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Study on Freeway Congestion Propagation in Foggy Environment Based on CA-SIR Model

Jiao Yao, Jiaping He, Yujie Bao, Jiayang Li and Yin Han *

Business School, University of Shanghai for Science and Technology, Shanghai 200093, China
* Correspondence: hanyin2000@126.com

Abstract: The visibility in a foggy environment has a significant impact on driver behavior and traffic flow status, especially for whole closed highways with long distances between entrances and exits. Foggy days are very likely to cause congestion and even secondary traffic accidents, which seriously affect the reliability of freeway operation. In order to explore the influence of a fog environment on freeway traffic jams, firstly, this paper was based on the analysis of the impact of visibility on foggy days. Light fog, medium fog and heavy fog were classified as one scenario, while dense foggy weather was set separately as an extreme scenario without considering lane change. Furthermore, it used the SIR model of infectious disease for reference, and combined with the cellular automata (CA) model, the car-following model and lane-changing rules in different scenarios were set based on safe driving distance and speed for two scenarios. Finally, the key parameters of CA-SIR were calibrated, such as congestion propagation, recovery probability, vehicle braking, and lane-changing probability. The simulation analysis showed that with the decrease in visibility and vehicle speed, the phenomenon of congestion propagation was more prominent, but the causes of queuing phenomenon were different. A low speed limit was the main reason for traffic jams in the light fog condition. In the medium fog condition, the frequency of traffic jams was related to the random braking probability of the visibility. In heavy fog conditions, the congestion area gradually moved upstream with the passage of time. Moreover, in the dense fog condition, the congested area gradually moved upstream with the passage of time; however, vehicles were more likely to accompany each other, and the congested area traveled downstream synchronously with the passage of time and did not dissipate easily. Therefore, in a foggy environment, the best speed limit should be better established under different visibilities, the flow of highway traffic should be strictly controlled if necessary, and in worse situations than high-density traffic in low visibility, to avoid the spread of congestion, the intermittent release of different lanes is suggested to be implemented.

Keywords: traffic engineering; congestion propagation; foggy environment; cellular automata epidemic (CA-SIR) model; freeway

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Citation: Yao, J.; He, J.; Bao, Y.; Li, J.; Han, Y. Study on Freeway Congestion Propagation in Foggy Environment Based on CA-SIR Model. *Sustainability* **2022**, *14*, 16246. https://doi.org/10.3390/su142316246

Academic Editors: Elżbieta Macioszek, Linchuan Yang, Yuanyuan Guo, Yaoming Zhou, Wenxiang Li and Jixiang Liu

Received: 19 October 2022
Accepted: 2 December 2022
Published: 5 December 2022

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1. Introduction

Adverse weather conditions such as fog, snow, heavy rain, and strong winds can negatively affect highways, especially in terms of road conditions, vehicle performance, visibility, and driver behavior. Drivers' driving behavior is sometimes difficult to quantify in response to such severe weather, and their perception is also affected by the impact of severe weather on their surroundings. The reduced visibility is more likely to increase the possibility of secondary accidents [1]. Wright and Roberg [2] found that severe weather is one of the fundamental causes of traffic congestion. Orosz et al. indicate that if a driver brakes or overtakes suddenly in certain limited situations, traffic congestion of up to 80 km may be observed, and the phenomenon is known as a "traffic tsunami" [3]. According to the Texas Transportation Institute [4], traffic congestion caused by episodic events such as severe weather accounted for 27% of the total number of traffic blockages. The report of the 2019 Blue Book of China Highway Network Operations showed that there were more than 20,000 traffic congestion blockages due to severe weather in 2019, and severe weather accounted for 17.4% of the causes of all congestion blockages. Among them, a foggy environment, as a more common type of severe weather, accounted for up to 9.5% [5], and the reduced visibility in a foggy environment leading to the restricted vision of drivers is an especially important factor affecting traffic flow characteristics [6]. Therefore, this paper attempts to carry out multi-scenario modeling and quantitative analysis of car following and lane changing to illustrate the effects of a foggy environment on the propagation of highway traffic congestion.

Firstly, a foggy environment has a significant effect on the behavioral characteristics of drivers. Zheng Shuxin et al. [7] studied the lane-change behavior of several drivers with different genders, ages, and driving ages through a high-simulation driving simulation cabin. It was found that as visibility decreases in a foggy environment, the lane-changing time increases while the lane-changing speed decreases, and as the reaction time before lane-changing increases, the car-following distance is shortened. Yan et al. [8] studied the effects of different risk levels on driver speed control in a foggy environment and found that, at a high risk level, the driver's slowed speed caused by the foggy environment was effective in reducing the severity of accidents, but it did not reduce the driver's risk of accident because drivers generally perceived that their own speed is slower than the actual speed in foggy weather. Zhang et al. [9] used Smart Eye to obtain information about the driver's gaze area, gaze angle, sweeping speed, and sweeping magnitude while driving in foggy weather and normalized the data to analyze the driver's gaze center of gravity. A series of conclusions were obtained: the driver's gaze speed fluctuated greatly when changing lanes on foggy days, and the gaze shift speed was significantly lower on foggy days than on sunny days.

Furthermore, regarding the effects of foggy conditions, extant research has focused on simulating driver behavior in foggy environments. There is a lack of research on driver behavior and performance in real-world environments. According to historical data from the Federal Highway Administration (FHWA) from 2007 to 2016 [10], about 15% of fatal crashes, 19% of crashes resulting in injuries, and 23% of crashes containing property damage occurred in severe weather. The challenge of low visibility, limited contrast, and perceptual distortion in foggy weather contributes to the large number of accidents that occur each year while driving in foggy weather. From a visual perspective, foggy environments can be described as involving a reduction in contrast in the vision field [11]. In a study of 566 interviewed drivers in Florida, Hassan et al. found [12] that when driving in foggy weather, drivers usually consider the vehicle in front as a means of guidance and maintain a similar speed to the vehicle in front. Particularly in conditions of limited visibility, drivers usually maintain a short headway from the vehicle in front. This tendency is thought to be the main reason for tailgating in foggy weather. Ahmed et al. [13] used various statistical methods to compare the behavior of drivers in foggy and sunny weather in order to better understand driver behavior in different weather conditions. The results showed that speed in dense fog and light fog was reduced by 10% and 2.8%, respectively, compared to the low speed in clear weather and that most drivers exceeded the speed limit in a given visibility condition.

In addition to the effects of foggy weather on drivers, macroscopic operating characteristics and patterns of traffic flow in this environment are also gradually receiving attention. Zhanhong Liu et al. [14] established a microscopic traffic flow model of foggy roads based on safety intervals using a cellular automata model. Additionally, car following in fog was simulated using the stochastic acceleration method, and the differences between fog and clear days were analyzed. Zhaowei Liu et al. [15] determined the effects of different levels of visibility on vehicle speed and the effect of road humidity on friction based on theoretical analysis for future unmanned driving in a foggy environment. Wenyan Feng et al. [16] chose the METANET traffic flow model to analyze the regional freeway network from a macroscopic perspective; moreover, they quantitatively analyzed the dynamic evolution of its driving conditions under different visibility levels. They also discussed the rule of influence of foggy days on the traffic operation of the regional freeway network so as to provide theoretical support for macroscopic traffic coordination and control of the regional freeway network.

The classic model for studying propagation is the SIR model. The SIR model and its modifications can be applied in different fields. Shah et al. used a generalized approach of SIR to accurately predict the spread of COVID-19-associated infections, recovery, and deaths in Pakistan [17]. The study by Miguel et al. showed that the SIR epidemic model can affect different communication layers of all nodes in a variety of Internet of Things (IoT) wireless networks [18]. According to the references, we can gather that the SIR epidemic model is more mature in the simulation studies of various types of propagation.

In summary, most of the existing studies have focused on the differences in driving behavior under foggy conditions and the effects on the operational characteristics of traffic flow. Regarding the congestion problem on the highway, prediction analysis is basically performed by the traffic flow model [19,20].

In contrast, there is a lack of systematic and in-depth investigations on traffic flow congestion, especially the evolution of the state of formation, propagation, and dissipation of freeway congestion. On the other hand, congestion propagation has many similarities with the classical SIR model of epidemics [21]. Each vehicle has three states: susceptibility (pre-crowding), affected (crowding), and exempted (post-crowding dissipation).

Therefore, the purpose of this paper is to study the congestion propagation mechanism of freeways more scientifically with a new method so that a theoretical basis for developing a control plan for freeway congestion in foggy environments can be provided. To better investigate the evolutionary details of propagation, this study combines it with the cellular automata (CA) model and divides the foggy environment links into two types of scenarios according to visibility.

Accordingly, the main contributions of this study are as follows:

(1) An analysis of the effect of visibility in a foggy environment;
(2) The establishment of the freeway congestion model based on the CA-SIR model in different foggy scenarios;
(3) The determination of key parameters of the CA-SIR model in a foggy environment;
(4) The case study and verification by MATLAB.

2. Model and Methods

2.1. Fundamental SIR Model

Lorenzo Pellis et al. verified that stochastic epidemic models can be extended to many other realistic models under specific conditions [22]. The model is able to ignore the temporal dynamics of the epidemic without affecting the final size distribution. The SIR infectious disease model is applied to the process of traffic congestion propagation in highways with three types of states: susceptible to congestion (S), in congestion (I), and removed from congestion (R) with the independent variable of time t, indicated as: $S(t)$, $I(t)$, and $R(t)$, respectively.

Vehicles in congestion affect the remaining uncongested vehicles in the surrounding area by random probability with λ as the average propagation rate. At the same time, the vehicles move away from the congested area with the average recovery rate of μ ($I \rightarrow R$ transition). The vehicles affected by the congested vehicles also become congested vehicles through the average propagation rate λ ($S \rightarrow I$ transition).

In the SIR propagation model, assume that the total number of vehicles within the whole process is N, which is kept constant. $S(t)$ is the free-flowing vehicle, $I(t)$ is the congested vehicle, and $R(t)$ is the departing vehicle, and then the differential equation between the three is:

$$\begin{cases} \frac{dS}{dt} = -\lambda I(t)\frac{S(t)}{N} \\ \frac{dI}{dt} = \lambda I(t)\frac{S(t)}{N} - \mu I(t) \\ \frac{dR}{dt} = \mu I(t) \end{cases} \tag{1}$$

Set separately:
The proportion of free-flowing vehicles to the total number of vehicles at time *t*:

$$s(t) = \frac{S(t)}{N}$$

The proportion of congested vehicles to the total number of vehicles at time *t*:

$$i(t) = \frac{I(t)}{N}$$

The proportion of departing vehicles to the total number of vehicles at time *t*:

$$r(t) = \frac{R(t)}{N}$$
$$s(t) + i(t) + r(t) = 1$$

Further, the nonlinear differential equation between the three is obtained as follows:

$$\begin{cases} \frac{ds}{dt} = \frac{d\left(\frac{S}{N}\right)}{dt} = \frac{1}{N} \cdot \left[-\lambda I(t)\frac{S(t)}{N}\right] = -\lambda i(t)s(t) \\ \frac{di}{dt} = \frac{d\left(\frac{I}{N}\right)}{dt} = \frac{1}{N} \cdot \left[\lambda I(t)\frac{S(t)}{N} - \mu I(t)\right] = \lambda i(t)s(t) - \mu i(t) \\ \frac{dr}{dt} = \frac{d\left(\frac{R}{N}\right)}{dt} = \frac{1}{N} \cdot [\mu I(t)] = \mu i(t) \end{cases} \quad (2)$$

2.2. Improved SIR Model

Since the original SIR model is a macroscopic static mathematical model based on ordinary differential equations, it may not be suitable for describing vehicles in congested conditions, especially those in constant motion. In addition, the differential equations in the SIR infectious disease model oversimplify the complex random behavior and are relatively complicated to solve computationally. In contrast, the cellular automata model simplifies the proof and solution challenges. It also allows for a better setting of complex stochastic behavior. Simulations can be performed with both time and space congestion propagation characteristics. Therefore, combining the two, an improved discrete model of CA-SIR is proposed.

Cellular automata is a discrete model with discrete time–space and state. It consists of four parts: cell, cell space *L*, cell neighbor *K*, and cell rule *F*. That is, $CA = (L, Sd, K, F)$, where *Sd* is the state set of the cell. Combined with the above description, the CA-SIR model can be used to accomplish the traffic congestion propagation problem by the following definitions.

(1) Cell space: A one-dimensional cell space containing *N* cells is established, and a cell in the one-dimensional cell space represents a vehicle in the network. The state of the next cell is determined by the state of the current cell and its neighbors.
(2) Cell state ensemble: let $Sd_{i,j}^t$ be the state of the cell in row *i* and column *j* at time *t*. Set $Sd_{i,j}^t = \{0, 1, 2\}$, where 0 represents the susceptible to congestion vehicles (*S*); 1 represents the vehicles in congestion (*I*); and 2 represents the vehicles not affected by congestion (*R*).
(3) Neighborhood rules: Moore-type neighbors.
(4) Evolution rule of cell:
    (1) When $Sd_{i,j}^t = 0$, if there are congested vehicles around the vehicle, each congested vehicle is influenced with probability λ. If the influence is successful, then $Sd_{i,j}^t = 1$; otherwise, $Sd_{i,j}^{t+1} = 0$;
    (2) When $Sd_{i,j}^t = 1$, the congested vehicle in the unit time step with the probability of b is transformed into a noncongested impact vehicle with probability. If the influence is successful, then $Sd_{i,j}^t = 2$; otherwise, $Sd_{i,j}^{t+1} = 1$;

(3) When $Sd_{i,j}^{t} = 1$ and $Sd_{i,j}^{t+1} = 2$, the vehicle leaves the congestion area and is no longer affected by the congestion.

In the congestion propagation process of freeways, the vehicle that generates congestion may potentially affect more subsequent vehicles. The more vehicles surrounding it, the faster the speed of congestion propagation and the wider the range of vehicles involved in the congestion.

2.3. CA-SIR Model of Freeway Congestion Propagation in Foggy Environment

The SIR infectious disease model is more mature in the simulation studies of various types of propagation. On the other hand, the cellular automata model generates propagation changes in the next moment through the interaction of individuals. In terms of traffic congestion propagation on freeways, while the assumptions of the SIR model cannot reproduce the actual traffic phenomenon, the cellular automata model can simulate the details of propagation through the evolution of its rules. The advantages of the two models combined can make the simulation closer to reality and more conducive to the analysis of the propagation process.

2.3.1. CA Model Setup for Highways and Visibility Effects

The classical one-way three-lane freeway is used as the model setting [23], where there are 500 cells within each lane, each cell represents one vehicle, and the cell length is set to 5 m so that the actual lane length is 2.5 km. There are two possibilities for each cell at any moment: occupied by vehicles or empty.

It is assumed that all vehicles in the model are small cars and that time, space, and vehicle speed are discretized by integers. The vehicles are randomly generated by Poisson distribution, the total number of vehicles N = 500, and from the beginning of the lane, the speed of the vehicle i at time t is $v_i(t)$ and $v_i(t) \in [0, v_{\max}]$, where $v_{\max}$ represents the maximum speed of the vehicle traveling. Since the set length of each cell is 5 m, it is established that $v_{\max}$ = 7 cell/s = 35 m/s = 126 km/h, which meets the speed limit requirement for driving on the freeway. Considering the influence of low visibility in different weather environments, the corresponding speed limit requirements in each visibility case in the cellular automata model were obtained, as shown in Table 1.

Table 1. The speed limit requirements corresponding to each visibility condition.

Definition	Visibility (m)	Speed Limit (km/h)	Speed Limit in the Cellular Automata Model (1 cell = 5 m)
Light	200–1000	80	20 (m/s) = 4 (cell/s)
Medium	100–200	60	15 (m/s) = 3 (cell/s)
Heavy	50–100	40	10 (m/s) = 2 (cell/s)
Dense	<50	20	5 (m/s) = 1 (cell/s)

Foggy weather can cause a significant change in visibility for drivers compared to sunny weather. This change also has an impact on traffic flow. While driving, drivers have 10–40% lower visual acuity in dynamic environments than in static environments. According to a related study [24], the relationship between meteorological visibility and a driver's visual distance can be obtained as shown in Equation (3):

$$L_s = \frac{0.6 d_q (\ln K + 3.912)}{3.912} \tag{3}$$

where L_s is the driver's visual distance, d_q is the visibility of the weather, and K is the contrast of the object itself. In the state of foggy weather, the object mostly appears gray or white, with the contrast generally taken as 0.35.

The driver's visual distance under foggy conditions is directly affected by visibility, and as the visibility range decreases, the driver's visual distance also decreases. In foggy weather environments, drivers cannot see the vehicle in front of them in the field of view, and at this time, the driving psychology is susceptible to change, and driving behavior tends to be conservative. The driver may adjust the speed within the visible distance in order to prevent the emergency braking of the vehicle when the distance ahead is small due to the low visibility.

2.3.2. CA-SIR Model for Different Fog Scenarios

(1) Scenario classification

According to the above study and the reasonable assignment for this study according to the relevant literature, the visibility distances were set to 400 m, 170 m, 75 m, and 40 m in light fog, medium fog, heavy fog, and dense fog, respectively [25], as shown in Table 2. The visibility distances corresponding to each visibility case are obtained from Equation (1). In this model, the cell length was set to 5 m, and therefore, the visible distance was taken down to a common multiple of 5, i.e., the driver's visible distances were 175 m, 75 m, 30 m, and 15 m. According to the minimum driving distance regulation of the Notice on Strengthening Traffic Management on Freeways under Low Visibility Meteorological Conditions of the Ministry of Public Security of China, the minimum safe distance d_{safe} for each visibility condition was finally obtained.

Table 2. Visibility distance and minimum safety distance corresponding to each visibility condition.

Definition	Visibility (m)	Vehicle Distance (m)	Visibility Distance L_s	Minimum Safety Distance d_{safe}
Light	400	>150	175 (m) = 35 (cell)	150 (m) = 30 (cell)
Medium	170	>100	75 (m) = 15 (cell)	75 (m) = 15 (cell)
Heavy	75	>50	30 (m) = 6 (cell)	30 (m) = 6 (cell)
Dense	40	—	15 (m) = 3 (cell)	15 (m) = 3 (cell)

On the freeway, the foggy environment, vehicle driving speed in different visibility conditions, and the safety distance that must be maintained are different, and the drivers' psychological characteristics and operational behavior are also different. Especially in extreme weather such as on dense fog days, the relevant implementation regulations provide that the maximum speed does not exceed 20 km/h and that drivers exit the freeway as soon as possible through the nearest exit to avoid secondary accidents. Due to the extreme weather, the driver's field of vision is extremely small, there is no reference system when driving on the freeway, and the lane-change situation is not considered; therefore, the basis for determining vehicle movement is also adjusted. In this study, the model was divided into two cases for research: light fog, medium fog, and heavy fog were grouped into scenario one; dense fog weather was set separately as scenario two.

(2) Vehicle following model of scenario 1

We integrated the corresponding visibility from Tables 1 and 2 to determine the speed limit conditions, vehicle distance, visual distance, and minimum safety distance under each visibility condition in the model. Different visibilities bring different sight distances, and driving speed has a significant impact on the driving state of the vehicle. In order to ensure the safety of vehicles on the highway and to avoid tailgating accidents in which the front and rear cars collide, a certain distance needs to be maintained so that the latter vehicle can have enough time to react, and this distance is called the safety distance.

According to Figure 1, there are 3 states of vehicles in the model proposed in this paper based on the different zones of front vehicles.

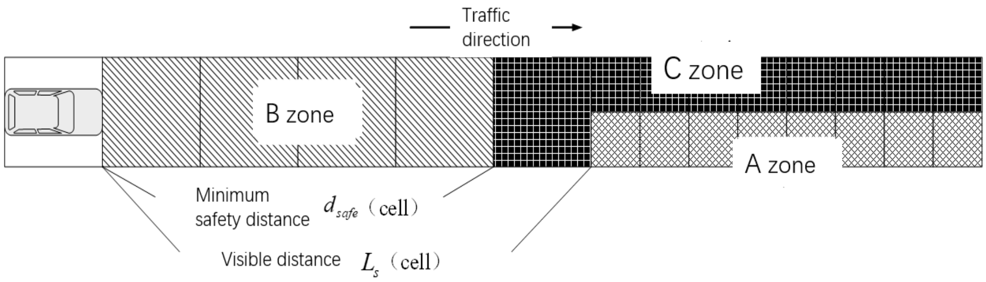

Figure 1. Schematic diagram of the area of the front car on a single lane of the freeway.

(1) The front vehicle is in the A zone (greater than the visible distance of current visibility). The rear vehicle can accelerate, and when the vehicle speed reaches the maximum speed, it can maintain the speed of driving until encountering the need to slow down.
(2) The front vehicle is in the B zone (less than the minimum safety distance of current visibility), and if the rear vehicle to continues to maintain its speed, it will cause rear-end collision with the front vehicle; therefore, the rear vehicle must slow down to maintain a safe distance.
(3) The front car is in the C zone (greater than the minimum safety distance of current visibility). The rear car makes a judgment according to the speed of the front car and the front car distance; therefore, there is a certain probability of a random deceleration behavior to adjust the speed.

Since a driver's effective sight distance is not necessarily within the safe distance, it is necessary to judge the distance of the car in front with the effective sight distance and the safe distance separately when building the model. To ensure the safety of driving in a foggy environment, drivers tend to be conservative in their behavior and adopt more deceleration behaviors and less acceleration behaviors.

The specific evolutionary rules are as follows.

(1) Judgment of the distance from the vehicle in front $d_{t,i}$ and the visibility distance L_s.

$$d_{t,i} = x_{t,i+1} - x_{t,i} - l_{car} \tag{4}$$

$$d_{t,i} = \begin{cases} L_s, & d_{t,i} \geq L_s \\ d_{t,i}, & d_{t,i} < L_s \end{cases} \tag{5}$$

where: $d_{t,i}$ indicates the distance between the first car and the car in front of it at the moment (cell); $x_{t,i}$,$x_{t,i+1}$ indicates the position of the car i and $i + 1$ at the moment (cell); l_{car} indicates the body length (cell), with l_{car}= 5 m; and L_s indicates the driver's visual distance.

(2) Vehicle state

1. Acceleration

A driver, when driving on foggy days, determines the acceleration of the vehicle according to whether there is a vehicle within the visible distance and whether the distance to the front car is greater than the minimum safe distance.

When there are vehicles in the same lane within the visual distance, the visual distance is greater than the distance in front, as shown in Figure 2a.

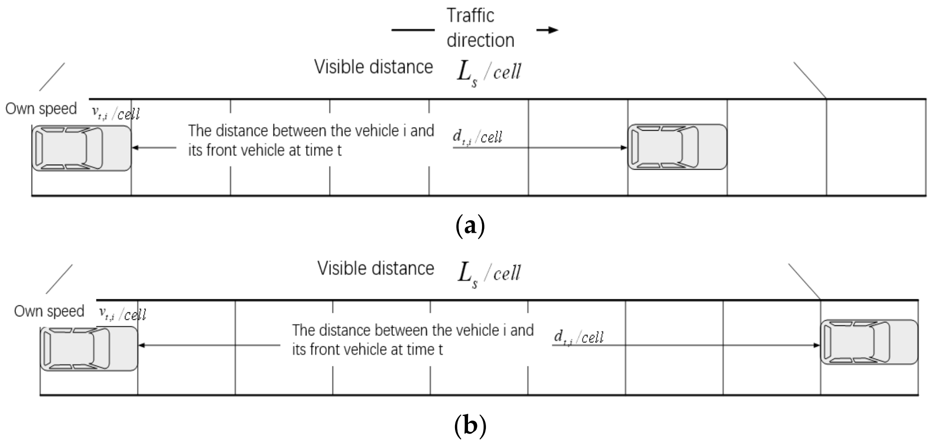

Figure 2. Visible distance and distance to the front vehicle on a single lane of the freeway. (**a**) Vehicles in the same lane within the visible distance; (**b**) No vehicle in the same lane within the visible distance.

When $d_{safe} < d_{t,i} \leq L_s$ and $v_{t,i} < d_{t,i}$,

$$v_{t,i} = \min(v_{t,i+1}, d_{t,i}, \alpha_n \cdot v_{\max}) \tag{6}$$

When there is no vehicle in the same lane within the visual distance, the visual distance is less than the distance in front of the vehicle, and the driver can accelerate within the visual distance, as shown in Figure 2b below.

When $d_{t,i} > L_s$ and $v_{t,i} < L_s$,

$$v_{t,i} = \min(v_{t,i+1}, L_s) \tag{7}$$

where: d_{safe} indicates the minimum safe distance (cell); $v_{t,i}$ indicates the speed of the first vehicle at the moment (cell/s); $v_{\max}$ indicates the maximum speed of the vehicle, i.e., the desired speed (cell/s); α indicates the speed coefficient under different visibilities; and $\alpha_n \cdot v_{\max}$ indicates the maximum desired speed (cell/s) under n visibility conditions. The smaller the visibility, the smaller the maximum expected speed; therefore, the specified value is within 0–1.

2. Random braking

A driver has the probability of performing small braking during nonacceleration and deceleration states.

$$v_{t,i} = \max(v_{t,i} - 1, 0) with P_{brake} \tag{8}$$

where P_{brake} is the random braking probability, which means that the vehicle has the probability P_{brake} of braking randomly.

3. Forced braking

When a driver is driving in fog and when there is a vehicle in the same lane within the visible distance, if the current vehicle speed at time *t* is larger or the distance from the vehicle in front is close to the minimum safe distance, the driver displays deceleration behavior:

$$d_{t,i} \leq L_s \text{ and } v_{t,i} > L_s, v_{t,i} = \min(v_{t,i} - 1, L_s) \tag{9}$$

4. Position update

$$x_{t+1,i} = x_{t,i} + v_{t,i} \times \Delta t \tag{10}$$

(3) Lane-changing rules for scenario 1 The number of vehicle lane changes in a foggy environment is significantly lower than that on a sunny day, and the lower the visibility, the smaller the probability of lane changes. When there is a slow vehicle

speed ahead or a vehicle in a congested state, and the speed of the adjacent lane is relatively fast, the subsequent vehicle may choose a suitable time to generate the lane-change behavior based on the visible distance, the vehicle speed, the following distance, and the speed of the neighboring vehicles in the adjacent lane. When the following conditions are met, vehicles may make a lane change.

(1) $d_{t,i} < \min\left(v_{t,i} + 1, d_{safe}\right)$. Indicates that the first vehicle is influenced by the vehicle ahead and probably will make a lane change.

(2) $d_{t,i,front} > \min\left(v_{t,i} + 1, d_{safe}\right)$. Indicates that there is enough lane-change space in the adjacent lane to provide a lane change for the first vehicle. $d_{t,i,front}$ is the distance (cell) between the first car and the nearest preceding car in the adjacent lane at the time.

(3) $d_{t,i,back} > \min\left(v_{t,i,back} + 1, \alpha_n \cdot v_{\max,i,back}, d_{safe}\right)$. $d_{t,i,back}$ is the distance between car i and the nearest car in the adjacent lane at time t (cell); $v_{t,i,back}$ is the speed of the nearest car in the adjacent lane at the time (cell/s); and $\alpha_n \cdot v_{\max,i,back}$ is the maximum speed of the nearest car in the adjacent lane at the time (cell/s) at visibility n.

(4) $rand() < \left(1 - P_{change}\right)$. P_{change} is the lane-change probability of the vehicle; $rand()$ is a random number between 0 and 1.

In this study, the lane change probabilities of vehicles in foggy environments were 0.41 (light fog), 0.23 (medium fog), and 0.14 (heavy fog).

(4) Vehicle following model of scenario 2

In a foggy environment, vehicles change lanes less frequently than in clear weather because they have lower visibility and shorter visual distance, and the judgment basis for lane change needs to be more precise than in clear weather.

Related research [26] shows that since freeways are generally in open areas, vehicles traveling in the same lane subconsciously shorten the distance to the vehicle in front to obtain the longest visible distance at that visibility in a foggy condition with 48 m visibility. The faster the vehicles in the adjacent lane, the faster the driver unconsciously maintains the same fast speed. The driver focuses on the vehicle in front, and it is difficult to observe the location of the rear vehicle through the rearview mirror. Therefore, for this kind of extreme weather environment (visibility of 50 m), ignoring the driver's individual lane change and considering the influence of vehicles in the adjacent lane, only the vehicle-following model under a dense fog environment was established.

In the model, according to the influence of the following distance and driving speed of the vehicle and the adjacent-lane vehicles, two parameters, γ and δ, are used to indicate the influence of the adjacent-lane vehicles on the following distance and speed of the vehicle, respectively. The larger γ is, the greater the impact of the distance difference between the current vehicle and the adjacent-lane vehicle on the driver in the visible range; the larger δ is, the greater the impact of the speed difference between the current vehicle and the adjacent-lane vehicle on the driver in the visible range. Based on the results of related studies [18], the values of 0.4 and 0.5 were taken for the two parameters, respectively.

Under consideration of the above conditions, in order to measure the influence of the left and right adjacent lanes on the braking probability of the vehicle, three unidirectional lanes were used as an example to study the congestion propagation phenomenon under a dense fog environment. The simulation diagram in a dense fog environment is shown in Figure 3. The following rules were set for the following operations.

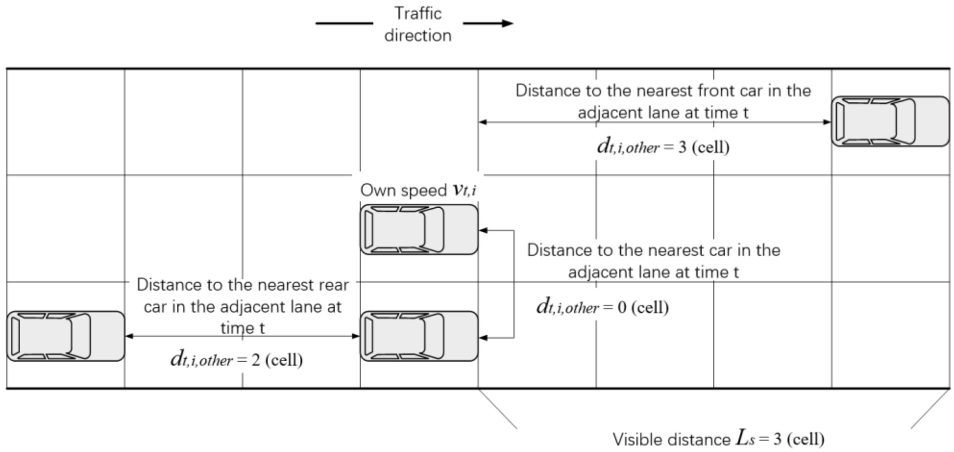

Figure 3. Simulation diagram of the distance between the vehicle and adjacent vehicles in the state of dense fog.

(1) Determine the random braking probability P_{brake}

$$\Delta v_{t,i,other} = \min(v_{t,i} - v_{t,i+1,other}) \tag{11}$$

$$P_{brake} = \begin{cases} \max\left\{0, P_0 \cdot \left[1 + \gamma \tanh\left(\left|L_s - d_{t,i,other}\right|\right) + \delta \frac{\Delta v_{t,i,other}}{v_{\max}}\right]\right\}, 0 \le d_{t,i,other} \le L_s \\ P_0, d_{t,i,other} > L_s \end{cases} \tag{12}$$

where the random braking probability P_{brake} is influenced by the vehicles in the adjacent lane; P_0 is the random braking probability of the vehicles in a dense fog environment that are not influenced by the adjacent lane; the speed of the vehicle i at time t is denoted as $v_{t,i}$, the speed of the nearest preceding vehicle i in the adjacent lane at time t is denoted as $v_{t,i+1,other}$; the maximum speed of the vehicle is $v_{\max}$; $\Delta v_{t,i,other}$ is the speed difference between the first vehicle and the nearest preceding vehicle in the adjacent lane at time t (cell/s); and $d_{t,i,other}$ is the distance between the first vehicle and the nearest preceding vehicle in the adjacent lane at the time (cell); $\gamma = 0.4$, $\delta = 0.5$.

(2) Vehicle state

1. Acceleration

$$v_{t,i} = \min(v_{t,i} + 1, \alpha_n \cdot v_{\max}) \tag{13}$$

2. Random braking The driver has the probability of braking in a small area during the nonacceleration and deceleration states.

$$v_{t,i} = \begin{cases} \max(v_{t,i}, 0), d_{t,i} > L_s \\ \max(v_{t,i} - 1, 0), 0 \le d_{t,i} \le L_s \end{cases} \; with P_{brake} \tag{14}$$

3. Forced braking

$$v_{t,i} = \min(v_{t,i}, d_{t,i} - 1) \tag{15}$$

4. Position update

$$x_{t+1,i} = x_{t,i} + v_{t,i} \times \Delta t \tag{16}$$

2.4. Determination of Model Key Parameters

According to the SIR model in Section 2.1, vehicles in congestion affect the remaining uncongested vehicles in the surrounding area by random probability with λ as the average propagation rate. At the same time, the vehicles move away from the congested area with the average recovery rate of μ ($I \rightarrow R$ transition). The vehicles affected by the congested vehicles also become congested vehicles through the average propagation rate λ ($S \rightarrow I$ transition). The state of the vehicles themselves changes as shown in Figure 4.

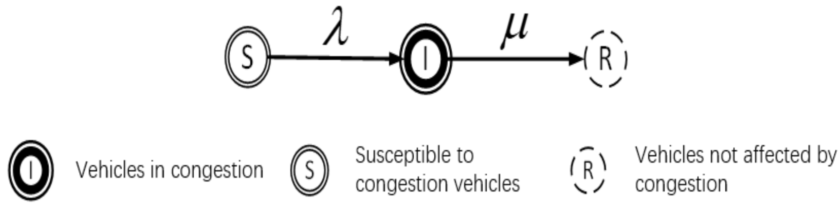

Figure 4. Vehicle changes according to SIR congestion propagation model.

According to the CA-SIR model in Section 2.2, the congestion propagation probability λ_{CA} and congestion recovery probability μ_{CA} are respectively related to different braking probabilities P_{brake} and lane-change probabilities P_{change}. By quantifying them and adding the speed limit requirements for different visibilities in a foggy environment, the congestion propagation probability λ_{CA} and congestion recovery probability μ_{CA} in this scenario are obtained as follows:

$$\lambda_{CA} = \frac{(1-\alpha_i) \times \overline{\lambda} \times \delta}{20 \times e^{-P_{change} \times P_{brake}}} \tag{17}$$

$$\mu_{CA} = \frac{(1-\alpha_i) \times \overline{\mu}}{20 \times e^{-P_{change} \times P_{brake}}} \tag{18}$$

where $\overline{\lambda}$ indicates the average congestion propagation probability, $\overline{\lambda} = 0.75$; $\overline{\mu}$ is the average congestion recovery probability, $\overline{\mu} = 0.4$; and the speed factor α_i in the foggy environment is affected according to different visibilities and takes a value between 0 and 1, and the equation is

$$\alpha_i = \frac{v_{i,\max}}{v_{\max}} \tag{19}$$

where $v_{\max}$ = 7 cell/s is the maximum speed in clear weather. $v_{i,\max}$ is the speed limit value in different foggy weather environments.

3. Results and Discussion

3.1. Assumptions and Parameters

According to Tables 1 and 2, the visibility environment in this study was divided into four types: light fog, medium fog, heavy fog, and dense fog, with different visibility distances under different visibilities and different degrees of influence on the driver's vision. The model's speed limit rules under each type were adopted from Table 1 to obtain the maximum speed of the vehicle (light fog), (light fog), (heavy fog), and (dense fog). The values of speed coefficients for different visibilities were 1, 0.75, 0.5, and 0.25, respectively.

Through the MATLAB simulation study, it was found that the model simulation is not feasible when the braking probability is too large under all four fog types. The vehicle causes or encounters congested conditions once it is driven out, the effect of the random Poisson distribution generation of the vehicle is invalid, and the model complies with the maximum speed limit requirement in low visibility with low overall vehicle speed. Therefore, once the driver brakes randomly on the vehicle in the slow speed state, the vehicle speed goes to zero while the impact range is larger. Vehicles affected by congestion due to foggy weather congestion, after starting to accelerate, also need to maintain the minimum safety distance, while the recovery speed is slow and can easily cause comprehensive traffic paralysis. Therefore, according to the relevant research [13], the set braking probabilities were 0.24 (light fog), 0.26 (medium fog), and 0.28 (heavy fog). The random braking probability for vehicles not affected by adjacent lanes in dense fog was 0.31 [20]. The lower the visibility, the lower the driver's willingness to change lanes, and the probabilities of changing lanes were set to 0.41 (light fog), 0.23 (medium fog), and 0.14 (heavy fog) for each of the three cases. In the case of dense fog, the driver's individual lane change was ignored.

3.2. Road Time–Space Change Graph under Foggy Environment

Due to the different minimum safety distances under different visibilities, in order to avoid the vehicles at the beginning of each lane maintaining the distance and causing congestion, and at the same time, considering that vehicles driving under foggy conditions are affected by the speed limit, the total time of the overall simulation is too long. Therefore, only the spatial and temporal changes of the road in the middle period were intercepted for research and analysis.

Figure 5 shows the time–space change graph of some vehicle with a visibility of 400 m under a light fog condition, where the vehicle traveled 1721 s in 500 cells, and 600–1200 s was selected as the main reference time in the model simulation process. In Figure 5, the straight line formed by the points of the same vehicle at different position–time points represents the speed of the vehicle (black arrow line), and the slope of the line represents the rate of the vehicle. The larger the slope, the slower the vehicle travels, and the arrow marks the direction the vehicle travels. From Figure 5, it can be found that the first vehicle to exit (the vehicle below the black arrow line) is less likely to be affected by the vehicle in front of it and travels at the highest rate at that visibility. The denser the black area, the higher the density of vehicles, which can quickly dissipate by changing lanes or accelerating in that visibility, avoiding traffic congestion.

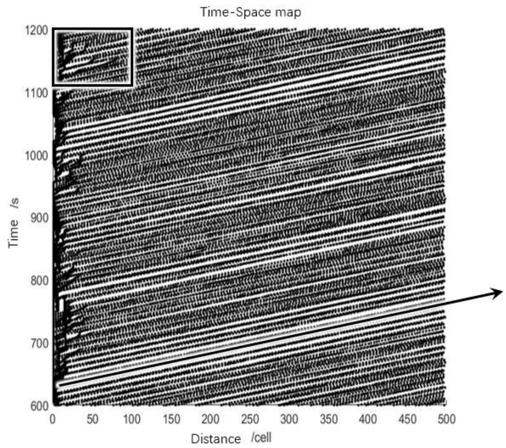

Figure 5. Vehicle time–space variation at 400 m visibility (light fog).

The denser traffic flow at the starting point is due to forced braking by vehicles needing to maintain a minimum safe distance from the vehicle in front, resulting in a brief gathering of vehicles at a nearby location. The maximum queue caused by the congestion is shown in Figure 5 in the black box, with a length of about 100 m and a duration of about 30 s, which dissipated on its own. After the distance and speed adjustment of the vehicles at the starting point, the subsequent simulation process was a not-obvious crowding process.

Figure 6 shows the time–space variation of some vehicles at 170 m visibility in medium fog, and the same 400–800 s range was selected as the main reference duration during the model simulation. The vertical line in the black box in the figure, which is different from the vehicle trajectory, represents the congestion phenomenon at this location. The gray arrow line represents the average speed of the vehicle at that visibility without the effect of congestion. The model simulations for the same number of vehicles lasted for a total of 1296 s. Comparing the information in Figure 6 with that in Figure 5, it can be observed that:

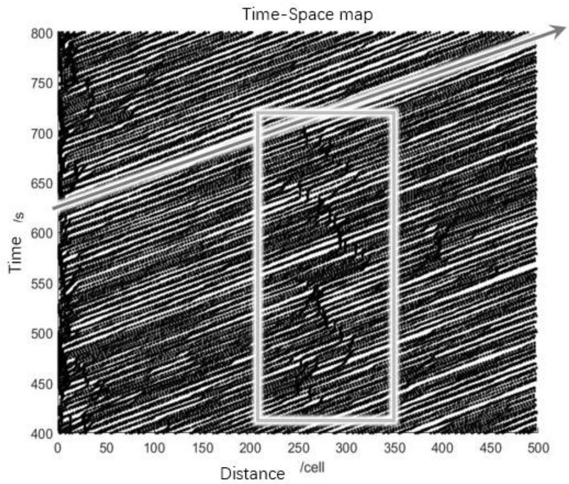

Figure 6. Vehicle time–space variation at visibility of 170 m (medium fog).

(1) The slope of the gray arrow line in Figure 6 is steeper than the slope of the black arrow line in Figure 5, which indicates that the average speed of vehicles under medium fog without the influence of congestion is lower than that under light fog, which was 16.03 m/s (light fog) and 8.63 m/s (medium fog), respectively, and the reduced visibility brought about reduced sight distance and reduced speed limit of the highway. The difference between the speed limit ratio of 25% for both vehicles and the average speed ratio of 46.16% for both vehicles was obvious, which indicates that the congestion phenomenon under the medium fog condition is characterized by a small range but a high frequency.

(2) Congestion in the medium fog state occurred frequently, but almost all appeared in the gray box (the 200th metric cell to the 300th metric cell); further, there was no obvious congestion propagation phenomenon, the overall frequency of congestion occurrence was related to the random braking probability in this visibility, and overall, there was no obvious pattern.

(3) The total elapsed time for the same number of vehicles traveling the same distance at 170 m visibility (1296 s) was inversely reduced compared with the total simulation time at 400 m visibility (1721 s), and the difference accounted for 24.7%, which was not caused by errors. By constantly changing the visibility in the light fog range, the overall simulation time was around 1680–1780 s, which was much higher than that in the medium fog condition. By analyzing the simulation content, it was found that the speed limit in accordance with the Road Traffic Safety Law was too low in the light fog state, and at the same time, vehicles did not hesitate to slow down in order to maintain the minimum safety distance, thus causing congestion, and although the congestion range was not large and could dissipate by itself, the overall time spent was longer.

Figure 7 shows the time–space changes of some vehicles in the heavy foggy condition when the visibility is 75 m. In order to clearly see the spatial and temporal diagram of the vehicles driving in this visibility, we intercepted and enlarged the model simulation process of 500–700 s as the main reference time. The black arrow line represents the speed of the vehicles in this figure when they are not affected by congestion, and the model simulation with the same number of vehicles at a safe distance lasted a total of 1234 s. Comparing Figure 7 with Figures 5 and 6, it can be found that:

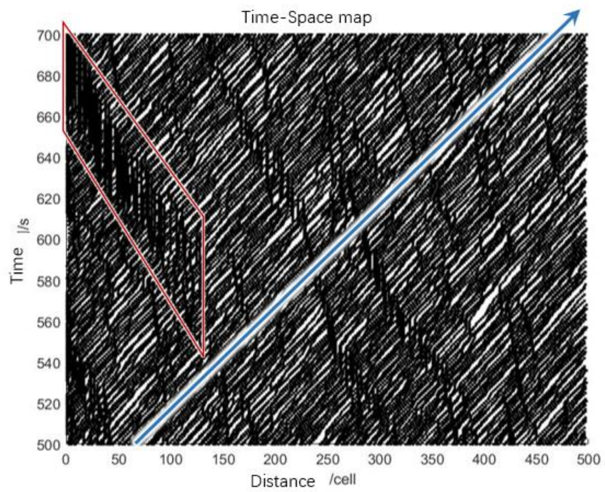

Figure 7. Vehicle time–space variation at visibility of 75 m (heavy fog).

(1) The slope of the blue arrow line in Figure 7 is greater, and the average vehicle speed when the visibility is 75 m was 3.28 m/s when not affected by congestion, which is a 62% decrease compared to a medium fog day. It is mainly because the foggy condition is more severely affected by visibility and the specified speed limit is lower.

(2) The congestion propagation phenomenon in the heavy fog condition was obvious, and as shown in the red area of Figure 7, the congestion range gradually moved upstream with the passage of time and became denser and denser. In addition, due to the reduced visibility and the influence of the speed limit, different driving styles of drivers brought obvious differences, with conservative drivers driving slower, braking more easily, and staying longer in the lane. It can cause traffic disorder and congestion to subsequent vehicles. At the same time, congestion propagation did not dissipate on its own in low visibility.

Therefore, in the heavy foggy condition, the congestion continues all the time, which means that it remains in the I state and does not reach the R state, much less return from the R state to the S or I state. The propagation of congestion is just a movement in space and does not involve passing or feedback between states. Therefore, to ease the traffic congestion phenomenon is the primary goal in a heavy fog environment on the freeway.

(3) The total elapsed time for the same number of vehicles traveling the same distance at 75 m visibility (1234 s) was about the same as the total simulation time at 170 m visibility on a medium fog day (1296), with a difference of less than 5%. This indicates that although the number of vehicles crowded in heavy fog is significantly greater than in medium fog, the average speed is also slower. However, the number of vehicles in heavy fog that needs to maintain the minimum safety distance was also smaller; therefore, despite the slower speed, the vehicle density was greater, and as a result, the overall time used in the simulation was almost the same.

In the vehicle time–space change map in Figure 8 for the dense fog state with a visibility of 40 m, the vehicle speed under the fog environment was very slow due to the speed limit; therefore, the entire model simulation time for the same number of vehicles lasted a total of 1962 s, and by intercepting and enlarging the model simulation process using 800–1100 s as the main reference time, we can see more clearly the time–space map of the vehicle driving under a given visibility. The red arrow line represents the speed of the vehicle when it is not affected by congestion.

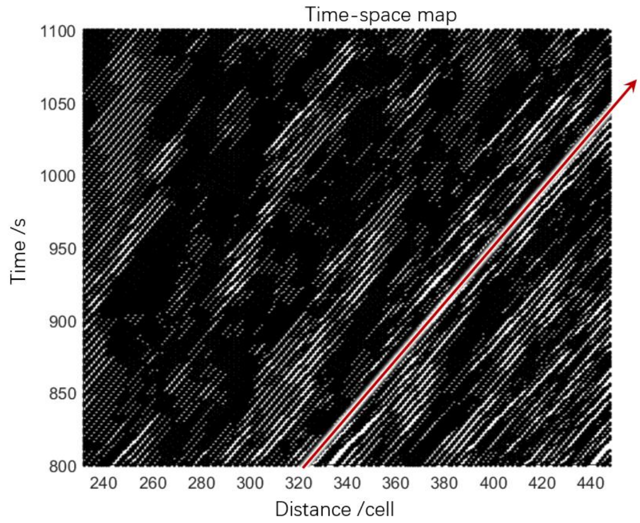

Figure 8. Vehicle time–space change map at visibility of 40 m (dense fog).

Comparing Figure 8 with Figures 5–7, according to the vehicle time–space variation diagrams under the four visibility levels, it can be found that:

(1) Due to the different maximum driving speeds, visible distances, and minimum safety distances in each visibility, the slope of the arrow line in Figure 8 gradually becomes larger, representing that the vehicle speed in the model gradually slows down even if it is not affected by congestion. On a dense fog day, the average speed was 2.51 m/s.

The average speed obtained from the simulation in all four foggy conditions without congestion was well below the maximum speed limit specified for the visibility, averaging only 55% of it. The most obvious was that in the heavy fog environment, at only 32.8% of the maximum speed limit. It can be seen that a foggy environment in general has an impact on the speed of vehicles, in addition to the dense fog days, and the reduction in visibility on the impact of speed gradually increased. On dense fog days, the general driving behavior of vehicles was more conservative, and the nearest vehicles within the visibility range tended to take the way of companionship, which could effectively reduce the risk generated by congestion under the speed limit conditions.

(2) The illustrations of the congestion propagation phenomenon in Figures 7 and 8 show that the biggest difference is that the congestion propagation in the foggy condition gradually moved upstream with time and the congestion range increased, while in the dense fog environment, when the traffic flow was too dense or the previous vehicle suddenly braked and caused congestion, the congestion range around the vehicle moved downstream synchronously with the passage of time. In other words, under heavy fog, vehicles in congestion move away, and new vehicles move into the congestion area upstream; however, under dense fog, vehicles in congestion move forward together with the surrounding vehicles at a slow speed and do not move away from the congestion area.

Therefore, in that visibility, in addition to speed limit measures, requiring vehicles in the nearest ramp to leave the highway as soon as possible, strictly controlling the density of vehicles, or implementing the intermittent release of multiple lanes is necessary to avoid causing congestion pile-ups or the traffic paralysis phenomenon, which is more likely to cause traffic accidents in low visibility.

3.3. Analysis of Speed Characteristics in Foggy Environment

Figure 9 shows the overall average vehicle speed for each visibility condition, and the vehicle speed in the model is in cell/s.

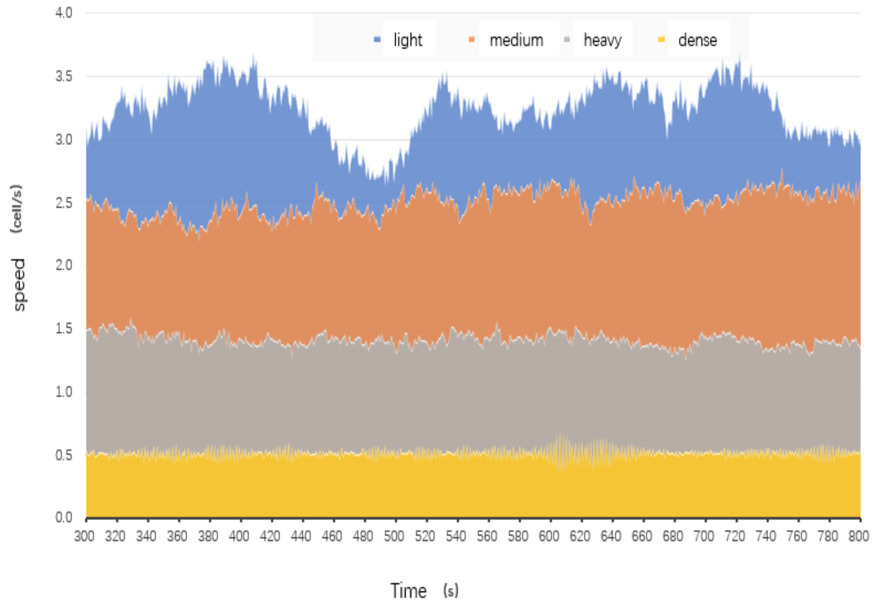

Figure 9. Overall average speed of vehicles at various visibility levels.

From this, it can be seen that:

The average vehicle speed fluctuated the most on light fog days, and as the visibility decreased, the average travel speed also decreased, and the up and down fluctuation decreased.

In the light fog environment, the overall speed variation was as low as 2.66 cell/s and as high as 3.7 cell/s. Combined with the time–space map in Figure 5 when the visibility is 400 m, it can be found that the fluctuation of the overall average vehicle speed is consistent with the sparse and dense distribution of traffic flow in Figure 5, which indicates that in a high-visibility environment, vehicles driving on the highway are still mainly influenced by the traffic flow, similar to in sunny weather, and although there is frequent acceleration and braking behavior, it is not too affected by the weather and almost not affected by the sight distance factor brought by light fog.

As visibility gradually decreased, the overall vehicle speed decreased and fluctuated to a smaller extent. The overall average vehicle speed began to be affected by the reduced visibility and speed limits. The overall traffic flow density gradually became greater, especially in dense fog conditions, and the travel speed was the slowest, causing an increase in traffic flow and a greater range of congestion and queuing vehicles. In addition, the visibility was reduced, the driver's field of vision was also reduced, and the greater impact of the vehicle in front and the surrounding vehicles was more likely to cause congestion propagation.

Therefore, in a foggy environment, freeway authorities should formulate the best speed limit value under different visibilities. If necessary, freeway authorities need to strictly control the amount of vehicle on the freeway. Even for high-density traffic in low visibility, highway authorities need to implement the intermittent release of different lanes of traffic to avoid the spread of congestion. In this case, shared mobility, such as bicycle sharing, can be considered to decrease vehicle volume and reduce congestion to improve safety [27,28].

4. Conclusions

For the foggy scenarios of freeways under different visibilities, this study constructed a CA-SIR cellular automata epidemic model to study this congestion propagation regulation. In the model construction, the key parameters in CA-SIR were determined by establishing the car-following and lane-changing rules for two foggy scenarios. Finally, the evolution of congested vehicles at each time point of congestion propagation on the freeway under a foggy environment was obtained.

Through related simulation analysis, it was found that as the visibility decreases and the vehicle speed decreases, the congestion propagation phenomenon gradually becomes prominent, and the congestion queuing phenomenon becomes more obvious. In light fog conditions, the speed limit is an important factor causing traffic congestion; in medium fog conditions, the amount of congestion generated is related to the random braking probability set by the vehicles; and in heavy fog conditions, the congestion area gradually moves upstream while vehicles keep driving away from the congestion area. In dense fog, affected by very low visibility, vehicles are more likely to choose to travel in groups, and the congestion range keeps moving downstream in parallel with the passage of time. It is difficult for vehicles to leave once they are affected by congestion, and the congestion does not dissipate easily.

This study mainly investigated freeway congestion propagation in foggy weather from the perspective of traffic flow. Moreover, the reduced visibility in an actual foggy weather environment may significantly affect drivers' psychology and related visual exhaustion and driving risk perception. These factors need to be further explored in depth and can be subsequently considered to be integrated into the model of congestion propagation.

Author Contributions: Conceptualization, J.Y.; methodology, J.H.; validation, Y.B.; formal analysis, J.H.; investigation, J.L. and Y.H.; resources, J.Y.; data curation, J.H.; writing—original draft preparation, J.H. and Y.B.; writing—review and editing, J.Y.; visualization, J.H.; supervision, Y.H.; project administration, Y.H.; funding acquisition, J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by Ministry of Education in China (MOE) Project of Humanities and Social Sciences (22YJAZH131) "Research on mechanism of route coordinated control of commuter traffic at the urban road network in the environment of big data". The authors, therefore, acknowledge with thanks the financial support of Ministry of Education in China (MOE).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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