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Research Article

Traffic Conflict Analysis of Motor Vehicles and Nonmotor Vehicles Based on Improved Cellular Automata

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In recent years, with the rapid development of China's logistics industry and urban service industry, electric bicycles have gradually become an important means of transportation in cities due to their flexibility, green technology, and low operating costs. Because electric bicycles travel though motor vehicle lanes and nonmotor vehicle lanes, the conflict between motor and nonmotor vehicles has become increasingly prominent, and the safety situation is not optimistic. However, most theories and models of mixed traffic flow are based on motor vehicles and bicycles and few involve electric bicycles. To explore the traffic safety situation in an urban mixed traffic environment, this paper first uses cellular automata (CA) to establish a three-strand mixed traffic flow model of motor vehicles, electric bicycles, and bicycles and verifies the reliability of the model by using a MATLAB simulation based on the actual survey data. Then, using the technology of traffic conflicts and the conflict rate as the index to evaluate the traffic safety situation, the change in the conflict rate with different road occupancies and different proportional coefficients of motor vehicles is studied. In the end, the conflict rate is compared between the mixed traffic flow and the setting of a physical isolation divider, which provides some suggestions on when to set a physical isolation divider to separate motor vehicles from nonmotor vehicles. The results show that in a mixed traffic environment, the conflict rate first increases and then decreases with increasing road occupancy and reaches a peak when the road occupancy is 0.6. In addition, in mixed traffic environments, the conflict rate increases with an increasing proportional coefficient of the motor vehicle. When the road occupancy rate is within the range of [0.6, 0.9] or when the proportional coefficient of motor vehicle is between [0.8, 0.9], a physical isolation divider can be set to separate motor vehicles and nonmotor vehicles from the space to improve traffic safety.

1. Introduction

With the advocacy of green transportation and the increasing congestion of motor vehicles on urban roads, an increasing number of people have chosen electric bicycles as a way of travel because of their convenience and flexibility. However, many roads in Chinese cities do not have a physical isolation divider between motor and nonmotor vehicle lanes. Inevitably, motor vehicles and nonmotor vehicles are mixed; this condition is referred to as a mixed traffic flow. Therefore, it is very meaningful to study the characteristics of a mixed traffic environment to better integrate electric bicycles into the urban transportation system of China.

Mixed traffic flow is a typical complex system with high uncertainty and nonlinearity. It is difficult to model the traffic phenomena by traditional traffic flow models (such as the fluid mechanics model and vehicle following model), and it is less efficient when performing numerical simulations. However, the cellular automata (CA) model has been widely used as an effective tool for studying complex system behavior in mixed traffic flow research [1]. In 1992, Nagel and Schreckenberg [2] proposed the NaSch model. Although the NaSch model can better reflect the basic phenomena of actual traffic, considering the differences in the driving characteristics and the phenomenon of metastable synchronous flow in actual traffic, some experts and scholars proposed some improved models based on the NaSch model, such as the reaction delay (RD) model [3], stochastic Nishinari–Fukui–Schadschneider (S-NFS) model [4], slow-to-stop (STS) model [5], and advanced deceleration (AD) model [6].

At present, research on mixed traffic flow using CA has achieved fruitful results, such as the mixed traffic flow of the different attributes of vehicles [7, 8], mixed traffic flow of motor vehicles and pedestrians [9, 10], mixed traffic flow of different types of nonmotor vehicles [11–13], and mixed traffic flow of motor and nonmotor vehicles represented by bicycles and cars [14–16]. However, in the recent years, there have been significant changes in the composition of nonmotor vehicles in China, where electric bicycles have become the main component of nonmotor vehicles. However, when studying the mixed traffic flow model of nonmotor and motor vehicles, most scholars usually choose bicycles to represent nonmotor vehicles. However, few studies include electric bicycles and thus do not fully reflect the actual situation of the mixed traffic flow of nonmotor and motor vehicles in the urban traffic of China. Moreover, in these models, motor and nonmotor vehicles are mostly studied according to one type of vehicle, seldom considering the different sizes of the occupying cell space and the influence of the different mechanical properties and driving characteristics on mixed traffic flow [17, 18].

In the urban road traffic of China, the proportion of electric bicycles in nonmotor vehicles is basically the same as or even more than that of bicycles and there is a significant difference in speed between them and electric bicycles travel faster. Because of its faster speed, the travel route is more variable and flexible and the impact on motor vehicles in mixed traffic flow is also different from that of bicycles. In view of the above, combined with the lack of research on electric bikes in the study of the nonmotor vehicle traffic flow at domestic and foreign research, it is necessary to also include the electric bicycle as a nonmotor vehicle in this mode of transportation and take it and bicycles as research objects of nonmotor vehicles and establish their cell models. Afterwards, a thorough analysis of the mixed traffic situation of the two and the motor vehicles was conducted to explore the influence of the three mixed flows on traffic safety. Therefore, a three-strand mixed traffic flow model of nonmotor vehicles and motor vehicles, including electric bicycles and bicycles, is established using CA. Then, using the technology of traffic conflict and the conflict rate as the index to evaluate the traffic safety situation, the change in the conflict rate under different road occupancies and different proportional coefficients of motor vehicles is studied.

The remainder of this paper is organized as follows. Section 2 describes the characteristics of the mixed traffic flow in China, and then determines the evaluation index of traffic safety and establishes the operation model of the mixed traffic flow. And then the validation of the model is verified, and the initial simulation parameters and simulation process are determined. Section 3 presents and analyses the results of simulation, including the effects of road occupancy and the proportional coefficient of the motor vehicle on the equivalent vehicle flow rate and the conflict rate. Section 4 further discusses the results of the study and determines the situation where a physical isolation divider needs to be established while ensuring safety and saving resources. Finally, the main conclusions are outlined in Section 5.

2. Methods

2.1. Driving Characteristics of Mixed Traffic Flow. Mixed traffic flow is one of the main characteristics of urban road traffic in China, and a nonphysical isolation divider (scribing separation) is one of the common carriers of the mixed traffic flow. Nonphysical isolation refers to the use of traffic signs to mark the line to achieve the separation of motor and nonmotor vehicles; except for the special point, the nonmotor vehicle lane does not allow motor vehicles to enter. This kind of isolation method occupies a considerable proportion of the urban traffic system in China. Because motor and nonmotor vehicles are only separated through a white solid line, road security is poor.

In the mixed traffic road section, when a nonmotor vehicle (bicycle or electric bicycle) or a motor vehicle exhibits a large volume of traffic, some vehicles will occupy the adjacent lane space so that a mixed phenomenon occurs. Usually, as motor vehicles have strict laws and regulations, they seldom turn to nonmotor lanes for fear of penalization. Therefore, this paper only analyzes the interference of nonmotor vehicles with high frequency in urban traffic on motor vehicles. Among them, the blocking interference refers to the fact that some nonmotor vehicles occupy the motor vehicle lane and hinder the normal driving of the rear motor vehicles, resulting in the slow down of the motor vehicles, thus resulting in delays, as shown in red nonmotor vehicles in Figure 1(a). Friction interference refers to motor vehicles and nonmotor vehicles that normally run in their respective lanes without crossing the boundary. However, due to the small lateral distance between them, the driver of the motor vehicle feels the lateral safety risk from the nonmotor vehicle and then slows down for the sake of safety and prudence, as shown in the red nonmotor vehicle in Figure 1(b).

2.2. Determining the Evaluation Index of Traffic Safety. At present, the existing methods for evaluating safety include the accident absolute number method, accident rate method, cause analysis method, analytic hierarchy process, gray evaluation method, traffic conflict method, and fuzzy evaluation method. Aiming at the research object (motor vehicle, bicycle, and electric bicycle), research scope (nonphysical isolation divider of urban traffic), and the particularity of the traffic flow operation and the research method (simulation of the CA model with MATLAB), combined with the applicability of the abovementioned safety evaluation methods, in this paper, traffic conflict technology (TCT) is selected as the method for evaluating safety. The traffic conflict rate is used as the evaluation index of traffic safety.

Traffic conflicts are actually manifestations of unsafe behaviors. These conflicts may develop into traffic safety accidents, or they may avoid traffic accidents by effective

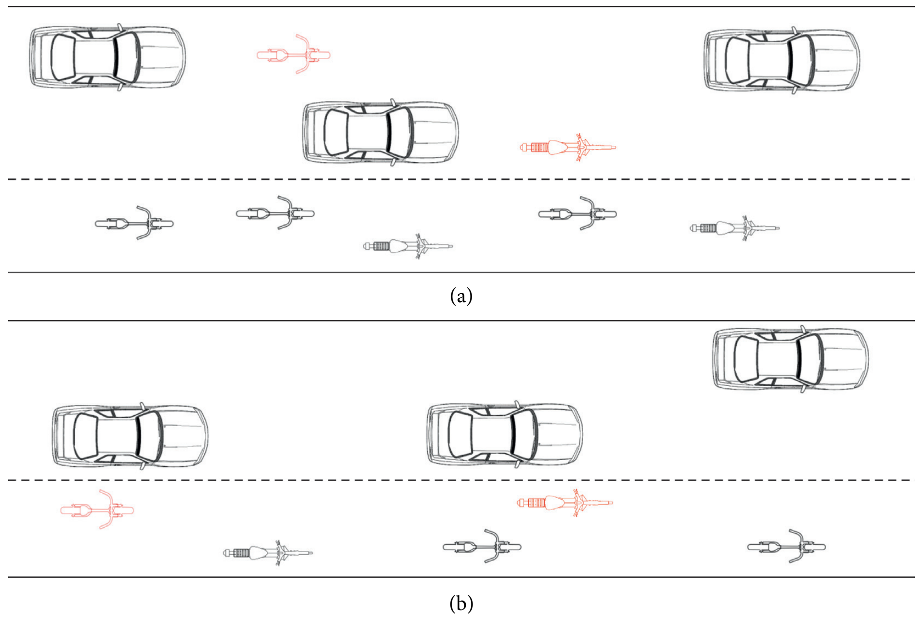

Figure 1: Interference of nonmotor vehicles with motor vehicles: (a) blocking interference; (b) friction interference.

hedging behaviors. The traffic conflict rate refers to the ratio between the number of possible conflicts (including avoided conflicts) and the traffic volume of traffic participants (such as motor vehicles, nonmotor vehicles, and pedestrians) [19].

During the process of observing actual traffic conflicts, most of the observed conflicts represent the evasive behavior and traffic violation behavior of motor and nonmotor vehicles when a conflict is about to occur and the actual conflicts are rarely observed. However, the avoidance behavior taken by motor vehicles or nonmotor vehicles to avoid conflicts is a possible traffic conflict. There are three basic methods to objectively quantify the severity of traffic conflicts according to the relevant knowledge of TCT: the space distance between road users, the time distance between road users, and the deceleration required to avoid accidents. Therefore, this paper chooses the deceleration required to avoid accidents as the quantitative conflict analysis index.

2.3. Establish the Operation Model of Mixed Traffic Flow. For the mixed traffic flow model of motor vehicles and nonmotor vehicles, including bicycles and electric bicycles, the CA model of mixed traffic flow (MTCA) is selected in this paper. This model mainly consists of two modules: the lane model and the vehicle model.

2.3.1. Establish the Model of Motor and Nonmotor Vehicles. According to the "Code for the Design of a Parking Garage Building" (JGJ 100-2015), the design size of the outer dimensions of small cars in China is $4.8\,\mathrm{m} \times 1.8\,\mathrm{m}$ [20]. Therefore, it can be considered that this size is the general size of the outer dimensions of small urban cars. Therefore, the model size of the car can be defined as 5.0 m in length and 2.0 m in width. In addition, the "Road Speed Limit Regulations and Speeding Penalty Standards" in China stipulates that the speed limit of urban roads is 40–60 km/h. This paper takes the maximum value of 60 km/h.

Due to the variety and size of bicycles, people of different heights and different needs choose different bikes. Therefore, this paper defines the cell size of the bicycle according to the size of the bicycle that is currently on the road, that is, the width is generally 0.5 m~0.7 m, and the length is generally 2 m. Considering the factors such as roll and yaw that the bicycle has during driving, the model size of the bicycle can be defined as 2.5 m in length and 1.0 m in width. According to the "Safety Requirements for Bicycles" (GB 3565-2005) and the test speed of the bicycle in the dry state and the wet state [21], the average value of the bicycle is set to 20 km/h.

According to the "General specifications for electric motorcycles and electric mopeds" (GB/T 24158-2009) in China, the outer dimensions of electric bicycles must meet the following requirements: length $\leq$ 2.00 m, width $\leq$ 0.80 m, and height $\leq$ 1.10 m [22]. It can be seen that the physical size of electric bicycles is basically the same as that of bicycles. To facilitate the simulation of the model, the cell size of an electric bicycle is defined as that of a bicycle. For the speed of electric bicycles, the "Safety Technical Specification for Electric Bicycles" (GB 17761-2018) also raises the maximum speed of electric bicycles to 25 km/h [23].

Therefore, the actual size and maximum speed of motor vehicles and nonmotor vehicles are shown in Table 1.

As shown in Table 1, the physical size of a bicycle and an electric bicycle is small compared with that of a car, so their cell size is defined as the unit cell size, that is, a rectangle with a length of 2.5 m and a width of 1.0 m. Then, the size of the motor vehicle model is 4 unit cells and the time steps are 1 s. At the same time, the actual unit of the cell size and the maximum speed of the motor vehicle and the nonmotor vehicle are, respectively, converted into the dimension (lattice and lattice/time step) in the CA model, where the unit of the maximum vehicle speed is rounded to an

Table 1: The size and maximum speed of motor vehicles and nonmotor vehicles (actual dimensions).

Vehicle type	Maximum speed (km/h)	Length (m)	Width (m)
Bicycle	20	2.5	1.0
Electric bicycle	25	2.5	1.0
Small vehicle	60	5.0	2.0

approximate value. The transformed results are shown in Table 2, where a length of one grid represents the actual length of 2.5 m and a width of one grid represents the actual length of 1 m.

Therefore, the definition of the cell size and maximum speed of the motor vehicle and nonmotor vehicle is shown in Table 2.

2.3.2. Establishing Lane Models of Motor Vehicles and Nonmotor Vehicles. The "Code for Transport Planning on Urban Road" recommends that the width of a single lane for nonmotor vehicles should be 1 m [24]. At the same time, the "Code for Design of Urban Road Engineering" has set the width of a single motor vehicle lane to 3.5 m [25] after fully considering the safety factors, such as vehicle running and swinging. Since the size of the vehicle cell in the model has been defined, to make the model conform to reality and not too complicated, the width of a single motor vehicle lane is set to 2 m, a total of 1 lane, occupying 2 rows of cells. The width of a single nonmotor vehicle lane is set to 1 m, a total of 2 lanes, occupying 2 rows of cells.

Because the research object is a straight road segment that does not include intersections, to make full use of the model and judge its safety situation under the mixed traffic condition of motor and nonmotor vehicles in the subsequent simulation analyses, the length of the model section is defined as road_len. = 120 grids, corresponding to an actual road length of 300 m (2.5 m ∗120).

By summarizing the above model, a two-dimensional discrete cell grid composed of four rows of cells with a length of 120 cells is shown in Figure 2. Among them, the motor vehicle lane is a single lane, occupying 2 rows of cells, and the nonmotor vehicle lane is 2 lanes, that is, bicycles and electric bicycles also occupy 2 rows of cells. The cell lines 1, 2, 3, and 4 together form a model of a one-way motor vehicle lane and a nonmotor vehicle lane.

2.3.3. Establish a Mixed Traffic Model Including the Characteristics of Three Traffic Flows. Since the research object of this paper is part of the section of the mixed traffic flow, the boundary condition of road grid points is defined as periodic. As a more ideal form of the model analysis, this "circular" road considers that the starting and ending points of the road are connected. When the vehicle exits from a section, it will enter the road again from the other end, which is often used for the steady-state analysis of the traffic flow when the road density remains unchanged.

In the model of mixed traffic flow, the driving space of the motor vehicle and the nonmotor vehicle, including the bicycle and the electric bicycle, is only separated by a virtual boundary. It is stated that the motor vehicle is not allowed to drive in the nonmotor vehicle lane, but the bicycle and the electric bicycle can drive in the motor vehicle lane. The reason for these operating rules is that in actual urban traffic, motor vehicles will be penalized if they drive in nonmotor vehicle lanes. However, nonmotor vehicles can easily "invade" the space of motor vehicle lanes due to their driving characteristics, the safety awareness of cyclists, legal concepts, and behavioral habits.

To render the model easy to simulate and make the overall situation conform to an actual situation, the applicable conditions of the model are defined as follows:

(1) All the motor vehicles in the model are small cars, and their sizes are the same
(2) The model does not consider the interference of buses on motor vehicles and nonmotor vehicles
(3) The current position occupied by the vehicle, the type, and speed of the occupied vehicle and other road states and the speed, direction, position, and other states of the vehicle are updated with each time step
(4) The vehicle position at time t, the vehicle traveling direction at time t, and the vehicle speed at time $t+1$ jointly determine the vehicle position at time $t+1$

In this model, the road system consists of four rows of cells, that is, three parallel lanes in the same direction. Each lane is composed of discrete grid points of the same length. Each grid point on the grid chain may be empty and may have occupied by only one car. The position of each grid point (cell) is represented by two-dimensional coordinates, that is, road(x, y), where $x = 1, 2, 3,$ and 4 are cell (row) labels, indicating that the vehicle is in a certain lane of the motor vehicle lane or nonmotor vehicle lane and $y = 1, 2, 3, \ldots, n$ is the label of the j-th cell in a certain lane, which is arranged from the left to the right in the forward direction of the vehicle.

During the evolution of the model, the behavior of the vehicle is abstracted into the following rules so that its own position and speed can be updated and changed.

(1) Update rules for the vehicle speed and forward direction:

$$v_i(t+1) = \min\left\{v_i(t) + 1, \mathrm{gap}_{i,t}, v_{\max}\right\}, \tag{1}$$

$$\mathrm{label}(t) = \begin{cases} -1, & \text{change lane to the left,} \\ 0, & \text{go straight,} \\ 1, & \text{change lane to the right.} \end{cases} \tag{2}$$

In formulas (1) and (2), $v_{\max}$ represents the maximum speed of the motor vehicle, bicycle, and electric bicycle. In terms of the motor vehicle, $\mathrm{gap}_{i,t}$ refers to

Table 2: Definition values of the vehicle cell size and maximum speed (model dimension).

Vehicle type	Maximum speed (time step)	Length (grid)	Width (grid)
Bicycle	2	1	1
Electric bicycle	3	1	1
Small vehicle	6	2	2

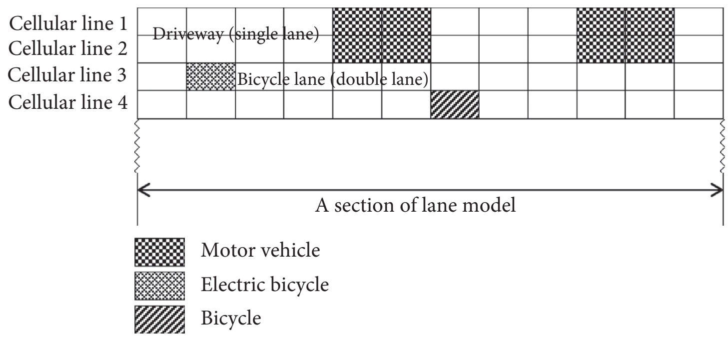

Figure 2: Schematic diagram of the model of the motor vehicle lane and the nonmotor vehicle lane.

the gap between the i-th vehicle and the front vehicle in only the straight direction at time t ($\text{car\_gap}_{i,t}$). In terms of nonmotor vehicles, the gap between the i-th car located in the left lane ($\max\{\text{left\_gap}_{i,t}, \text{front\_gap}_{i,t}, \text{right\_gap}_{i,t}\} = \text{roadleft\_gap}_{i,t}$, $\text{label}(t) = -1$), straight direction ($\max\{\text{left\_gap}_{i,t}, \text{front\_gap}_{i,t}$ $\text{right\_gap}_{i,t}\} = \text{front\_gap}_{i,t}$, $\text{label}(t) = 0$), or right lane ($\max\{\text{left\_gap}_{i,t}, \text{front\_gap}_{i,t}, \text{right\_gap}_{i,t}\} = \text{right\_gap}_{i,t}$, $\text{label}(t) = 1$) and front vehicle at time t. Considering the safety of nonmotor vehicles, the default order of the lane changing of nonmotor vehicles is set to go straight > change to the right lane > left lane.

Formula (1) expresses the following vehicle speed change behavior: at time t, the $v_i(t)$ of the vehicle i is not $v_{\max}$ and is smaller than the gap of the vehicle in front of this lane or in an adjacent lane ($\text{gap}_{i,t}$), and then the vehicle can accelerate. When the $v_i(t)$ of vehicle i is not $v_{\max}$ and is greater than the gap of the vehicle in front of this lane or adjacent lane ($\text{gap}_{i,t}$), the vehicle will decelerate. When the vehicle is at the maximum speed ($v_{\max}$), the vehicle may maintain the speed and may also decelerate depending on the values of $v_{\max}$ and $\text{gap}_{i,t.}$ This effect makes this formula directly describe the acceleration and deceleration behavior of the vehicle. That is, for a vehicle in the next time step, the speed is the minimum value of the following three speed values: $v_i(t) + 1$, $\text{gap}_{i,t,}$ and $v_{\max}$. Since the relationship between the above three speeds at time $t + 1$ and time t is uncertain, this rule can be expressed for both the acceleration and deceleration behaviors of vehicles. The function $v_i(t)$ is used to represent the speed of the vehicle at time t, and the speed of any vehicle is always between 0 and the maximum speed, that is, $v_i(t) \in [0, v_{\max}]$.

(2) The rules of random moderation:

$$\text{If } \delta_t < P, \quad \text{then } v_i(t+1) = \max\{v_i(t+1) - 1, 0\}. \tag{3}$$

Formula (3) reflects the behavior that vehicles slow down during conservative driving. At each step t of the vehicle, vehicle i produces a random number δ_t between (0, 1) and P represents the random deceleration probability. The random deceleration probability is related to the traffic density; when the traffic density is small, the random deceleration probability is also small, and when the traffic density increases, the random deceleration probability will also increase [26, 27]. To reflect the influence of different traffic congestion conditions on overtaking lane changes and random interference behaviors, different values of P were selected at different traffic densities.

(3) The rules of conflict between motor vehicles and motor vehicles and the conflict between motor vehicles and nonmotor vehicles:

The reason for conflicts between motor vehicles and motor vehicles and conflicts between nonmotor vehicles and nonmotor vehicles is described as follows. When the front motor vehicle brakes due to the environment of the roads, and the driver's psychology or a nonmotor vehicle suddenly changes lane and occupies the lane of motor vehicles and other conditions, the speed of the rear motor vehicle is drastically reduced due to the emergency avoidance of these vehicles:

$$\text{If } \text{car\_}v_i(t) - \text{car\_}v_i(t+1) \geq \text{value\_dece}, \text{ then num\_conf} = \text{num\_conf} + 1, \tag{4}$$

where value_dece represents the braking deceleration of the motor vehicles and Num_conf represents the number of conflicts.

According to the "Technical Specifications for Safety of Motor Vehicles Operating on Roads" (GB7258-2012) and related literature, the average deceleration of a motor vehicle with at least $6.2\,\mathrm{m/s^2}$ no-load inspection can meet the standard [28, 29]. To facilitate the calculation and consider the defined length of a cell, this article takes $7.5\,\mathrm{m/s^2}$ as the threshold for the conflict between a motor vehicle and a motor vehicle and the conflict between a motor vehicle and a nonmotor vehicle.

Formula (4) indicates that the speed difference between time t and time $t+1$ of the motor vehicle is greater than or equal to 3 grids/time step, namely, $7.5\,\mathrm{m/s^2}$ in the actual dimensions, and then the number of collisions is considered to increase once.

(4) The rules of the gap update:

$$\begin{cases} \text{car\_gap}_{i,t+1} = y_{i+1,t+1} - y_{i,t+1} - L_{\text{car}}, \\ x_{i+1,t+1} = x_{i,t+1}. \end{cases} \quad (5)$$

Formula (5) shows the rules of the gap update for the i-th motor vehicle in a single lane, where x, y refer to the horizontal and vertical coordinates, respectively, of the vehicle at the cell point of the road (the forward direction of the vehicle is the vertical coordinate) and L_{car} refers to the length of the motor vehicle.

$$\begin{cases} \text{left\_gap}_{i,t+1} = y_{i+1,t+1} - y_{i,t+1} - L_{\text{non\_car}}, \\ x_{i+1,t+1} = x_{i,t+1} - 1, \end{cases} \quad (6)$$

$$\begin{cases} \text{front\_gap}_{i,t+1} = y_{i+1,t+1} - y_{i,t+1} - L_{\text{non\_car}}, \\ x_{i+1,t+1} = x_{i,t+1}, \end{cases} \quad (7)$$

$$\begin{cases} \text{right\_gap}_{i,t+1} = y_{i+1,t+1} - y_{i,t+1} - L_{\text{non\_car}}, \\ x_{i+1,t+1} = x_{i,t+1} + 1. \end{cases} \quad (8)$$

Formulas (6)–(8) represent the rules of the gap update for nonmotor vehicles on the common clearance update rules for nonmotor vehicles in the left lane, current lane, and right lane, and $L_{\text{non\_car}}$ indicates the length of the nonmotor vehicle.

(5) The rules of the location update:

Because this model has only one motor vehicle lane, the motor vehicle can neither overtake nor change lanes. The rules are as follows:

$$\begin{cases} x_{i,t+1} = x_{i,t}, \\ y_{i,t+1} = y_{i,t} + v_{i,t+1}. \end{cases} \quad (9)$$

Nonmotor vehicles can not only use the nonmotor vehicle lane but also use the motor vehicle lane to overtake and change lanes, so the horizontal and vertical coordinates of the position will change accordingly:

$$\begin{cases} x_{i,t+1} = x_{i,t} + \text{label}_{i,t}, \\ y_{i,t+1} = y_{i,t} + v_{i,t+1}. \end{cases} \quad (10)$$

2.4. Verification of the Validation of the Model. To verify the validity of the model, it is necessary to compare the errors between the model results and the actual mixed flow data. In this paper, Xi'an Wenyi North Road is selected for the simulation. During the early peak period, the observation length of the lane is 50 m, the width of the motor vehicle lane is 3 m, and the width of the nonmotor vehicle lane is 3 m. Through the investigation, it is found that the vehicle equivalent flow of this road section is 400 pcu/h, and the number of conflicts between motor vehicles and motor vehicles and between motor vehicles and nonmotor vehicles is 36 times/h. Therefore, the conflict rate is 0.09 times/pcu/h. Other survey data are collated as shown in Table 3.

Since the CA model consists of a series of discrete lattice point chains, the traditionally defined traffic density may not be applicable here. In the CA model of this paper, the car occupies 4 cell space, and the bicycle and the electric bicycle each occupy 1 cell space. If the road model built in the Section 2.3.2 is covered by the motor vehicle, then the maximum traffic density of the road is only 0.4, which is obviously not realistic. Therefore, this paper uses the road occupancy rate to express the road density, that is, the proportion of lane cells in the road model occupied by motor vehicles and nonmotor vehicles.

According to the survey data, the simulation parameters of the running model of Wenyi North Road can be determined as follows: road_len = 20 grids is 50 m; the proportional coefficient of motor vehicle is the number of cars in all vehicles, that is, p_car = 0.3; the proportion of electric bicycles in nonmotor vehicles is p_ebic = 0.75; and the road occupancy, that is, $p_{\text{occ}} = 0.3$. Because the traffic density is small, the slowing down probability is small; when the traffic density is large, the slowing down probability is large [26, 27], and there are pedestrians crossing the lane in this section, so the random slowing down probability needs to be slightly larger, that is, $P = 0.3$. The total simulation time is $T = 8000$ s. The traffic flow data of the last 2000 time step are statistically analyzed, and the simulation results are compared with the actual situation. The results are shown in Table 4.

It can be concluded from the above table that in terms of the vehicle flow rate, the average error between simulated data and measured data is only 6.3%. In terms of the conflict rate, the measured collision rate is 0.09 times/pcu/h and the simulated data are 0.08 times/pcu/h; the data are very close. Therefore, it can be argued that the model built in this paper can reliably simulate the mixed traffic flow of motor vehicles and nonmotor vehicles.

2.5. Determine the Initial Simulation Parameters and Simulation Process. After verifying the validation of the model, the simulation is carried out in MATLAB software to compare and analyze the data rates, such as the flow rate and

Table 3: Flow and density statistics of Wenyi North Road during morning rush hour.

Vehicle type	Traffic flow (veh/h)	Traffic density (veh/km)	p_{occ}
Car	249	100	0.3
Bicycle	147	120	
Electric bicycle	456	200	

the conflict rate, of mixed traffic in urban roads under different road occupancy rates and proportional coefficients of vehicles and then to study the safety status. However, before the simulation, the initial simulation parameters need to be determined.

The initial parameters of the influence of different road occupancy rates on safety are determined as follows: the length of the lane model is 300 m, that is, road_len = 120. The proportional coefficient of the motor vehicle is determined by the average value after observing multiple road sections, that is, p_car = 0.3. The ratio of electric bicycles to the number of nonmotor vehicles is p_ebic = 0.6. Under different road occupancy (pocc) rate conditions, we have different slowing down probabilities, that is, $P \in [0.1, 0.9]$. The slowing down probability is small, when the traffic density is small, and the slowing down probability is large, when the traffic density is large [26, 27]. This paper assumes that the slowing down probability changes synchronously with the road occupancy rate. The total simulation time is $T = 8000$ s, and the traffic flow data of the last 2000 s are statistically analyzed.

The initial parameters of the influence of different proportional coefficients of motor vehicles on safety are determined as follows: the length of the lane model is 300 m, that is, road_len = 120. The road occupancy rate (p_{occ}) is 0.3 when the traffic flow is relatively free. Because this paper assumes that the slowing down probability changes synchronously with the road occupancy rate, then the slowdown probability is 0.3, that is, $P = 0.3$. Because the proportion of bicycles and electric bicycles in nonmotor vehicles on urban roads is relatively stable, this paper only studies the safety of a mixed traffic environment caused by different proportions of motor vehicles and nonmotor vehicles. By observing multiple road sections, it is found that the proportion of bicycles to nonmotor vehicles is 0.4 and the proportion of electric bicycles to nonmotor vehicles is 0.6. The proportion of motor vehicles to the total number of vehicles is p_car ∈ [0.1, 0.9]. The total simulation time is $T = 8000$ s, and the traffic flow data of the last 2000 s are analyzed statistically. The steps of the model simulation program are described as follows:

Step 1: initialization of the simulation program. The simulation parameters in the model are initially set, such as the number of lanes, road length, road occupancy, the proportion of motor vehicles and nonmotor vehicles, the proportion of electric bicycles to nonmotor vehicles, the number of simulation cycles, and the number of simulation steps.

Step 2: set up both the initial vehicle location distribution rule (road_initialization) and the vehicle speed record matrix (vehicle_v). After establishing the road matrix, the distribution rules of motor vehicles, bicycles, and electric bicycles in each lane are formulated and the initial position of the vehicles is randomly arranged. The rules must ensure that the first row of cells is empty to avoid the vehicles generated by them being unable to add their subsidiary body cells. At the same time, the last row of cells is guaranteed to be occupied; otherwise, when only one vehicle exists in a lane, it is impossible to judge the number of space cells in front of it. Furthermore, because the motor vehicle occupies four cells, it is required that the adjacent cells not all generate motor vehicles. The velocities of motor vehicles and two types of nonmotor vehicles are placed in the vehicle_v matrix.

Step 3: develop vehicle addition rules. In the iteration process after the start of the operation, motor vehicles and nonmotor vehicles are generated at a set probability with a random speed at the entrance to the road.

Step 4: the vehicle starts to run and iterate. The vehicles change lanes, overtake, and move forward according to their own evolutionary rules. Each simulation runs 8000 steps (that is, 8000 s). To ensure that the results obtained are the normal conditions of the mixed traffic environment, only the last 2000 steps are selected.

Step 5: the output statistics and matrices of the flow, average speed, and step speed of different types of vehicles are obtained.

Step 6: the program is finished.

3. Results

The flow rate of motor vehicles, bicycles, and electric bicycles represents the traffic volume converted into one hour by the three vehicles. In this paper, it is the result of converting the data from the 2000 s into 1 h. The equivalent flow rate of the vehicle refers to the flow rate after the conversion of the bicycle and the electric bicycle into the motor vehicle according to the conversion ratio of the bicycle and the electric bicycle to the motor vehicle. This paper is converted according to the cell number occupied by each vehicle, that is, both the bicycle and the electric bicycle are regarded as 1/4 motor vehicles. The simulated results after conversion are shown in Tables 5 and 6. The relationship between the road occupancy and the proportional coefficient of vehicle and the equivalent vehicle flow rate and the conflict rate are shown in Figures 3 and 4, respectively.

Figure 3 shows the following:

(1) With an increase in the road occupancy, the equivalent vehicle flow rate first increases and then decreases. When the road occupancy (p_{occ}) is 0.5, the equivalent vehicle flow rate reaches a peak. This is because when $p_{occ} < 0.5$, the number of motor vehicles and nonmotor vehicles on the road is gradually increased and the equivalent flow rate of the car

Table 4: Comparison of measured and simulated results.

Type of data	Traffic flow (veh/h)			Equivalent flow rate of car (pcu/h)	Number of conflicts	Conflict rate (time/pcu/h)
	Car	Bicycle	Electric bicycle			
Actual data	249	147	456	400	36	0.09
Simulation data	228	160	464	384	29	0.08
Error	8.43%	8.84%	1.75%	4.00%	19.44%	11.10%
The average error		6.3%			—	

Table 5: Equivalent vehicle flow rate and conflict rate under different road occupancy rates.

Road occupancy	Traffic flow (veh/h)			Equivalent flow rate of car (pcu/h)	Number of conflicts	Conflict rate (time/pcu/h)
	Car	Bicycle	Electric bicycle			
0.1	121	106	174	191	27	0.14
0.2	165	130	235	256	79	0.31
0.3	236	191	332	367	154	0.42
0.4	347	273	494	538	294	0.54
0.5	428	331	573	654	431	0.66
0.6	376	342	579	606	673	1.11
0.7	344	348	583	577	548	0.95
0.8	326	356	587	561	389	0.69
0.9	312	361	591	550	158	0.29

Table 6: Equivalent vehicle flow rate and conflict rate under different proportional coefficients of motor vehicle.

Proportion of cars	Traffic flow (veh/h)			Equivalent flow rate of cars (pcu/h)	Number of conflicts	Conflict rate (time/pcu/h)
	Cars	Bicycles	Electric bicycles			
0.1	113	392	731	394	52	0.13
0.2	184	455	545	434	81	0.19
0.3	317	387	500	539	167	0.31
0.4	421	270	455	603	252	0.42
0.5	572	193	301	696	302	0.43
0.6	585	140	268	687	301	0.44
0.7	591	126	144	659	303	0.46
0.8	599	78	103	644	374	0.58
0.9	612	34	68	638	402	0.63

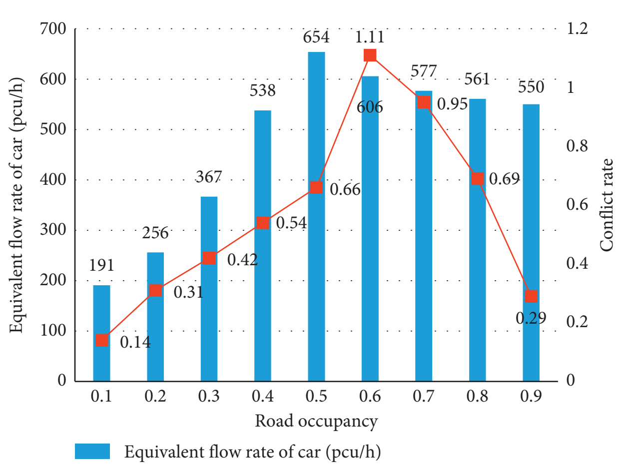

Figure 3: The curves of the equivalent vehicle flow rate and conflict rate chart under different road occupancy rates.

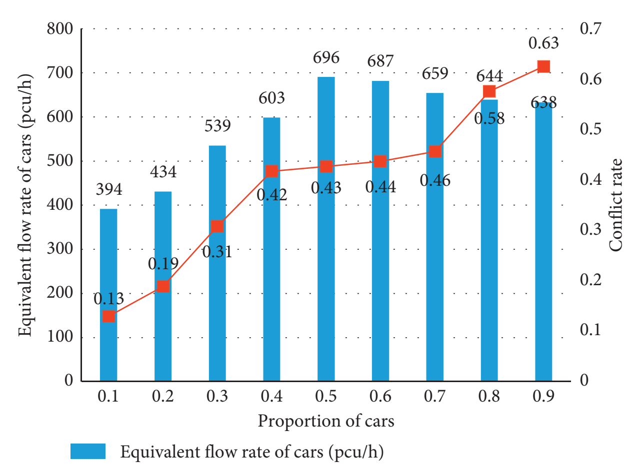

Figure 4: The curves of the equivalent vehicle flow rate and conflict rate under different proportional coefficients of the motor vehicle.

is also gradually increased. However, when $p_{\mathrm{occ}} > 0.5$, the number of motor vehicles in the road decreases gradually, while the number of nonmotor vehicles increases somewhat, but the increase is not large, so the equivalent flow rate of the car presents a downward trend. The change in the number of motor vehicles and nonmotor vehicles is due to the fact that when the road occupancy rate is not high, the road is unobstructed and the possibility of traffic jams is not high, while the speed of the motor vehicles is much higher than the speed of the nonmotor vehicles; in this case, people tend to choose motor vehicles to travel, so the flow rate of the motor vehicles rises. When the road occupancy rate is high, the road is more congested and the speed of motor vehicles is slow and because the nonmotor vehicle is more flexible and can take advantage of the gap to travel, at this point the speed of the nonmotor vehicles will be higher than the speed of the motor vehicles, so people will be more inclined to choose the nonmotor vehicle to travel, resulting in an increase in the flow of the nonmotor vehicle and a decrease in the flow of the motor vehicle.

(2) The conflict rate also shows a trend of increasing first and then decreasing, but unlike the equivalent vehicle flow rate, its peak appears at $p_{\mathrm{occ}} = 0.6$. When $p_{\mathrm{occ}} < 0.6$, with the increase of road occupancy, the number of motor vehicles and nonmotor vehicles is also increased, but the traffic is still relatively smooth. At this time, there are mainly three types of conflicts: the conflict between motor vehicles and motor vehicles, the conflict between motor vehicles and nonmotor vehicles, and the conflict between nonmotor vehicles and nonmotor vehicles; higher the road occupancy, the higher the conflict rate, so the conflict rate will show an upward trend. However, when $p_{\mathrm{occ}} > 0.6$, the road becomes more and more congested with the increase of road occupancy, and the average speeds of the three vehicles in the lane are reduced to different degrees. The motor vehicles are lined up to move forward at approximately uniform speed, and there is less conflict with each other. However, at this time, the nonmotor vehicles in nonmotorized lanes are unable to comply with traffic regulations. They will scramble for lanes with each other in order to ensure their own driving speed. They may even occupy the motor vehicle lane to seek a greater speed, which will cause the motor vehicles in the relative rear to take a sharp brake in order to avoid collision with these occupied nonmotor vehicles that overtake the lanes. Therefore, the conflict at this time mainly includes: the conflict between motor vehicles and nonmotor vehicles and the conflict between nonmotor vehicles and nonmotor vehicles, while the conflict between motor vehicles and motor vehicles is relatively reduced, thus reducing the conflict rate.

Figure 4 shows the trend of the equivalent vehicle flow rate and the conflict rate under different proportional coefficients of the motor vehicle. It can be seen that

(1) In the state of the mixed traffic environment, the conflict rate increases with the increasing proportional coefficient of the motor vehicle (p_car). When p_car ∈ [0.1, 0.4], the conflict rate increases rapidly. When p_car ∈ [0.4, 0.7], the conflict rate grows slowly and steadily; when p_car ∈ [0.7, 0.9], the conflict rate continues to increase by a large margin. When the road occupancy is constant, the proportional coefficient of the vehicle has a significant impact on road safety.

(2) The equivalent vehicle flow rate will increase first and then decrease slightly as the proportional coefficient of motor vehicle increases. This result is because when p_car ∈ [0.7, 0.9], the increase rate of the motor vehicle flow rate is small, while the flow rate of the bicycle and electric bicycle decreases greatly, so the equivalent vehicle flow rate shows a downward state.

4. Discussion

In the above, the effects of road occupancy and the proportional coefficient of the motor vehicle on the equivalent vehicle flow rate and the conflict rate are studied. It can be seen that in the state of a mixed traffic environment, the conflict rate increases with the proportional coefficient of the motor vehicle, and as the road occupancy rate increases, it tends to increase first and then decrease. However, on the whole, the conflict rate is high. The use of a physical isolation divider to separate motor vehicles and nonmotor vehicles is a safe and effective way to reduce the conflict rate, but not all roads need to be provided with a physical isolation divider; otherwise, resources will be wasted. Therefore, we will determine the situation where a physical isolation divider needs to be established by studying the changes in the conflict rate before and after physical isolation.

In the above, the CA model of the mixed traffic flow is established, and the evolution rules of the CA model with a physical isolation divider also include the updating rules on the vehicle speed and forward direction, the rules of random moderation, the rules of gap update, and the rules of location update. These evolution rules are consistent with the basic ideas of the evolution rules of the model in a mixed traffic environment, but the model content is far less complex than the former. Specifically, this model does not need to consider the interference between nonmotor vehicles and motor vehicles, and nonmotor vehicles can only change lanes and overtake other vehicles in nonmotor vehicle lanes. That is, when writing the simulation program, it is defined that when the nonmotor vehicle is located at Cellular line 3, it is prohibited to change lanes to the left. After the simulation program runs, the conflict rates before and after using the physical isolation divider are compared, as shown in Figure 5.

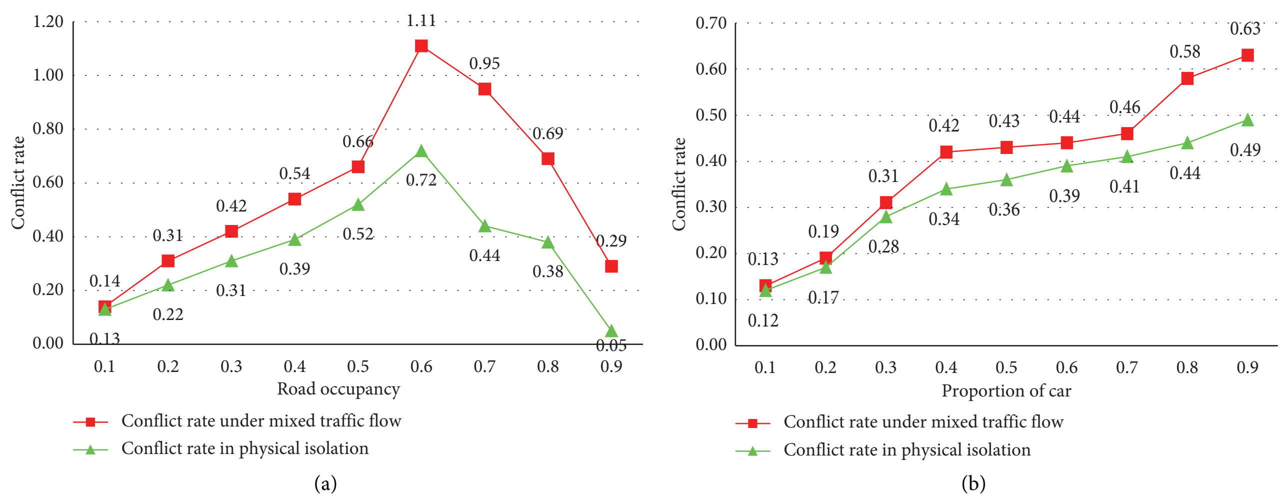

Figure 5: Comparison of conflict rates before and after setting the physical isolation divider: (a) comparative diagram of the conflict rate before and after the physical isolation divider under different road occupations; (b) comparison of conflict rates before and after setting the physical isolation divider under the different proportional coefficients of the motor vehicle.

In Figure 5(a), by comparing the conflict rates under different road occupancies before and after setting the physical isolation divider, it can be concluded that regardless of whether the lane is in any road occupancy, the conflict rate in the state of a mixed traffic environment is greater than the collision rate with the physical isolation divider. Because there is only a conflict between the motor vehicle and the motor vehicle when there is a physical isolation divider, the interference effect of the nonmotor vehicle on the motor vehicle is avoided. When $p_{\text{occ}} \in [0.1, 0.5]$, the conflict rate in the state of mixed traffic environment is higher than that in the physical isolation state, but the increase is small, with an average increase of only 0.09. When $p_{\text{occ}} \in [0.6, 0.9]$, the conflict rate in the state of the mixed traffic environment is significantly higher than that in the physical isolation state, which increases by an average of approximately 0.35.

Figure 5(b) shows that with different proportional coefficients of the motor vehicle, the conflict rate with the physical isolation divider also increases with the proportional coefficient of the motor vehicle. However, the conflict rate in the physical isolation state is still lower than that in the state of the mixed traffic environment. When the proportional coefficient of motor vehicle is p_car ∈ [0.1, 0.7], the conflict rate in the physical isolation state is only 0.04 lower than that in the state of the mixed traffic environment, and when p_car ∈ [0.8, 0.9], the conflict rate in the physical isolation state is 0.14 which is lower than that in the state of the mixed traffic environment.

Therefore, it can be concluded from the above analysis that when $p_{\text{occ}} \in [0.6, 0.9]$ or p_car ∈ [0.8, 0.9], the motor vehicle and nonmotor vehicle can be separated from each other in space by setting a physical isolation divider to improve traffic safety.

5. Conclusion

Based on the CA method, this paper establishes a mixed traffic flow model for urban roads, uses TCT, selects the conflict rate as the evaluation index of traffic safety, and analyzes the change in the conflict rate and the equivalent vehicle flow rate under different road occupancy rates and proportional coefficients of motor vehicles. Using MATLAB simulations, the conflict rate and the equivalent vehicle flow rate change rules are as follows.

In mixed traffic environments, the equivalent vehicle flow rate tends to increase first and then decrease with the increasing road occupancy rate, reaching a peak when the road occupancy rate (p_{occ}) is 0.5. The conflict rate also first increases and then decreases with an increase in the road occupancy rate, but its peak value appears at the road occupancy of 0.6. The conflict rate is significantly higher when the road occupancy is in the range of [0.6, 0.9] than when the road occupancy is in the range of [0.1, 0.5].

In the state of the mixed traffic environment, the equivalent vehicle flow rate increases first and then decreases with an increase in the proportional coefficient of the motor vehicle, and the conflict rate increases with the proportional coefficient of the motor vehicle.

The study provides recommendations for the establishment of physical isolation dividers for urban roads and contributes to improving urban road safety. The recommendations of the study are as follows: when the road occupancy (p_{occ}) is in the range of [0.6, 0.9] or when the proportional coefficient of the motor vehicle (P_car) is in the range of [0.8, 0.9], motor vehicles and nonmotor vehicles can be separated from the space by setting a physical isolation divider to reduce the conflict rate and thus improve traffic safety.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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