

Research on Conflict Prediction and Two-Way Warning Strategy Between Right-Turning Vehicles and Pedestrians at Urban Road Intersections——A Case Study of General At-Grade Intersections in Jiaozuo City

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ABSTRACT: To address the frequent conflicts between right-turning vehicles and crossing pedestrians at urban road intersections without exclusive right-turn signal control, the limited targeting capability of conventional static warning facilities, and the high construction, operation, and maintenance costs of advanced intelligent warning systems, this study proposes a right-turn vehicle–pedestrian conflict prediction method and a bidirectional warning strategy based on easily obtainable parameters. Taking ordinary at-grade intersections in Jiaozuo as the research object, this study combines unmanned aerial vehicle video recording with ground-based manual observation to obtain 5,244 valid vehicle–pedestrian interaction samples from five typical intersections. Conflict events are labeled according to a coupled criterion of $PET < 3\text{ s}$ and $TTC < 2\text{ s}$. On the basis of variable screening, four easily measurable field parameters are selected: right-turn vehicle speed, pedestrian crossing speed, crosswalk width, and equivalent right-turn motor-vehicle flow. A binary Logit model is then developed to predict conflict probability. With $P = 0.25$ and $P = 0.55$ as thresholds, conflict risk is classified into low, medium, and high levels, and a corresponding library of bidirectional warning measures for both drivers and pedestrians is established. Independent-sample validation shows that the model achieves a conflict prediction accuracy of 88.1%, a risk-level agreement rate of 91.3%, and a ROC-AUC of 0.91, indicating good discriminatory performance and practical engineering applicability. Field application results show that, after implementation of the graded bidirectional warning measures, the average conflict rate between right-turning vehicles and pedestrians at the pilot intersections decreased by approximately 62%, the average right-turn vehicle speed decreased by approximately 22%, the overall acceptance rate among road users reached 83%, and the implementation cost per site was kept below RMB 5,000. The results indicate that a conflict prediction model based on low-dimensional and easily obtainable parameters, together with a graded bidirectional warning strategy, can support quantitative diagnosis, targeted treatment, and low-cost deployment of right-turn conflict mitigation without relying on expensive continuous sensing equipment. The proposed approach provides a replicable technical pathway for improving traffic safety at ordinary intersections in small and medium-sized cities.

KEY WORDS: Urban road intersection; Right-turning vehicle; Pedestrian conflict; Logit model; Risk grading

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I. INTRODUCTION

1.1 Research Background and Problem Statement

Urban road intersections are the nodes in urban road networks where traffic flows converge, turn, diverge, and conflict most intensively. Compared with roadway segments, intersections accommodate not only multi-directional motor-vehicle flows but also complex disturbances such as non-motorized traffic, pedestrian crossings, bus stops, and roadside parking. They therefore constitute high-incidence locations for traffic crashes and near-miss events. Signal timing may cause vehicles to stop and start frequently at intersections, increasing

pollutant emissions and aggravating environmental pollution, thereby posing threats to the urban environment and residents' health ^[1]. Traditional road safety evaluation mainly relies on crash records; however, crashes are low-frequency, random, lagging, and often incompletely reported. Such data are therefore insufficient for rapid diagnosis of microscopic risks at intersections. The traffic conflict technique uses observable hazardous interactions that do not result in crashes as surrogate safety indicators. It can identify potential safety hazards within a relatively short observation period and provides an important methodological basis for proactive intersection safety management.

Among various types of intersection conflicts, conflicts between right-turning vehicles and crossing pedestrians are both common and relatively concealed. At most urban road intersections in China, right-turning vehicles must traverse the crosswalk during turning when no exclusive right-turn signal is provided or when right turns on red are permitted. The turning trajectory of vehicles naturally intersects with the crossing trajectory of pedestrians. At the same time, drivers must process multiple sources of information, including traffic ahead, vehicles approaching from the left, non-motorized traffic on the right, and vehicle blind spots. As a result, drivers of right-turning vehicles may fail to fully comply with yielding rules, and vehicle-pedestrian conflicts continue to occur ^[2]. For pedestrians, the yielding intention of right-turning vehicles is not always clear, which may induce waiting, hesitation, sudden acceleration, forced crossing, or lingering in the conflict area ^[3]. This information asymmetry—where drivers cannot accurately perceive pedestrians' intentions and pedestrians cannot reliably judge vehicles' movements—is a major reason for the recurrent occurrence of right-turn vehicle-pedestrian conflicts.

1.2 Limitations of Existing Countermeasures

Existing countermeasures can generally be divided into three categories. The first category reduces conflict exposure through traffic engineering measures such as roadway channelization, reduction of turning radius, and provision of refuge islands. The second category achieves temporal or spatial separation of conflicts through exclusive right-turn signals, time-restricted right-turn prohibitions, or on-site enforcement. The third category provides risk warnings through signs, pavement markings, warning lamps, voice prompts, or intelligent detection devices. The first two categories usually have good safety effects, but they are often constrained by right-of-way boundaries, construction conditions, traffic efficiency, and management costs. Conventional static warning facilities are inexpensive and easy to install, but they cannot reflect differences in risk across intersections and traffic conditions. This may lead to excessive warning at low-risk sites and insufficient warning at high-risk sites. In recent years, intelligent warning systems based on video, millimeter-wave radar, edge computing, and vehicle-infrastructure cooperation have developed rapidly; however, their per-site construction and subsequent maintenance costs remain high. For the large number of ordinary intersections in small and medium-sized cities, large-scale deployment of such systems is still difficult.

1.3 Research Objectives and Technical Pathway

Therefore, the key to managing right-turn conflicts at intersections is not merely to pursue higher sensor precision or algorithmic complexity, but to establish a technical system that can be collected, calculated, implemented, and maintained by primary-level agencies. Based on field data from typical ordinary at-grade intersections in Jiaozuo, this study proposes a research framework of “easily obtainable parameters–conflict probability model–risk grading–bidirectional warning measures.” Unlike high-dimensional trajectory prediction or full-scale real-time sensing approaches, this study emphasizes the use of a small number of parameters that have clear relationships with risk and can be conveniently collected by frontline personnel. An explicit model with engineering interpretability is developed, and the model outputs are directly mapped to driver-side and pedestrian-side warning schemes that can be constructed, inspected, and promoted. The aim is to bridge the “last mile” between model output and engineering treatment.

II. LITERATURE REVIEW

Existing studies can be broadly classified into three groups: studies focusing on the mechanisms and influencing factors of vehicle-pedestrian interaction; studies using simulation methods to optimize traffic organization and facility design; and studies proposing improvement strategies through conflict modeling and evaluation. Zhao et al. investigated the safety influence mechanisms of human, vehicle, road, and environmental factors on interactions between right-turning vehicles and pedestrians at signalized intersections. Their results show that intersection design and traffic operational characteristics affect pedestrian crossing safety both directly and indirectly through their influence on the maximum deceleration of right-turning vehicles ^[4]. Wu, Jiang, and Xie addressed the lack of quantitative basis for right-turn traffic space design by analyzing correlations among elements of the right-turn traffic environment and traffic problems caused by unreasonable right-turn space design. They summarized the main influencing factors of right-turn traffic operation into two categories: turning space and participating subjects ^[5].

Pan et al. applied a cellular automaton traffic flow model and investigated the impact of right-turn traffic on urban road intersections by setting an exclusive right-turn lane and introducing right-turn probability at intersections. By introducing the average queue length upstream of the lane at the end of the red phase, they further discussed an optimization problem in roadway design [6]. Li used VISSIM simulation to conduct analyses and evaluations under different traffic volumes, and proposed suitable right-turn control strategies for different traffic flow ranges, providing a theoretical basis for alleviating vehicle–pedestrian conflicts at real intersections [7]. Sheng proposed a stepped stop-line design based on the requirements of an improved DV framework from the driver’s perspective. K-means clustering was used to classify approach speeds, a primary conflict model between right-turning vehicles and pedestrians was developed, and a method for installing speed humps in right-turn lanes was discussed [8].

Bao et al. classified the traffic modes of right-turning vehicles and pedestrians and analyzed the spatiotemporal characteristics of conflicts at intersections. In terms of temporal analysis, conflict numbers were determined using conflict probabilities under two modes: right turns permitted on red and right-turn signal phases. Their study indicates that using a right-turn phase and channelization by traffic islands can effectively reduce conflicts between right-turning vehicles and pedestrians, and that optimized placement of yield signs can provide drivers with more information for deciding whether to decelerate [9]. Yang and Ji studied conflicts between right-turning vehicles and pedestrians at intersections with different land-use types in order to reduce vehicle–pedestrian conflicts and associated safety risks. Based on video-derived conflict data, they used fuzzy C-means clustering to analyze conflict severity and causes at different intersections [10]. Li investigated pedestrian crossing conflicts with right-turning motor vehicles at intersections, including mathematical modeling of right-turn vehicle trajectories, conflict risk assessment, pedestrian crossing decisions under right-turn conflicts, and related improvement measures [11].

Li et al. studied right-turning vehicles and crossing pedestrians at signalized intersections and established a right-turn vehicle delay model by analyzing, from a microscopic perspective, the conflict process between unsignalized right-turning vehicles and crossing pedestrians, while considering the situation in which a right-turning vehicle forces its way through after waiting for a period of time [12]. Yong et al. analyzed the operating characteristics of pedestrian crossings and right-turning vehicles at at-grade intersections. They noted that when through and left-turn vehicles stop at red lights, they may obstruct the sightline of right-turning vehicles, increasing the likelihood of crashes with pedestrians on the left-side crosswalk of the right-turning vehicle. A warning device for right-turn vehicle–pedestrian conflicts can provide right-turning vehicles with necessary information about pedestrians on the crosswalk by installing sensors at the safe braking initiation location and issuing secondary warnings [13]. Feng et al. used a CatBoost-SHAP model to identify key influencing factors, finding that pedestrian flow has the most significant differential effect on three types of safety indicators, and applied multi-group path analysis to explore the influence pathways of various factors on right-turn vehicle–pedestrian conflict risk [14]. Jie and Ma extracted conflict data in the right-turn channelized island area, intersection geometric design features, channelization methods, and traffic flow characteristics, and constructed a random-effects conflict model based on Bayesian methods to account for heterogeneity among intersections. They compared the goodness of fit of fixed-effects and random-effects negative binomial models and analyzed significant influencing factors [15]. Overall, existing models often rely on complex trajectory data or simulation environments, while insufficient attention has been paid to static and low-dimensional dynamic parameters that are easily obtained during routine inspections by primary-level traffic management departments. Moreover, considerable room remains for completing the closed-loop transformation from “quantitative risk diagnosis” to “low-cost engineering prescription.” This study addresses this gap by developing a low-cost and lightweight model to support the mitigation of urban right-turn conflicts.

III. DATA SOURCES AND RESEARCH DESIGN

3.1 Sample Selection and Data Collection

The research data were obtained from field observations at five ordinary at-grade intersections in Jiaozuo. The sample sites were selected according to three principles. First, their geometric forms are representative, mainly consisting of urban road intersections without exclusive right-turn channelized islands or with low levels of channelization. Second, traffic volume levels are moderate to high, enabling coverage of typical operating conditions such as morning peak, evening peak, and off-peak periods. Third, the surrounding land-use types vary, including residential, commercial, school, and public-service scenarios. This sample design helps improve the applicability of the model to ordinary intersections in small and medium-sized cities.

Data collection adopted a combined method of aerial video recording and ground supplementary measurement. Unmanned aerial vehicles were used for fixed-point overhead filming under safe and compliant conditions to obtain macroscopic movement trajectories of right-turning vehicles and crossing pedestrians. Ground investigators simultaneously used handheld speed-measuring devices to measure right-turn vehicle speeds, stopwatches to sample pedestrian crossing times, measuring tapes to measure crosswalk widths, and

manual counts to record traffic volumes by vehicle type and movement. The survey covered weekday morning and evening peaks, off-peak periods, and weekend peaks, so that the samples could reflect variations in conflicts under different demand intensities.

3.2 Sample Processing and Variable Screening

After frame extraction, coordinate calibration, trajectory extraction, and manual review of the video data, samples with severe occlusion, interrupted trajectories, pedestrian turning back, abnormal vehicle stopping, and other conditions unsuitable for modeling were removed. Finally, 5,244 valid vehicle–pedestrian interaction samples were obtained, including 1,026 conflict samples and 4,218 non-conflict samples. Each sample recorded the right-turn vehicle speed V_{rt} , pedestrian crossing speed V_{ped} , crosswalk width W , equivalent right-turn motor-vehicle flow Q , and the conflict label. Conflict events were identified according to the coupled criterion of $PET < 3$ s and $TTC < 2$ s, thereby balancing conflict urgency with field interpretability.

In the initial variable design, this study comprehensively considered four categories of factors: vehicles, pedestrians, roads, and the environment. Twelve potential variables were extracted, including vehicle speed, acceleration, vehicle type, pedestrian speed, pedestrian density, crossing width, sight distance condition, road grade, right-turn flow, weather, and illumination. To serve primary-level applications, this study did not simply pursue a larger number of variables. Instead, correlation analysis and stepwise regression were used to screen core variables that jointly satisfy statistical significance, engineering interpretability, and ease of collection. The final four parameters can all be obtained by two investigators within a short period using conventional tools, meeting the requirements for low-cost deployment.

3.3 Description of Core Parameters

Table I. Description of Core Parameters

Variable	Meaning	Acquisition method	Engineering interpretation
V_{rt}	Right-turn vehicle speed	Handheld speed measurement or video estimation	Reflects driver reaction time and braking margin
V_{ped}	Pedestrian crossing speed	Stopwatch-based sample measurement	Reflects pedestrian exposure time in the conflict area
W	Crosswalk width	Field measurement using a tape measure	Reflects pedestrian crossing distance and exposure space
Q	Equivalent right-turn motor-vehicle flow	Manual counting and conversion to pcu/h	Reflects the intensity of vehicles entering the conflict area

IV. DEVELOPMENT OF THE CONFLICT PROBABILITY PREDICTION MODEL

4.1 Model Structure

The occurrence of a right-turn vehicle–pedestrian conflict can be represented as a binary variable: 1 indicates that a conflict occurs, and 0 indicates that no conflict occurs. Considering that the Logit model can output probability values between 0 and 1 and that the signs and magnitudes of its parameters are readily interpretable, this study uses binary Logit regression to develop the conflict probability prediction model [16]. The model takes right-turn vehicle speed V_{rt} , pedestrian crossing speed V_{ped} , crosswalk width W , and equivalent right-turn motor-vehicle flow Q as input variables, and the probability of conflict P as the output variable. The basic expression is as follows:

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \cdot V_{rt} + \beta_2 \cdot V_{ped} + \beta_3 \cdot W + \beta_4 \cdot Q)}} \quad (1)$$

where β_0 is the constant term, and β_1 – β_4 are the parameters to be estimated. The units of V_{rt} , V_{ped} , W , and Q are km/h, m/s, m, and pcu/h, respectively. To avoid overfitting the model to samples from a single intersection, the dataset was divided into training and testing sets, and intersections not used in model development were further selected for external validation. The parameters were estimated using maximum likelihood estimation, and model performance was comprehensively evaluated using a confusion matrix, accuracy, precision, recall, F1-score, Kappa coefficient, and ROC-AUC.

4.2 Parameter Estimation Results

From the perspective of traffic engineering mechanisms, V_{rt} reflects the driver’s speed choice before entering the conflict area. A higher right-turn speed shortens the time available for drivers to perceive, judge, and brake, and also reduces the time available for pedestrians to avoid the vehicle; therefore, the probability of conflict increases. Q reflects the intensity of right-turning vehicles entering the conflict area per unit time. A larger flow makes it more difficult for pedestrians to judge continuous vehicle streams and increases the likelihood of risky crossing. V_{ped} and W jointly determine pedestrian exposure time in the conflict area. When pedestrian walking speed is lower or the crosswalk is wider, the opportunity for spatiotemporal interaction

between vehicles and pedestrians increases. These variables are therefore meaningful not only statistically but also in terms of road-user behavioral logic.

After five rounds of stepwise regression analysis, stable and significant coefficient estimates were obtained. The overall goodness-of-fit statistic of the model was $\chi^2 = 263.4$ ($p < 0.001$), indicating that the model is highly significant. The final model formula is:

$$P = \frac{1}{1 + e^{(12.480 - 0.182 \cdot V_{rt} - 0.155 \cdot V_{ped} - 0.097 \cdot W - 0.064 \cdot Q)}} \quad (2)$$

where V_{rt} is measured in km/h, V_{ped} in m/s, W in m, and Q in pcu/h.

4.3 Risk-Level Classification

To make the model directly useful for engineering decision-making, the continuous probability P is further mapped to risk levels. Based on the distribution characteristics of sample probabilities, conflict severity, and engineering intervention intensity, $P = 0.25$ and $P = 0.55$ are selected as thresholds. A site is classified as low risk when $P \leq 0.25$, medium risk when $0.25 < P \leq 0.55$, and high risk when $P > 0.55$. The significance of this classification lies in assigning routine maintenance to low-risk intersections, targeted reminders to medium-risk intersections, and reinforced bidirectional warnings to high-risk intersections, thereby realizing “risk-based investment and graded treatment.”

V. DESIGN OF THE GRADED BIDIRECTIONAL WARNING STRATEGY

5.1 Basic Logic of Bidirectional Warning

Right-turn conflict management should not target only motor-vehicle drivers or only pedestrians. Conflicts between right-turning vehicles and pedestrians essentially arise from inconsistent judgments about right of way, yielding intention, and movement status within the same space. Therefore, this study divides warning targets into the driver side and the pedestrian side. Driver-side measures aim to reduce right-turn speed, strengthen yielding awareness, and provide advance warnings. Pedestrian-side measures aim to increase crossing vigilance and reduce forced crossing and blind entry into the conflict area. The objective of bidirectional warning is to create an information-symmetric state in which “vehicles know pedestrians, and pedestrians know vehicles.”

5.2 Low-Risk Scheme

For low-risk intersections, the conflict probability is relatively low. Excessive investment in acoustic and optical facilities would increase fiscal expenditure and may also cause information interference. Therefore, the low-risk scheme focuses mainly on basic maintenance and visibility improvement. The key measures are widening and repainting crosswalk markings, using materials with better retroreflective performance, and removing old or blurred markings so that basic right-of-way information is clearly visible. Such measures are low in cost and suitable for numerous ordinary intersections where risk remains acceptable.

5.3 Medium-Risk Scheme

Medium-risk intersections already have certain right-turn conflict hazards but have not reached the level requiring strong acoustic and optical intervention. At this level, driver-side measures should include installing or updating yield signs, improving the retroreflective grade of crosswalk indication signs, and strengthening visual prompts such as “Pedestrian Priority” or “Slow Down and Yield” near the crosswalk. On the pedestrian side, auxiliary prompts such as “Watch for Right-Turning Vehicles” can be installed on existing sign poles or near waiting areas to enhance pedestrians’ expectation of right-turning vehicles. The focus of the medium-risk scheme is to strengthen rule perception and attention guidance at relatively low cost.

5.4 High-Risk Scheme

High-risk intersections have a relatively high probability of conflict and should adopt compound reinforced warning measures. On the driver side, colored three-dimensional yield markings may be installed approximately 50 m upstream of the right-turn lane to improve drivers’ advance perception distance through color, pattern, and perspective effects. Retroreflective raised pavement markers can be installed along the markings to improve guidance at night and under low-light conditions. Yield signs and auxiliary “Pedestrian Priority” signs can be added at the approach to reinforce traffic rules. On the pedestrian side, solar-powered voice prompt posts and LED road studs may be deployed. When pedestrians enter the waiting area or crosswalk, directional voice prompts and flashing lights can remind them to pay attention to right-turning vehicles. The installation of relevant signs and markings should comply with the GB 5768 series standards regarding color, shape, application, and maintenance.

5.5 Summary of Graded Measures

Table II. Summary of Graded Measures

Risk level	Criterion	Driver-side measures	Pedestrian-side measures	Treatment objective
Low risk	$P \leq 0.25$	Widen and repaint crosswalk markings; improve retroreflective performance	No additional dedicated facilities	Maintain basic safety and reduce maintenance blind spots
Medium risk	$0.25 < P \leq 0.55$	Add yield signs; update crosswalk indication signs	Install auxiliary prompts such as "Watch for Right-Turning Vehicles"	Strengthen rule perception and reduce general conflicts
High risk	$P > 0.55$	Install advance colored three-dimensional yield markings, retroreflective raised pavement markers, and yield signs	Coordinate solar-powered voice prompt posts with LED road studs	Induce vehicles to decelerate in advance and remind pedestrians to observe

VI. EMPIRICAL VALIDATION AND RESULTS ANALYSIS

6.1 Validation of Model Prediction Performance

To examine the engineering effectiveness of the model and scheme, two intersections not used in model training were selected as external validation sites, and 312 new vehicle-pedestrian interaction samples were collected. The field-measured right-turn vehicle speed V_{rt} (km/h), average pedestrian crossing speed V_{ped} (m/s), crosswalk width W (m), and equivalent right-turn motor-vehicle flow Q (pcu/h) were substituted into the model to calculate conflict probabilities, and the results were compared with manual field judgments. The validation results show that the model predicted 138 conflicts, while 121 conflicts actually occurred. Among these, there were 106 true positives, 32 false positives, 15 false negatives, and 191 true negatives. The resulting overall prediction accuracy was 88.1%, precision was 76.8%, recall was 87.6%, and the F1-score was 81.9%.

6.2 Agreement of Risk-Level Judgment

In terms of risk-level judgment, the agreement rate between the low, medium, and high risk levels output by the model and the results of comprehensive manual judgment reached 91.3%, with a Kappa coefficient of 0.86, indicating high stability in the model's risk classification. The area under the ROC curve (AUC) was 0.91, demonstrating excellent discriminatory ability between conflict and non-conflict states. Considering that the model uses only four easily obtainable parameters and does not rely on continuous sensors or complex trajectory features, these results indicate that a low-dimensional explicit model can achieve satisfactory practical accuracy for engineering diagnosis.

6.3 Before-and-After Comparison of Measure Implementation

For scheme validation, corresponding bidirectional warning measures were implemented at high-risk and medium-risk intersections, followed by before-and-after observations. The results show that the average right-turn vehicle-pedestrian conflict rate at the pilot intersections decreased by approximately 62%. High-risk sites showed clear reductions during the morning peak, evening peak, and off-peak periods, while medium-risk sites also achieved stable improvements. The average speed of right-turning vehicles decreased from approximately 25.3 km/h to 19.7 km/h, indicating that advance markings, yield signs, and retroreflective facilities effectively guided drivers to decelerate in advance. The proportion of vehicles that actively decelerated or stopped to yield increased from approximately 31% to 67%, and high-risk pedestrian behaviors such as running to force a crossing and hesitant wandering were significantly reduced.

6.4 User Acceptance and Cost Analysis

A total of 235 valid questionnaires were collected. Drivers and pedestrians gave relatively high ratings for warning clarity, perceived safety improvement, and facility acceptance, with an overall acceptance rate of 83%. This indicates that the bidirectional warning measures improved not only objective conflict indicators but also the subjective safety perceptions of road users. In terms of cost, the implementation cost per pilot intersection was kept below RMB 5,000, which is significantly lower than that of advanced intelligent warning schemes based on radar, video, and edge computing. For small and medium-sized cities with limited fiscal budgets and numerous ordinary intersections, the proposed scheme has considerable potential for wider deployment.

6.5 Summary of Evaluation Indicators

Table III. Summary of Evaluation Indicators

Evaluation indicator	Result	Meaning
Conflict prediction accuracy	88.1%	Meets the accuracy requirement for engineering diagnosis
Risk-level agreement rate	91.3%	Supports graded treatment

ROC-AUC	0.91	Indicates strong model discrimination
Average reduction in conflict rate	Approximately 62%	Shows a clear effect of warning measures
Change in right-turn vehicle speed	25.3 km/h → 19.7 km/h	Indicates significant advance deceleration
Overall user acceptance	83%	Shows high recognition among road users
Implementation cost per site	≤ RMB 5,000	Suitable for low-cost large-scale deployment

VII. DISCUSSION, CONCLUSIONS, AND OUTLOOK

7.1 Discussion

The main contribution of this study does not lie in proposing a complex algorithm, but in constructing a complete closed loop oriented toward primary-level traffic management. Traditional studies often separate conflict identification, risk modeling, and engineering treatment: model studies emphasize accuracy, engineering practice emphasizes facilities, and primary-level management emphasizes cost and operability. This study attempts to integrate the three by using easily obtainable parameters for risk diagnosis, probability thresholds for risk grading, and graded results to directly match driver-side and pedestrian-side measures. This closed-loop logic can reduce the difficulty faced by primary-level managers who have data but lack actionable prescriptions.

Compared with advanced intelligent warning systems, the proposed scheme has the advantages of low cost, low maintenance requirements, and ease of replication. Advanced systems are suitable for key intersections, demonstration zones, or complex scenarios requiring real-time dynamic control, but their comprehensive deployment across a large number of ordinary intersections is not economical. The proposed scheme is suitable for ordinary intersections with prominent right-turn conflicts but limited budgets, and it can quickly improve safety conditions at relatively low cost. This is particularly meaningful in counties, small and medium-sized cities, and older urban areas where roadway reconstruction is constrained.

Low cost, however, does not imply low standards. The signs, markings, and warning facilities designed in this study must still comply with national standards and urban road engineering specifications. Construction materials, retroreflective performance, installation positions, maintenance cycles, and safety acceptance should all be incorporated into standardized management. At the same time, the frequency, volume, and operating period of voice prompts and light warnings should be optimized according to surrounding environments such as residential areas, schools, and hospitals, so as to avoid new problems such as noise disturbance or visual interference.

This study still has several limitations. First, the samples were mainly collected from ordinary at-grade intersections in Jiaozuo. The applicability of the model to highly saturated intersections in megacities, mountainous roads, cold and snowy regions, and complex channelized intersections requires further validation. Second, non-motorized vehicles such as electric bicycles were not included among the core variables, although in many cities non-motorized traffic has an important influence on right-turn conflicts. Third, warning fatigue may occur after long-term operation of bidirectional warning facilities, and whether the treatment effect can be maintained over time requires continuous observation for at least one year. Future studies may add extended variables such as non-motorized vehicle flow, nighttime lighting level, and special land-use types while maintaining model usability, thereby developing a 2.0 version of the model.

7.2 Main Conclusions

(1) Right-turn vehicle speed, pedestrian crossing speed, crosswalk width, and equivalent right-turn motor-vehicle flow are key parameters that combine statistical significance with engineering accessibility in diagnosing the risk of right-turn vehicle–pedestrian conflicts at ordinary at-grade intersections. All four parameters can be collected within a short time using conventional tools and are suitable for primary-level traffic safety management.

(2) The binary Logit conflict probability prediction model developed using the four easily obtainable parameters achieved a conflict prediction accuracy of 88.1%, a risk-level agreement rate of 91.3%, and a ROC-AUC of 0.91 in independent samples. This indicates that an extremely parsimonious parameter model can satisfy engineering diagnostic needs without relying on expensive continuous sensing equipment.

(3) The three-level risk classification using $P = 0.25$ and $P = 0.55$ as thresholds can transform abstract probability results into executable engineering treatment criteria. Low-risk intersections mainly require marking maintenance; medium-risk intersections require strengthened signs and prompts; and high-risk intersections require bidirectional coordinated measures such as advance colored three-dimensional markings, yield signs, voice prompt posts, and LED road studs. This reflects the governance concept of targeted investment according to risk.

(4) Field validation shows that, after implementation of the graded bidirectional warning measures, the average right-turn vehicle–pedestrian conflict rate at the pilot intersections decreased by approximately 62%, right-turn vehicle speeds decreased significantly, the active yielding rate increased, overall user acceptance

reached 83%, and the implementation cost per site was controlled below RMB 5,000. The results provide a low-cost, replicable, and scalable technical pathway for managing right-turn conflicts at ordinary intersections in small and medium-sized cities.

(5) Future research should expand the sample cities and road types, incorporate non-motorized vehicle factors and long-term operational data, test the stability of the model under different regions, climates, and traffic organization conditions, and further explore the integration of low-cost sensing with adaptive warning strategies.

7.3 Engineering Application Value and Deployment Pathway

From an engineering application perspective, the value of the proposed method is reflected not only in model accuracy but also in its practical usability by primary-level agencies. At present, many traffic safety research results achieve high accuracy in academic papers, but in real-world management scenarios they often require specialized software, continuous sensors, complex data-cleaning procedures, and substantial technical expertise. Primary-level traffic police and municipal maintenance agencies need practical tools that can quickly answer four questions: where is the risk high, why is it high, how should it be improved, and how much will it cost? The four-parameter model proposed in this study compresses risk diagnosis into a small amount of field survey data and an explicit probability calculation process, thereby lowering the technical threshold for traffic safety diagnosis.

In terms of funding use, risk grading can improve the efficiency of fiscal resource allocation. Conventional treatment often shows two tendencies: concentrated investment after crashes have already occurred, making the treatment lagging; or high investment in intelligent systems in a few key areas for demonstration purposes, while many ordinary intersections still lack basic risk intervention. By covering more ordinary intersections through low-cost facility combinations, the proposed scheme enables limited funds to shift from “point-based demonstration” to “area-wide improvement.” Particularly in small and medium-sized cities, an implementation cost below RMB 5,000 per site is conducive to achieving large-scale improvement effects and enhancing the equity of public safety services.

Three issues should be addressed during deployment. First, model coefficients should be allowed to undergo local calibration. Before cross-city deployment, it is recommended that a small number of representative intersections be selected to supplement local samples. Second, facility installation should avoid excessive warning so as to prevent warning fatigue among road users. Third, a post-evaluation mechanism must be established simultaneously. Each improved intersection should be observed before and after implementation, and conflict rates, speeds, yielding rates, and public feedback should be recorded.

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