

Simulation Study on Comparative Analysis of Three Types of Signal Control Strategies at Intersections under Different Penetration Rates of Connected and Autonomous Vehicles

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Abstract

During the urban traffic transition period characterized by the long-term mixed flow of human-driven vehicles (HV) and connected and automated vehicles (CAV), research lacks a systematic quantitative comparison of multiple signal control strategies across the full spectrum of CAV penetration rates. Based on the SUMO microscopic simulation platform, this paper constructs a standard urban four-way intersection model, calibrates the differentiated IDM car-following parameters for HV and CAV, sets up 6 levels of CAV penetration rate scenarios from 0% to 100%, and conducts full-factorial experiments on 3 mainstream signal control strategies: fixed timing, queue detection, and CAV green wave coordination. Average queue length, average delay, and average number of stops selected as core evaluation indicators, combined with the entropy weight method to complete a multi-indicator comprehensive performance evaluation, and the significance of the results is verified through paired t-tests. The results show that: an increase in CAV penetration rate can significantly optimize intersection throughput efficiency, but marginal benefits diminish after the penetration rate exceeds 0%; queue-sensing control exhibits optimal robustness in the low-to-medium penetration rate range of 0%~40%, making it a cost-effective for the mixed-traffic transition period; CAV green wave coordinated control achieves optimal comprehensive performance when the penetration rate is $\geq 40\%$, whereas at low penetration rates, efficiency is inferior to sensing control due to idle V2X guidance resources; Fixed timing control performs the worst across all scenarios. A dynamic selection matrix for phased signal control strategies is constructed based on simulation conclusions, providing theoretical and engineering reference for the upgrading of signal control at urban intersections during different stages of intelligent connected vehicle penetration.

Keywords

Connected and Automated Driving; Mixed Traffic Flow; Signal Control; SUMO Simulation; Penetration Rate; Vehicle-infrastructure Cooperation.

1. Introduction

Electrification, connectivity, and intelligence are the core trends in global transportation development; CAVs, with their V2V/V2I communication precise car-following control characteristics, can significantly improve intersection capacity[1]. In the coming decades, urban road networks will experience a long-term mixed state of HV and CAV, leading to a significant decline in the adaptability traditional signal control strategies designed for human driving[2].

Current domestic and international research can be divided into three categories: First, the impact analysis of CAV on basic traffic flow characteristics mostly focuses on highways, with insufficient

research on urban single-point intersections; Second, the optimization of single-type signal control algorithms is lacking a cross-generational comparison of control strategies; Third is the research on vehicle-infrastructure cooperative green wave control, which assumes a high CAV penetration rate and an ideal communication environment, ignoring the problem strategy failure in low penetration rate scenarios. Existing achievements have not yet fully covered the 0%~100% penetration rate range under a unified simulation framework, comparing the adaptation ranges three practical control strategies: fixed timing, queue detection, and CAV green wave coordination[3]. To this end, this paper takes single-point urban arterial intersections as the research object, builds a mixed traffic flow simulation environment based on the O TraCI interface, quantitatively reveals the evolution laws of the penetration rate on the effectiveness of three types of control strategies, identifies the applicable threshold intervals of each strategy and proposes a phased dynamic control scheme to make up for the deficiency of the lack of systematic comparison in existing studies.

2. Simulation Model and Experimental Design

2.1 Modeling of Intersection Road Networks and Traffic Demand

Build a simulation road network of a standard four-way intersection, with an approach length of 600m, the approach lanes are channel into three lanes for left turn, straight, and straight-right, the lane width is 3.5m, and the intersection corner radius is 15.

Traffic flow settings: East-West incoming 900 pcu/h, North-South incoming 1100 pcu/, total flow 4000 pcu/h; turning proportions: straight 60%, left turn 30%, right turn 100 vehicle arrivals follow a Poisson distribution, considering only small passenger cars, with no interference from large vehicles.

2.2 HV and CAV Tracking Parameter Calibration

The IDM intelligent driver following model is adopted to characterize the dynamic differences between the two types of vehicles[4], with core parameters shown in Table 1. The safety time headway and minimum stopping distance of CAVs are much smaller than those of human-driven vehicles, which is the microscopic basis for improving traffic capacity. Table 1 Core parameters of HV and CAV-IDM models

Table 1. Core Parameters of IDM Model for HV and CAV

Parameter	HV	CAV
Desired speed $v_0/(m \cdot s^{-1})$	16.7	16.7
Safety T/s	1.5	0.6
Minimum stopping distance s_0/m	2.0	1.0
Maximum acceleration $a_{max}/(m \cdot s^{-2})$	2.6	3.0
Comfortable deceleration $b/(m \cdot s^{-2})$	4.5	3.0

2.3 Implementation Logic of Three Types of Signal Control Strategies

1) Fixed timing control: The timing is calculated using the Webster minimum delay method, with four-phase control, a total lost time of 12s an optimal cycle of 80s, 25s for east-west straight, 15s for east-west left turn, 25 for north-south straight, and 15s for north-south left turn; the timing remains fixed and unchanged throughout the simulation[5].

2) Queue-based sensing control: Based on TraCI, the number of queued vehicles in each lane is read in real time, with a minimum green time 10s, a maximum green time of 40s, and a unit extension interval of 3s; the initial green light forces passage, phase switches early if the queue is cleared, and continues to extend to the maximum green time if not cleared, adapting to random traffic flow fluctuations[6].

3) CAV green wave cooperative control: By broadcasting the remaining traffic light duration via V2I, the CAV calculates the optimal guidance speed based on distance to the stop line; it smoothly decelerates to the target speed when predicting a red light arrival, achieving non-stop passage; assuming zero communication latency and zero loss, it explores the theoretical optimal performance of the strategy[7].

2.4 Experimental Protocol and Evaluation System

Independent variable settings: 6 levels of CAV penetration rate: 0%, 20%, 40%, 60%, 80%, 100%; 3 control strategies, totaling 18 groups of full-factorial experiments. For each group, 5 sets of random seeds are for repeated simulations, and the mean is taken to eliminate random error.

Select three major efficiency indicators: average queue length, average vehicle delay, and average number of stops; adopt the entropy weight method to objectively assign weights calculate the comprehensive score, and use the paired sample t-test ($\alpha=0.05$) to verify the significance of the strategy differences

3. Simulation Results and Pattern Analysis

3.1 Evolutionary Pattern of a Single Indicator

1) Average queue length: The queue lengths of the three strategies decrease monotonically with the increase in penetration rate. At 100% penetration rate, the queue lengths of fixed timing, sensing control, and green wave coordination are reduced by 61.9%, 66.3%, and 75.2% respectively compared to the purely manual scenario. In the 0%~40% penetration interval, sensing control achieves the shortest queue; after the penetration rate reaches $\geq 60\%$, the advantage of CAV green wave coordination in queue dissipation is significantly amplified[8].

2) Average vehicle delay: As the penetration rate increases from 0% to 100%, the reduction in delay for the three types reaches 63.3%, 68.9%, and 81.2%, respectively. In a purely manual scenario, green wave coordination without vehicle guidance results in a delay of 36.2s/veh, which is higher than the 33.8s/veh of actuated control; at 40% penetration rate, the delay of green wave coordination overtakes that of actuated control, and the advantage gap widens as the penetration rate

3) Average number of stops: In the 100% CAV scenario, the average number of stops under green wave coordination is only 0.1/veh, with traffic flowing almost continuously; at medium-to-low penetration rates, the stop frequency under queue-sensing control is significantly lower than that of timing, making it suitable for existing intersections with non-connected devices.

3.2 Comprehensive Performance Evaluation based on Entropy Weight Method

The entropy weight method calculates the indicator weights as follows: delay 0.413, queue length 0.312, and of stops 0.275, with delay being the most sensitive indicator for travelers. The comprehensive score ranking results are:

- 1) 0%~20% penetration rate: queue detection control > CAV green wave coordination > fixed timing;
- 2) 40%~100% penetration rate: CAV green wave coordination > queue detection control > fixed timing.

3.3 Statistical Significance Test

The paired t-test results show that: there is a significant difference between fixed timing and the other two strategies under full penetration ($p < 0.05$); there is no significant difference between adaptive control and green wave coordination at 0% penetration ($p = 0.082 > .05$); after the penetration rate reaches 20%, the difference between the latter two types of intelligent control becomes significant,

and the higher the penetration rate, smaller the p-value, indicating a more prominent optimization effect of green wave coordination.

4. Phased Signal Control Strategy Adaptation Scheme

Based on the simulation quantification conclusions, taking the CAV penetration rate as the criterion, construct an engineered dynamic strategy selection matrix:

- 1) Penetration rate 0%~20%: Primarily promote queue-sensing control, optimize the layout of roadside detectors, no investment in Vx equipment required, can reduce delay by 15%~20%;
- 2) Penetration rate 20%~40%: Based on queue detection, RSU is pilot-deployed on main roads with heavy traffic, speed guidance is locally enabled;
- 3) Penetration rate 40%~60%: Mixed control mode, CAV green wave coordination enabled during peak hours, switching to sensing control off-peak hours, overall delay reduced by 30%~40%;
- 4) Penetration rate 60%~100%: Deploy CAV green wave collaborative control across the entire domain, combined with regional arterial road, reducing delays by over 40%.

At the same time, a real-time adaptive control framework is proposed: it consists of a penetration-aware module, a policy decision engine, a parameter self-tuning module, introducing a hysteresis threshold to avoid frequent policy switching oscillations, and adapting to the differentiated characteristics of CAV penetration across different urban areas

5. Conclusion and Outlook

5.1 Main Conclusion

- 1) The increase in CAV penetration rate provides a positive gain to intersection throughput efficiency, but the marginal optimization benefits significantly diminish after the penetration rate exceeds 6%, making it unnecessary to blindly pursue 100% autonomous driving adoption across the entire domain;
- 2) The three types of signal control strategies have distinct penetration rate adaptation intervals: queue-sensing control is the optimal low-cost solution during the 0%-40% mixed-traffic transition period; CAV green wave coordination only offers significant performance advantages when the penetration rate is $\geq 40\%$; fixed timing is only applicable old intersections with low traffic and no modification conditions;
- 3) The return on investment for large-scale deployment of the V2X green wave coordination system in low penetration rate scenarios is relatively low; urban traffic should be advanced in stages, prioritizing the optimization of existing sensing and control facilities.

5.2 Limitations and Future Work

This paper focuses solely on the simulation of a single isolated intersection and does not consider the coordination of multiple intersections on the main road; it assumes CAV communication and uniform vehicle parameters, without incorporating real-world interferences such as communication latency, heterogeneous control parameters from different automakers, and the game-theoretic behavior of drivers. Future work can extend to multi-intersection network simulations, integrate energy consumption and safety indicators to construct multi-objective optimization models, and rely on real-world data from intelligent connected vehicle demonstration zones to calibrate the simulation model, thereby enhancing the engineering applicability of the conclusions.

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