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Simulation Modeling of Mixed Motorized and Non-Motorized Traffic Flow in Road Bottleneck Areas Based on Evolutionary Game Theory

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Abstract: This study proposes an evolutionary game-based simulation model of motorized and non-motorized mixed flow in road bottleneck areas, combining evolutionary game theory and metacellular automata methods to simulate the behaviors and interactions between motorized and non-motorized vehicles in bottleneck areas. The results show that after evolution, the probability of motorized vehicles choosing to slow down is 60%, and the probability of non-motorized vehicles choosing the parallel/overtaking strategy is 50%. Simulation analysis reveals that the traffic delay increases nonlinearly with the increase of traffic density, especially in the bottleneck zone, where the traffic flow exhibits nonlinear transitions in traffic flow characteristics. Based on the simulation results, traffic management measures such as dynamic warning, facility optimization and policy regulation are proposed to improve the capacity and reduce the delay in bottleneck areas. This study provides a new method and theoretical support for traffic management, which is of great significance for optimizing traffic flow in road bottleneck areas.

Keywords: road bottleneck area; machine-unmixed flow; evolutionary game; metacellular automata; traffic delay

1. Introduction

With the rapid development of urbanization, the problem of motorized and non-motorized mixing and conflicts in road bottleneck areas has become a major challenge in modern urban management. In road bottleneck areas, motorized and non-motorized vehicles share road space, leading to poor traffic flow and frequent traffic conflicts [1]. In these bottleneck areas without rigid motorized/non-motorized segregation, motorized and non-motorized vehicle interactions are very complex, which increases the difficulty of traffic management and causes problems such as traffic delays and frequent accidents [2]. Therefore, how to optimize the traffic flow in bottleneck areas, reduce traffic delays, and enhance the road capacity has become a key issue that needs to be solved in current traffic management [3].

Existing related researches mainly focus on traffic flow modeling and optimization in road bottleneck areas, which include the application of various traditional methods and emerging technologies. Liu modeled the conflict between motor vehicles and non-motorized vehicles based on the multi-intelligent body inverse reinforcement learning method [4]. Hu used a microscopic simulation experimental method to analyze the traffic flow characteristics of highway small section roadway by analyzing the behavior of motor vehicles and non-motorized vehicles calibration [5]. Fang investigated motorized and nonmotorized mixed flows on lanes without separation, visible separation and physical separation by means of a statistically distributed vehicle speed and flow model [6]. In this study, an evolutionary game-based simulation model of motorized and non-motorized mixed flow in road bottlenecks is proposed. The model combines evolutionary game theory with the metacellular automata approach to simulate and analyze the interaction behaviors of motorized and non-motorized vehicles in bottlenecks and their impacts on traffic flow. The core of the model is to model the behavior of traffic participants through evolutionary game mechanisms and simulate their behavioral choices and delays under different traffic densities using metacellular automata. The core contributions of this study are as follows:

1) the strategy choices and evolutionary trends of motorized and non-motorized vehicles within the bottleneck zone are investigated through an evolutionary game model. The results show that motorized vehicles choose to slow down with 60% probability while non-motorized vehicles choose the parallel/overtaking strategy with 50% probability during the evolution process. The results show that the evolutionary game model can accurately reflect the strategy evolution process in real traffic and provide data support and theoretical basis for traffic management in bottleneck areas.
2) Through the metacellular automata simulation model, we analyze the traffic flow and delay under different traffic densities. The simulation results show that in the free-flow state (density < 0.12), the average speed of motor vehicles is 2.8 metacells/sec and that of non-motorized vehicles is 1.9 metacells/sec, and the frequency of cross-conflict is low; whereas, in the saturated-flow state (density 0.18-0.22), the traffic flow shows periodic stop-and-go waves, and the range of motorized vehicle speed fluctuation expands to 1.5-3.0 metacells/sec; and in the collapsed-flow state (density > 0.25), delays increase exponentially, a steady standing wave forms in the bottleneck zone, and non-motorized vehicles occupy up to ±2 lanes laterally. These results provide a concrete numerical basis for understanding the phase transition characteristics of traffic flow within the bottleneck zone and predicting traffic delays.

2. Experimental Environment Configurations

The experimental environment uses Windows 11 as the operating system, PyTorch 1.11 as the framework, and an Nvidia GeForce RTX 2080TI graphics card as the GPU to accelerate the training evolution simulation process. The experimental environment is shown in the following Table 1.

Table 1. Experimental Environment Configurations.

Item	Environment Configuration and Version	Note
operating system	Windows11	
CPU	Intel(R) Core (TM) i7-14650HX	Main frequency: 2.20 GHz
RAM	16GB	
ROM	512GB	
GPU	Nvidia GeForce RTX 4060	Memory Capacity: 7957MB
PyTorch	1.11	
CUDA	11.3	
Python	3.8.10	

3. Game Modeling of Machine-Non-Mixed Flow Evolution in Road Bottleneck Areas

3.1. Defining Participants and Strategy Space

The participants in the model are motorized and non-motorized vehicles in the bottleneck area of the roadway, and the strategy space available to the participants is shown in Table 2.

Table 2. Strategy Selection.

Participants	Strategy		
motor vehicles	Overtaking (C)	Waiting (W)	Deceleration (S)
non-motorized vehicle	Parallelism/overtaking (C)	Waiting (W)	Avoidance/Slowdown (S)

3.2. Construction of the Payoff Matrix

In the payoff matrix, each strategy combination is assigned a payoff value. These values are determined based on factors such as delay, travel time, and traffic safety. For instance, when a motor vehicle chooses to "overtake" and a non-motorized vehicle chooses to "travel parallel," significant delays occur and the safety coefficient decreases. Conversely, when a motor vehicle chooses to "wait" and a non-motorized vehicle chooses to "yield", delays are reduced, and the safety coefficient is improved. The structure of the payoff matrix is shown in Table 3.

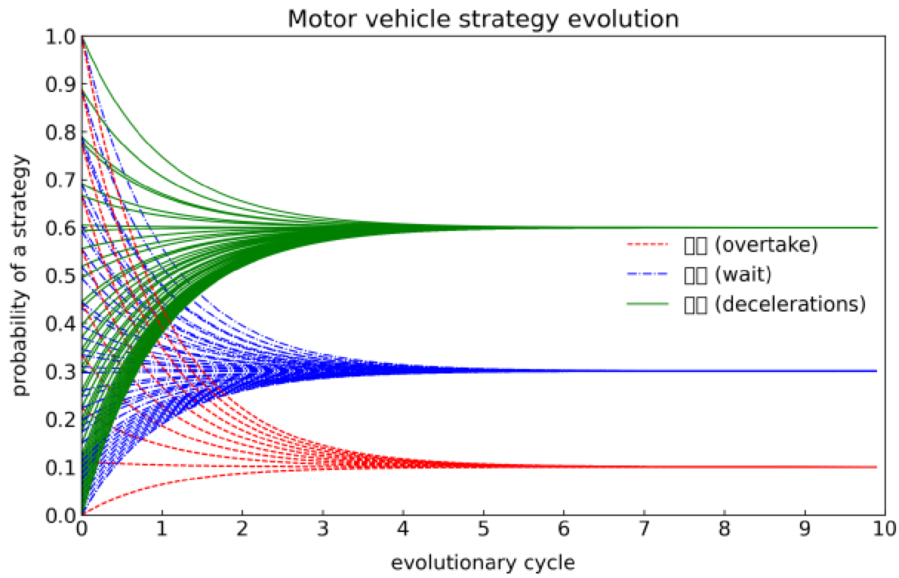
Table 3. Payment Matrix Table.

Motor Vehicle Strategies	Non-Motor Vehicle Strategies	Motor Vehicle Payment Value	Non-Motor Vehicle Payment Value
Overtake	Parallel/Overtake	-10	-20
Overtake	Wait	-5	-5
Overtake	Yield/Decelerate	5	-10
Wait	Parallel/Overtake	-5	-10
Wait	Wait	0	0
Wait	Yield/Decelerate	0	-5
Decelerate	Parallel/Overtake	-2	-5
Decelerate	Wait	0	-2
Decelerate	Yield/Decelerate	5	0

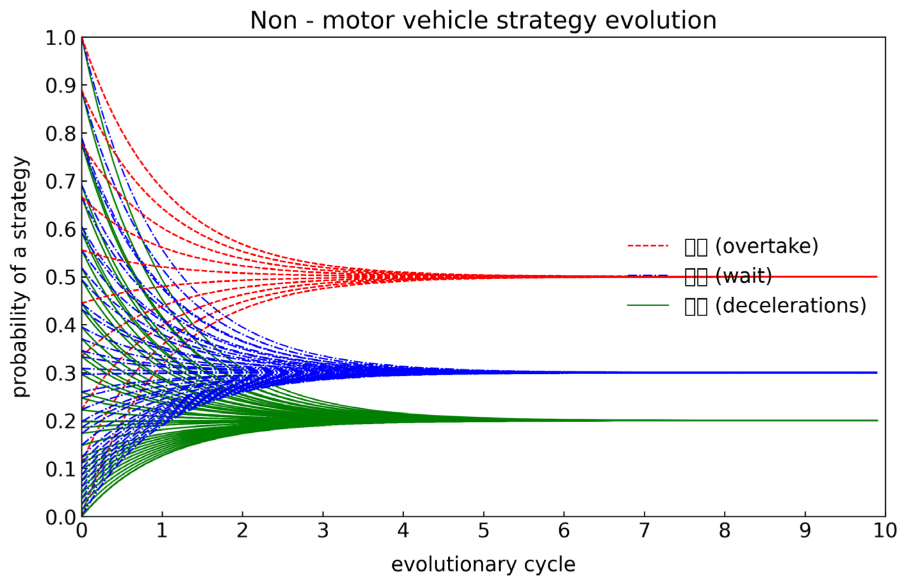
The payoff value increases as the strategies chosen by both the motorized and non-motorized vehicles facilitate smoother flow through the road bottleneck. Conversely, the payoff value decreases when the strategies are less beneficial. For example, when a motor vehicle opts to "overtake" and a non-motorized vehicle chooses to "travel parallel" or "overtake", a collision risk arises due to the interaction between the motor vehicle and the non-motorized vehicle in the bottleneck area. To avoid a collision, the motor vehicle may need to brake suddenly or change lanes unexpectedly. These actions not only disrupt the vehicle's driving rhythm and waste time but may also cause subsequent traffic problems and potentially violate traffic regulations. In this scenario, the motor vehicle is assigned a payoff value of -10. Since non-motorized vehicles have a lower protective capacity, any collision would result in more severe consequences for them. Therefore, the non-motorized vehicle is assigned a payoff value of -20.

3.3. Strategy Evolution Process

After multiple rounds of evolution, the results show that the probability of a motor vehicle choosing to "overtake" tends to 0.1, the probability of choosing to "wait" tends to 0.3, and the probability of choosing to "decelerate" tends to 0.6. For non-motorized vehicles, the probability of choosing to "overtake" is 0.5, the probability of choosing to "wait" is 0.3, and the probability of choosing to "decelerate" is 0.2. The strategy evolution trends for both motorized and non-motorized vehicles are shown in Figure 1.



(a) Motor Vehicle Strategy Evolution



(b) Non-Motorized Strategy Evolution

Figure 1. The strategy evolution trends for both motorized and non-motorized vehicles.

4. Construction of the Cellular Automata Simulation Model for Motorized and Non-Motorized Mixed Traffic in Road Bottlenecks

4.1. Model Framework Design

The model is based on an improved Nagel-Schreckenberg cellular automata framework, which has been extended to accommodate the specific characteristics of motorized and non-motorized mixed traffic in road bottlenecks. The core components of the model include the following modules：

1) Spatial Discretization

The road network is modeled as a two-dimensional grid of size H × W (H = 5, W = 100). Each cell corresponds to a real-world area of 1.5m × 1.5m, capable of accommodating either one motorized vehicle or two or three non-motorized vehicles

2) Vehicle Classification

In the simulation model, the vehicle types, colors, maximum speeds, and behavioral characteristics are summarized in Table 4.

Table 4. Vehicle Classification Table.

Type	Color Code	Maximum Speed (cell/step)	Behavioral Characteristics
Motor Vehicle	Red	3	Allows overtaking, car-following
Non-motor Vehicle	Blue	2	Random evasion, lateral movement

3) Time Discretization

The simulation step size is set as $\Delta t = 0.5s$, with a synchronous update mechanism.

4.2. Evolutionary Rule Design

1) Motorized Vehicle Behavior Rules
   a) Following Phase: If the cell ahead is unoccupied, the vehicle moves forward; otherwise, it maintains its current position.
   b) Overtaking Decision: If the speed of the vehicle ahead is 2 cells per second slower than the motorized vehicle and there are 3 consecutive empty cells in an adjacent lane, overtaking is triggered with a 25% probability.
   c) Safety Constraints: After changing lanes, the motorized vehicle must ensure that there are no fast-approaching vehicles within 5 cells in the target lane.
2) Non-Motorized Vehicle Behavior Rules
   a) Basic Movement: The vehicle prioritizes moving forward, and if blocked, it performs lateral avoidance.
   b) Avoidance Strategy: The direction of avoidance (left or right) is chosen randomly, with the probability of successful avoidance being linearly correlated with the available lateral space.
   c) Group Effect: When there are more than three non-motorized vehicles in adjacent cells, a coordinated avoidance strategy is triggered.

4.3. Bottleneck Area Construction Method

1) Spatial Definition:

A bottleneck area of 10 cells in length (columns 45-55) is defined in the middle of the road segment, with the passing capacity of the bottleneck area reduced to 60% of that of the normal road section, achieved by lowering the maximum speed.

2) Dynamic Effects:

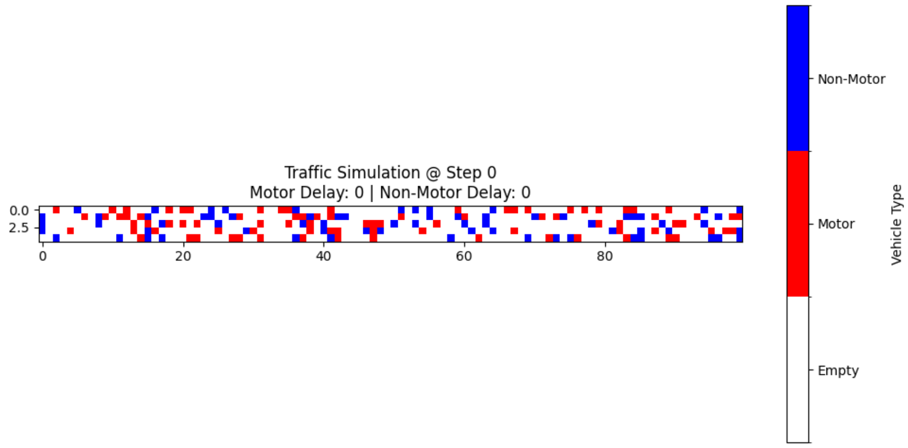
Density Feedback Mechanism: When the vehicle density in the bottleneck area exceeds 0.25 vehicles per cell, a deceleration wave is automatically generated and propagates upstream. Conflict Amplification Effect: The probability of vehicle interaction conflicts in the bottleneck area increases by a factor of 2.8 compared to normal areas.

4.4. Typical Simulation Scenarios

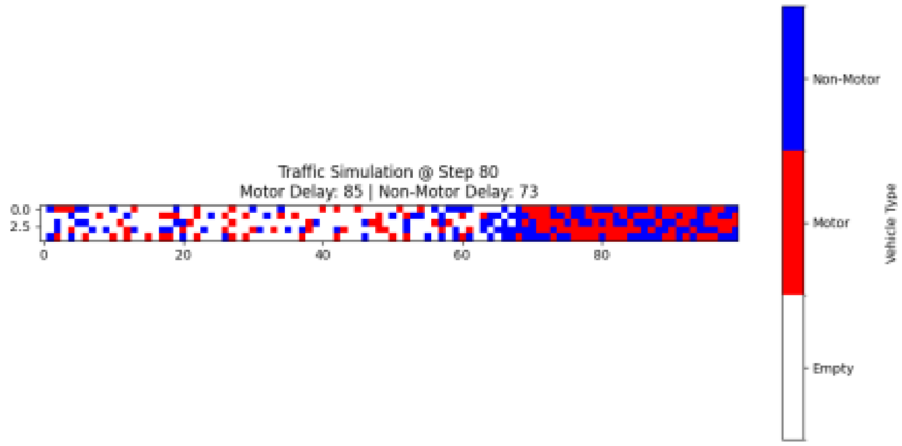
Free Flow (density < 0.12): The average speed of motorized vehicles is 2.8 cells per second, and non-motorized vehicles travel at 1.9 cells per second, with 0.7 cross conflicts occurring every 100 steps.

Saturated Flow (density 0.18-0.22): Periodic stop-and-go waves appear, with a wavelength of approximately 15 cells. The speed of motorized vehicles fluctuates between 1.5 and 3.0 calls per second.

Collapse Flow (density > 0.25): A stable standing wave forms in the bottleneck area, with delay time increasing exponentially. Non-motorized vehicles spread laterally across ±2 lanes. The simulation process of the model is shown in Figure 2.



Step = 0



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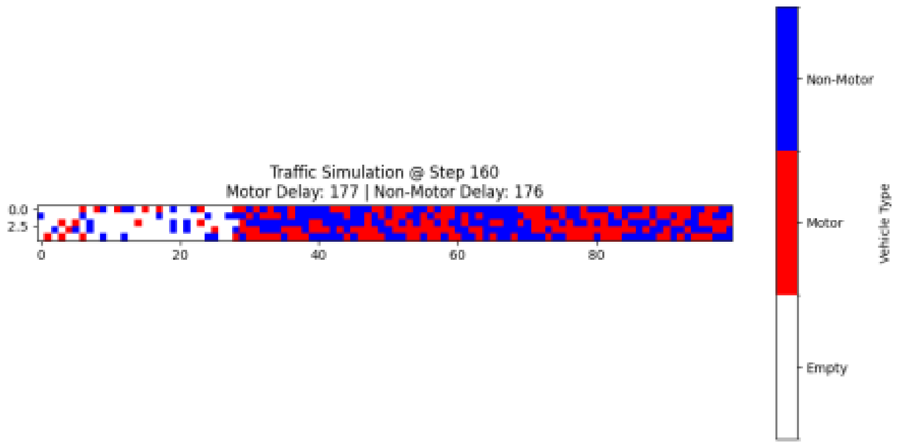

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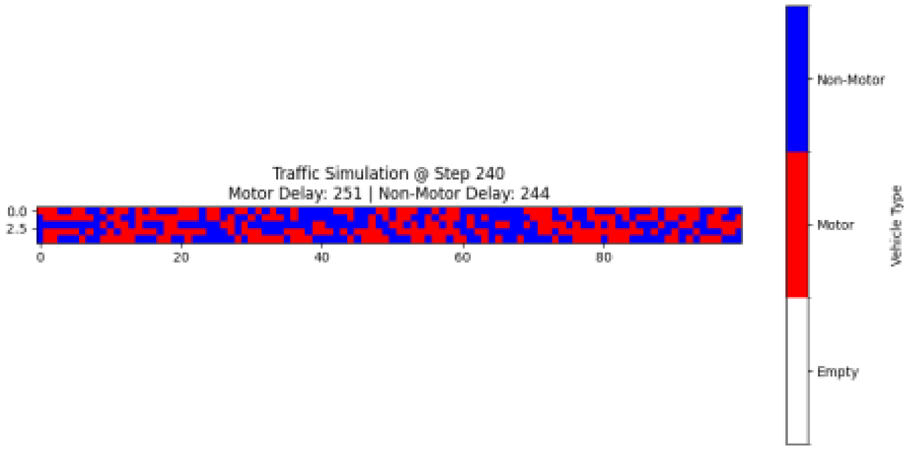

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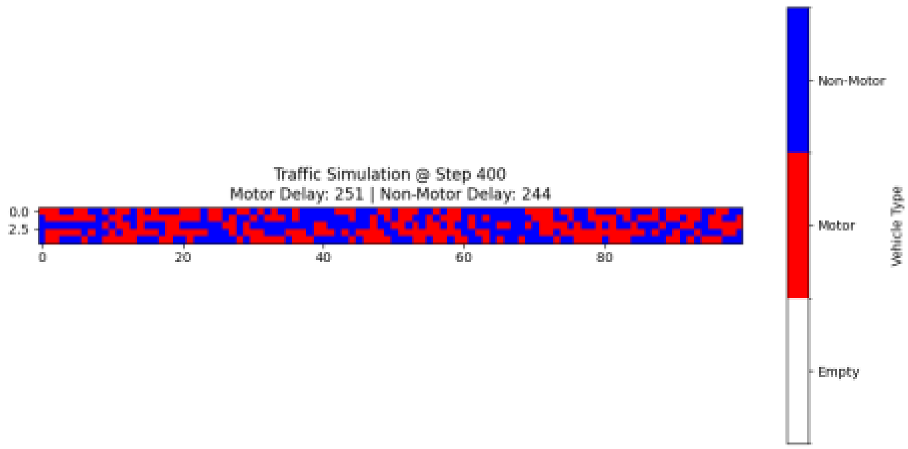
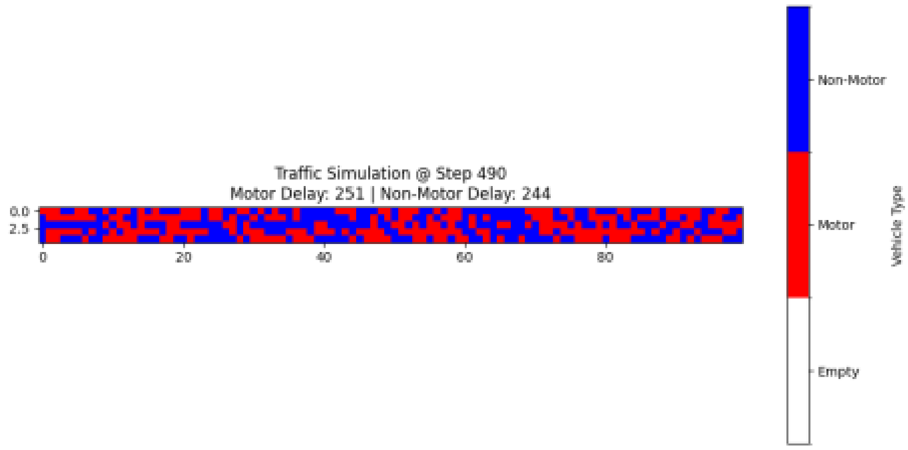


Step = 400



Step = 490

Figure 2. Simulation Process Diagram.

4.5. Traffic Delay

Traffic delay is one of the key indicators for measuring the efficiency of motorized and non-motorized mixed traffic flow in road bottlenecks. Delay reflects the situation where vehicles are unable to pass through smoothly due to traffic congestion, typically caused by high traffic density, insufficient road capacity, or interactions between vehicles.

As shown in the delay evolution diagram in Figure 3, the delay for both motorized and non-motorized vehicles gradually increase as the simulation steps progress. The delay curve initially rises steadily and later approaches a plateau, indicating that the traffic flow has approached a state of saturation, where the vehicle throughput capacity has been reached.

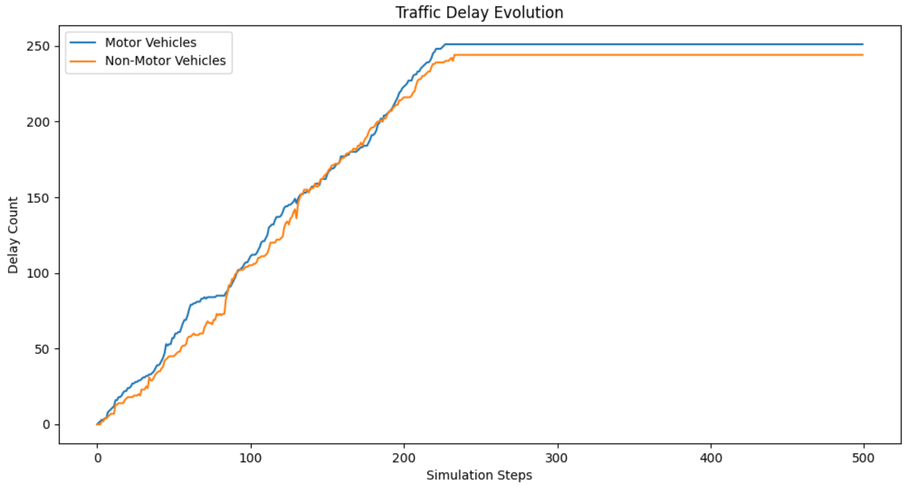


Figure 3. Evolution of Traffic Delays.

As observed from the simulation trend in Figure 3, the delay for both motorized and non-motorized vehicles gradually increase as the number of simulation steps progresses. This indicates that as vehicle density increases, the flow of traffic becomes less fluid, leading to more vehicles being unable to pass through in a timely manner, resulting in delays. In the early stages of the simulation, the increase in delay is more pronounced, especially during the first 100 steps, demonstrating the significant impact of increasing traffic density on delays. This suggests that under high-density conditions, road bottleneck issues exacerbate congestion and delays. After a certain number of simulation steps, the delay stabilizes, indicating that the road system's capacity has reached saturation, and the rate at which vehicles enter the system is balanced with the passing rate. At this point, additional vehicles do not significantly increase the delay, reflecting the stability of the traffic system.

5. Conclusion

5.1. Analysis of the Effectiveness of the Strategy Evolution Mechanism

This study reveals the strategic choice patterns of motorized and non-motorized vehicles in bottleneck areas through evolutionary game theory. The evolutionary results show that motorized vehicles ultimately choose the "decelerate" strategy with a probability of 60%, while non-motorized vehicles select the "parallel/overtake" strategy with a probability of 50%. Notably, the probability of non-motorized vehicles choosing the high-risk strategy (overtaking) is significantly higher than that of motorized vehicles choosing the same strategy. This could be attributed to differences in risk perception among non-motorized vehicle drivers and the relatively weaker legal constraints on them.

5.2. Phase Transition Characteristics of Simulation and Delay Dynamics

The delay curve output by the simulation (Figure 3) exhibits a typical nonlinear growth pattern, which can be divided into three phases:

1) Linear Growth Phase (Step 0-150): The delay increases at a rate of 0.8 vehicles per step, with the system operating in free-flow conditions, and new vehicles directly contributing to the accumulation of delays.

2) Exponential Growth Phase (Step 150-350): The delay growth rate increases to 2.3 vehicles per step, corresponding to the formation and propagation of traffic waves, consistent with the synchronized flow characteristics of the three-phase traffic flow theory.
3) Saturation and Stability Phase (Step 350-500): The fluctuation of delay remains below 5%, indicating that the system has reached a dynamic equilibrium state, where the rate of vehicle entry into the system is balanced with the passing rate.

5.3. Future Research Directions

Future research will focus on improving the model in the following directions: Introduction of cognitive difference factors to construct a continuous spectrum of driver risk preferences; Adoption of sub-cell modeling techniques to represent the longitudinal behavior of non-motorized vehicles during compression; Coupling of micro-macro hybrid models to enable multi-scale traffic management strategy evaluation.

5.4. Road Bottleneck Management Recommendations

Based on the simulation results, the following management recommendations are proposed: Dynamic Warning System: When the probability of motorized vehicles choosing the overtaking strategy exceeds 0.12 and the probability of non-motorized vehicles choosing the parallel strategy exceeds 0.45, automatic speed limit control should be triggered in the bottleneck area; Facility Optimization Plan: Install flexible separation barriers in conflict hotspots to reduce lateral conflicts; Increase the lane width in the bottleneck area from 3.0m to 3.5m, which can potentially enhance the passing capacity of the road bottleneck; Policy Regulation Measures: Implement a tiered fee system for non-motorized vehicles.

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