), and Deceleration to Safety Time (DST). Compared to traditional conflict frequency statistics, these indicators reveal the spatiotemporal interaction patterns among traffic participants from a dynamic evolution perspective, enabling the assessment of available avoidance space and response pressure prior to conflict occurrence.

Within the simulation framework, vehicle yielding probability is systematically varied, and independent experiments are conducted under both signalized and unsignalized intersection scenarios to capture the response trends of each indicator across different strategies. The specific definitions of the indicators and their associated risk threshold settings are summarized in Table 2.

Indicator Name	Calculation Formula	Risk Threshold
TTC	$\frac{ v_{ego} - v_{target} \times \cos \theta}{\delta s}$	Potential risk: ≤ 3.5 s Potential risk: ≤ 6 s Critical risk: ≤ 1.5 s
PET	$ t_{target} - t_{ego} $	≤ 2.5 s
DST	$a = \frac{v_0^2 - v_s^2}{2s}$	Hazardous condition: ≥ 2.5 m/s ² Safe range: < 1.5 m/s ²

Table 2. Risk Threshold Definitions

Under unsignalized conditions, traffic participants primarily rely on local perception and autonomous decision-making to navigate the intersection, resulting in greater behavioral variability and a higher likelihood of entering conflict-prone game scenarios. Simulation results indicate that as the vehicle yielding probability increases from 50% to 80%, the average Time to Collision (TTC) rises from 2.4 seconds to 4.7 seconds, the Post Encroachment Time (PET) decreases from 9.5 seconds to 6.2 seconds, and the Deceleration to Safety Time (DST) reduces from 3.1 m/s² to 2.0 m/s². These changes reflect a significant mitigation of conflict potential and a smoother, more proactive yielding behavior.

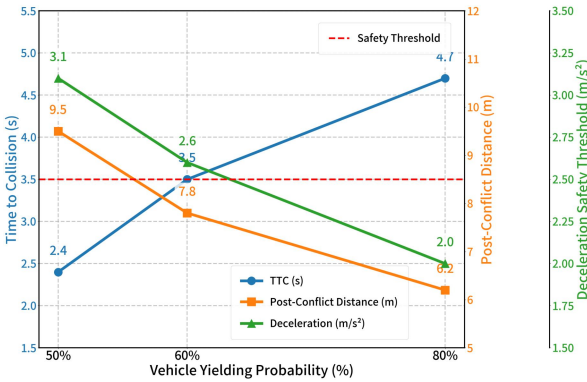


Figure 6. Temporal Safety Indicators Analysis under Unsignalized Conditions.

In signalized scenarios, although the overall conflict level is mitigated by traffic signal regulation, localized risks persist during signal transition periods (e.g., onset and end of green phases, right-turn movements). Increasing the yielding probability similarly demonstrates positive effects: TTC extends from 3.8 seconds to 5.8 seconds, PET decreases from 18.0 seconds to 10.1 seconds, and DST lowers from 2.7 m/s² to 1.6 m/s², further enhancing stability and response margins during pedestrian-vehicle interactions. Overall, yielding strategies exhibit significant safety benefits under both control regimes, with more pronounced conflict reduction effects in unsignalized contexts.

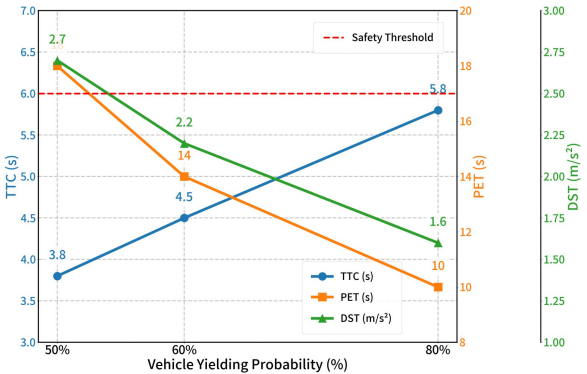


Figure 7. Temporal Safety Indicators Analysis under Signalized Conditions.

5. Conclusion

This study focuses on traffic safety issues arising from pedestrian-vehicle interactions at complex urban intersections, innovatively integrating dynamic non-cooperative game theory with multi-agent modeling to develop a simulation framework that combines high behavioral fidelity with adaptive decision-making capabilities. This framework enables detailed representation of the dynamic game processes among traffic participants in the absence of centralized control mechanisms.

Through in-depth analysis of typical intersections under signalized and unsignalized control, the study reveals significant differences in spatial conflict distribution, risk factors, and behavioral response mechanisms between the two traffic control modes. Under signalized conditions, conflict hotspots are primarily concentrated at the mid-section of pedestrian crosswalks and right-turn lane entries, reflecting the overlapping right-of-way conflicts caused by mismatches between signal phase design and pedestrian-vehicle behaviors. In contrast,

unsignalized intersections exhibit more dispersed and dynamic spatial conflict patterns, with high-risk zones frequently emerging in vehicle blind spots, reaction boundaries, and entry areas to the intersection, underscoring the instability of traffic order driven by local perception and autonomous decision-making.

The study further incorporates key microscopic safety indicators—Time to Collision (TTC), Post Encroachment Time (PET), and Deceleration to Safety Time (DST) — to quantitatively assess the impact of different behavioral strategies on system safety. Results demonstrate that increasing vehicle yielding probability significantly enhances overall traffic safety: TTC is prolonged, providing drivers with greater reaction margins; PET is reduced, shortening the duration of risk exposure; and DST decreases, indicating smoother and more controlled evasive maneuvers. Concurrently, moderating pedestrian aggressiveness effectively mitigates conflict intensity, with the combined intervention of both strategies yielding synergistic risk reduction effects.

In summary, this research transcends traditional static-rule-based traffic safety analysis by dynamically capturing the mechanisms of conflict generation and risk evolution in non-cooperative pedestrian-vehicle interactions. The proposed dynamic game – multi-agent coupled simulation framework offers a robust quantitative basis for behavior optimization and intelligent transportation system design in complex traffic environments, and provides theoretical support and practical guidance for risk identification and mitigation strategies in autonomous driving applications, demonstrating significant potential for broader application and impact.

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