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Research on Traffic Flow Characteristics Based on 2-4-6 Second Car-Following Criteria

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Abstract

In order to clarify the impact of weather conditions such as sunny, rainy, and snowy days on traffic, a one-dimensional single lane cellular automaton traffic flow model is established. These three typical weather conditions are characterized in the model via minimum safe time headways of 2 seconds, 4 seconds, and 6 seconds, respectively. Through numerical simulations, two curves are obtained: one describing the relationship between traffic flow and vehicle density under different weather conditions, and the other depicting the relationship between mean velocity and vehicle density. The research results indicate that under moderate vehicle density, weather conditions exert a considerable impact on traffic flow and mean velocity. However, at extremely low and higher vehicle densities, traffic flow and mean velocity are immune to weather conditions. In addition, the model proposed in this article reproduces nonlinear phenomena such as non-equilibrium phase transitions and metastable states that are consistent with actual traffic.

Keywords

Traffic Flow, Cellular Automaton, Car-Following Model, Metastable State

1. Introduction

With the continuous increase in the number of motor vehicles, road traffic safety issues have received great attention [1]-[4]. The driving status of vehicles is extremely sensitive to the external environment, among which the weather condition is one of the key factors affecting driving safety and traffic flow. Different weather conditions alter the road adhesion coefficient and driver reaction time, thus forming 2-4-6 second graded car-following criteria. The criteria refer to maintaining a following distance of 2 seconds on dry roads, 4 seconds on wet and slippery roads in rainy weather, and 6 seconds in icy, snowy, or foggy conditions.

It has great practical guiding significance to study the characteristics of traffic flow under different weather conditions, which can help solve problems encountered in actual traffic and improve traffic performance. Domestic and foreign transportation engineering scholars have conducted in-depth research in this area and achieved a series of findings [5]-[8].

Tan H L, *et al.* established a new traffic flow grid fluid dynamics model to study visibility effects [9]. The research results indicate that as visibility decreases, traffic flow becomes increasingly stable, but the negative effect is a decrease in traffic flow. Faryal A *et al.* proposed a micro traffic flow model based on weather conditions, where the instantaneous value of acceleration is given by a predetermined differential equation [10]. The results demonstrate that traffic flow decreases as expected in adverse weather conditions, but the traffic conditions become more stable.

The rest of this paper is organized as follows. In Section 2, the cellular automaton traffic flow model with an adjustable minimum safe time headway factor is proposed to adapt to different weather conditions. Then in Section 3, the numerical simulation results and related discussions are presented. Section 4 is the conclusion, which summarizes the research results and looks forward to the practical reference value of the graded car-following model for formulating intelligent driving strategies.

2. Model Construction

The 2-second car-following rule originated from the North American defensive driving system. In response to the degradation of braking performance caused by adverse weather conditions such as rain, snow, and fog, the industry has extended the vehicle braking theory to form a set of graded car-following criteria based on 2-4-6 second protocol.

The 2-second time headway can provide sufficient braking buffer. The reaction time from the driver discovering a dangerous situation to stepping on the brake pad is about 1 second, with the remaining 1 second used for vehicle braking and deceleration. If the time headway is insufficient, a rear-end collision accident is highly likely to occur when the vehicle ahead brakes suddenly.

Adverse weather conditions can easily cause a decrease in road adhesion coefficient, interfere with driver judgment, prolong driver reaction time, and increase the braking distance of motor vehicles. Choosing regular time headways that increase multiplicatively facilitates drivers' memory, which is why the 2-4-6 second graded car-following criteria emerged.

The discrete characteristics of vehicles under rainy and snowy conditions are better than those under normal weather conditions, so using cellular automata models to analyze such traffic flow problems has unique advantages [11]. When implementing the update rules of cellular automata, the simulation adopts a constant time step, and each iteration corresponds to a physical duration of one second. The headway parameter measured in seconds is converted into a safety distance characterized by the number of cells. After completing the conversion, the relevant constraints can be conveniently embedded into the iterative update rules of the cellular automaton model to constrain the driving behavior of vehicles.

Therefore, a single lane cellular automaton traffic flow model is established under different weather conditions, where vehicle states are updated in parallel according to the following rules [12].

1) Predict the minimum velocity of the vehicle ahead at the next moment,

$$v_{i+1}^{*}(t+1)=\min\left\{v_{\max}-1, v_{i+1}(t), \max\left(0, d_{i+1}(t)-1\right)\right\} \tag{1}$$

2) Calculate the safe driving gap,

$$\begin{array}{ll} \text{IF}\left(v_i(t)>v_{i+1}^{*}(t+1)\right) & d_{safe}=\tau*\left[v_i(t)-v_{i+1}^{*}(t+1)\right] \\ \text{Else} & d_{safe}=0 \end{array} \tag{2}$$

3) Refresh the current velocity,

$$v_i(t+1)=\min\left\{v_{\max}, v_i(t)+1, \max\left(0, d_i(t)-d_{safe}\right)\right\} \tag{3}$$

4) Move forward at the adjusted velocity,

$$x_i(t+1)=x_i(t)+v_i(t+1) \tag{4}$$

Here, $i=1,2,3,\cdots,N$, characterizing the identification number of the vehicle. The parameters $v_i(t)$ and $x_i(t)$ are the instantaneous velocity and position of the *i*th vehicle at time t, respectively. The parameter $d_i(t)=x_{i+1}(t)-x_i(t)-1$ is the empty cells between vehicle i and the nearest neighbor vehicle $i+1$ in front of it.

The parameter τ characterizes the minimum safe time headway between vehicles, which is evaluated not as a fixed distance in meters, but as a time indicator. The faster the vehicle velocity, the automatically larger the corresponding physical spacing. The weather scenarios in this study only produce variations in the prescribed time headway, rather than capturing the comprehensive influences of rainfall and snowfall on visibility, braking performance, driver behavior and road friction.

3. Numerical Simulation and Result Analysis

During numerical simulations, the road is discretized into a one-dimensional cell ring with a length of $L=10000$, and each cell can only be occupied by one vehicle at most. The actual road length corresponding to the size of each cell is 6.5 m, so the total length of the simulated road is 65 km. The maximum velocity of each vehicle is limited to 5 cells/s, which is equivalent to 117 km/h in actual traffic.

The traffic flow is given by the calculation formula $J=\rho\bar{v}$, in which $\rho=N/L$ is the vehicle density and $\bar{v}=\frac{1}{N}\sum_{i=1}^{N}v_i$ is the mean velocity. The mean velocity and traffic flow here are calculated as statistical averages across all vehicles, time steps (excluding transients), and multiple independent simulation runs.

This article selects a circular road, which means that the periodic boundary condition is adopted to maintain a constant number of vehicles on the road. There are two types of initialization schemes available for selection. One is random initialization, where vehicles are randomly arranged according to the preset vehicle density, and their initial velocities are randomly selected within the range from zero to the maximum value. The second is homogeneous initialization, where vehicles are evenly spaced along the road and assigned a uniform velocity.

The random initialization corresponds to random departure scenarios, while the homogeneous initialization corresponds to vehicle scheduled departure modes. Except for Figure 5 and Figure 6, which clearly indicate the use of homogeneous initialization, all other simulations adopt a random initialization scheme.

For a specified density, the model first iterates 20,000 time steps to eliminate transient effects, and then calculates the mean of the subsequent 5000 time steps as a single sample. In order to reduce the deviation caused by system configuration, 20 independent random seeds are used for simulation. Except for Figure 2 and Figure 6, each data point in the other figures is the mean of 20 sets of sample results.

Under the unified model framework, the evolution trend of the same kind relationship curves is basically the same, and the main discrepancy is that the response amplitude and the characteristic point position of the dependent variable are different. Next, we will analyze each simulation result one by one.

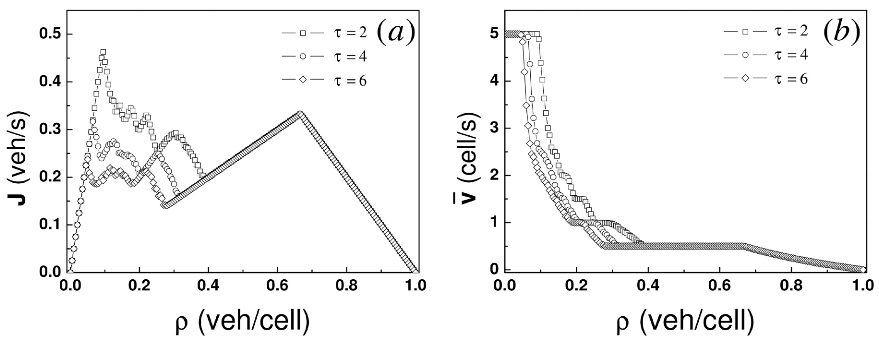

Figure 1. Two types of curves derived from numerical simulation under different weather conditions, (a) traffic flow versus vehicle density; (b) mean velocity versus vehicle density. The parameters are set to $\tau = 2,4,6$.

Figure 1(a) shows the relationships between traffic flow and vehicle density under different weather conditions. The curves in the figure can be divided into three parts: free flow, start stop flow, and congested flow. When the vehicle density is low enough, vehicles can freely travel at maximum velocity, and the traffic flow increases linearly with vehicle density. When the vehicle density on the road reaches a critical value, the remaining traffic space cannot meet the maximum velocity of vehicles, and the proportion of slow vehicles in the lane increases, resulting in a decrease in road traffic flow. In high-density areas, regardless of weather conditions, vehicles are limited in their available driving space and can only rely on frequent starting and stopping to move slowly forward.

The relationship curves between mean velocity and vehicle density under different weather conditions are plotted in Figure 1(b). When the vehicle density is low enough to result in sufficient driving space, weather conditions become insignificant, and all vehicles can maintain maximum velocity. When the vehicle density increases slightly, the available gaps between vehicles are rapidly compressed. To ensure driving safety, drivers can only slow down. The deceleration of an individual vehicle triggers a chain deceleration effect, resulting in an appreciable decrease in the mean velocity of the entire lane. The three curves collapse together when vehicle density exceeds 0.38. In the meantime the vehicle density has replaced weather as a key factor affecting the operation of traffic flow.

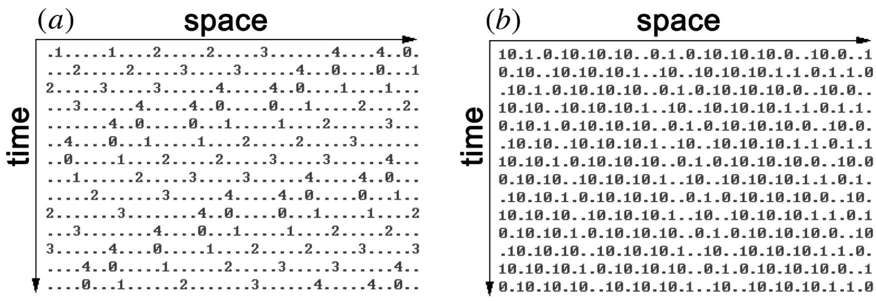

Figure 2. Two screenshots of vehicle velocity evolution at different traffic densities under the same weather condition. Please note that these are partial screenshots, not the entire evolution diagram. The parameters are set to $\rho = 0.16$, $\tau = 2$ in panel (a) and $\rho = 0.64$, $\tau = 2$ in panel (b).

Given that the traffic flow shown in Figure 1(a) exhibits multimodal characteristics with increasing vehicle density, it is necessary to conduct in-depth research on its internal evolution patterns, as shown in Figure 2. The ratio of vehicle density between Figure 2(a) and Figure 2(b) is 1:4. At the low density, vehicles generally exhibit a driving characteristic of accelerating first and then braking. At the high density, vehicles display intermittent motion, stopping for one second after advancing one cell, and repeating the cycle.

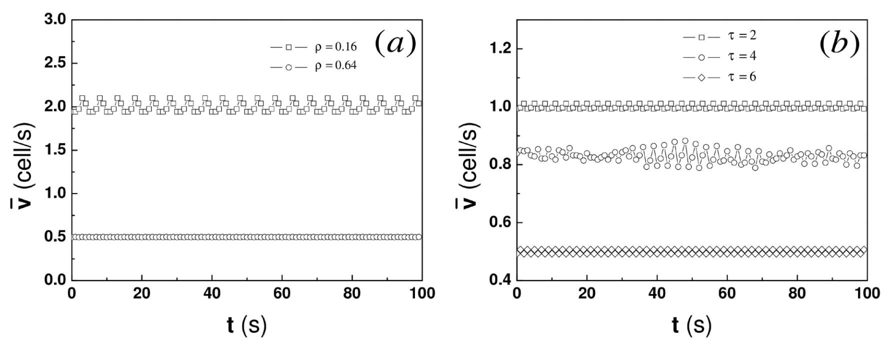

Figure 3. (a) The evolution of the mean velocity of vehicles over time under the same weather condition but different vehicle densities. The parameters are set to $\rho = 0.16, 0.64$ and $\tau = 2$. (b) The evolution of the mean velocity of vehicles over time at the same vehicle density but different weather conditions. The parameters are set to $\tau = 2, 4, 6$ and $\rho = 0.28$.

To quantitatively describe the difference in mean velocity at different densities, Figure 3(a) is plotted. The results show that the ratio of mean velocity of vehicles under low density to high density is 4:1. For these two traffic scenarios, the velocity ratio and density ratio satisfy a reciprocal relationship, so the traffic flows remain identical.

Figure 3(b) shows the evolution of the mean velocity of vehicles over time under different weather conditions at the same traffic density. As the severity of the weather increases, the vehicle velocity noticeably decreases. The driving environment on rainy days is complex, and the velocity fluctuates greatly. However, in normal weather conditions, the road conditions are good, and the mean velocity is high with little fluctuation. In icy and snowy weather, drivers tend to drive cautiously at a lower but smooth velocity.

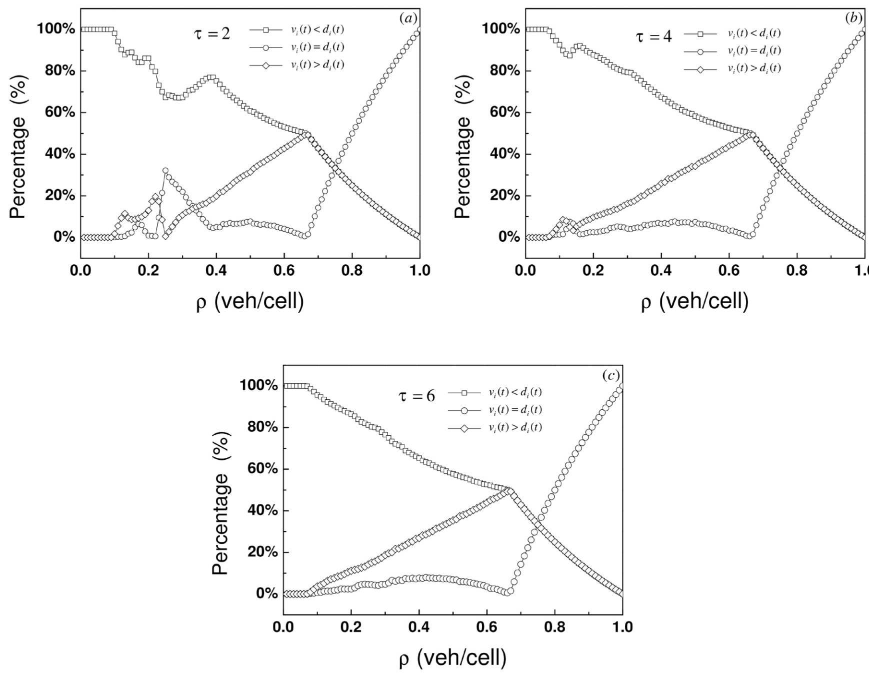

Figure 4. Proportion distribution diagrams of three types of car-following states under different weather conditions. The parameters are set to $\tau = 2$ in panel (a), $\tau = 4$ in panel (b) and $\tau = 6$ in panel (c).

The proportion distributions of three types of car-following states under different weather conditions are illustrated in Figure 4. The three types of car-following states refer to the surplus following state where the velocity is less than the number of empty cells ahead, the critical following state where the velocity is equal to the number of empty cells ahead, and the constrained deceleration state where the velocity is greater than the number of empty cells ahead.

Despite varying weather conditions, the unified model yields similar distribution law. At low densities, vehicles in the surplus following state dominate. As the vehicle density increases, their proportion rapidly decreases until they completely disappear. The evolution law of vehicles in the critical following state is that their proportion is almost zero over a long density range. Once the vehicle density reaches a critical value, their proportion rapidly increases until they reach 100%.

For vehicles in the constrained deceleration state, their statistical proportion exhibits a unimodal evolution characteristic, gradually increasing from an initial value of 0 to a peak, then continuously decreasing, and finally falling back to 0.

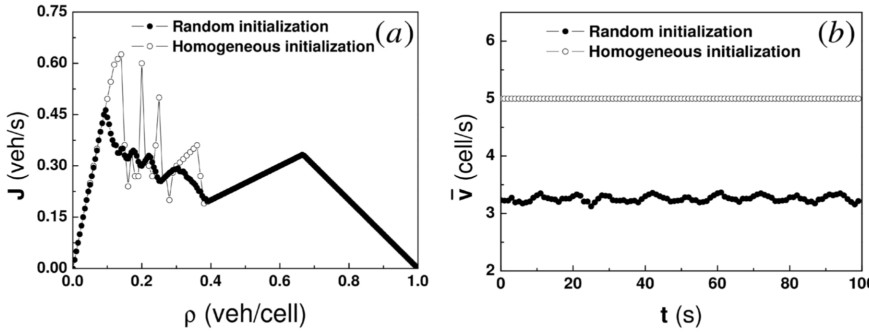

Figure 5. (a) The relationships between traffic flow and vehicle density obtained from two different initialization conditions. The parameter is set to $\tau = 2$. (b) The evolution of mean velocity of vehicles over time obtained from two different initialization conditions. The parameters are set to $\tau = 2$ and $\rho = 0.12$.

Two different initialization methods are adopted to generate the flow-density relationship curves, as illustrated in Figure 5(a), to verify whether metastable states exist in the model. Comparing the two curves, it is found that they completely overlap in the low-density and high-density regions, while they are staggered in the medium density region. In this staggered region, traffic flow is no longer a single value function of density, and this specific range is commonly known as the metastable region. Under the same vehicle density, the upper branch has a larger traffic flow and higher mean velocity, while the lower branch has a smaller traffic flow and lower mean velocity.

Figure 5(b) displays the evolution of the mean velocity of vehicles over time from two different initial configurations when the vehicle density is set to 0.12. The mean velocity corresponding to the upper branch is 5, while the mean velocity corresponding to the lower branch is about 3.3. The statistical results are taken from the data after 20,000 time steps of evolution, and the initial 20,000 time steps have been removed to eliminate transient effects.

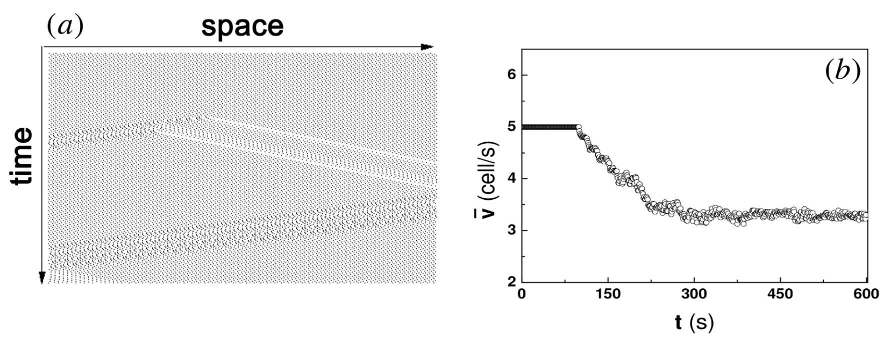

Figure 6. The spatiotemporal evolution diagram (a) and velocity evolution diagram (b) of the traffic system starting from homogenization initialization after experiencing a small disturbance during the evolution process. The parameters are set to $\tau = 2$ and $\rho = 0.12$.

Figure 6(a) depicts the spatiotemporal evolution behavior of vehicles in the upper branch. After being disturbed, the vehicles fall into the lower branch, and the simulated vehicle density setting is consistent with Figure 5(b). The upper branch is in an unstable equilibrium state and can maintain its current state for a long time without external disturbances. Once a small disturbance occurs, it will quickly transfer to the stable state of the lower branch, which meets the definition of metastability. When the vehicle density is set to 0.12, vehicles in the upper branch are evenly and densely arranged and travel at maximum velocity. After being disturbed, the homogeneous arrangement of vehicles is destroyed, and their mean velocity sharply decreased to about 65% of the maximum velocity, as shown in Figure 6(b).

4. Conclusion

The single lane cellular automaton model is adopted in this article to study the impact of different weather conditions on road traffic flow. As expected, in adverse weather conditions, it is necessary to slow down in order to ensure driving safety, resulting in a decrease in traffic flow. The results also indicate that the safety driving model proposed in this article reduces vehicle velocity fluctuations and improves driving safety. Meanwhile, it can be observed from the spatiotemporal evolution diagram of the system that there are phase separation and metastability near the critical density. However, in actual transportation, it is clearly impractical to have all vehicles run according to the same rules at the same time. Therefore, studying the status update modes of vehicles is very promising and can serve as a direction for future research. Despite some limitations, the traffic simulation presented in this article can provide theoretical basis and practical guidance for the design of intelligent driving systems and road traffic planning.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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