Effects of rainy weather on traffic accidents of a freeway using cellular automata model*

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The aim of this work is to investigate the influence of rainy weather on traffic accidents of a freeway. The micro-scale driving behaviors in rainy weather and possible vehicle rear-end and sideslip accidents are analyzed. An improved CA model of two lanes one-way freeway is presented, where some vehicle accidents will occur when the necessary conditions are simultaneously satisfied. The characteristics of traffic flow under different rainfall intensities are discussed and the accident probabilities are analyzed via the simulation experiments by using variable speed limit (VSL) and incoming flow control. The results indicate that the measures are effective especially during heavy rainstorms or short-time heavy rainfall. According to different rainfall intensities, an appropriate strategy should be adopted in order to reduce the probability of vehicle accidents and enhance traffic flux as well.

Keywords: cellular automata (CA) model, freeway, rainy weather, rear-end, sideslip

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1. Introduction

Driving on a highway in rainy weather can become unsafe.[1–3] It may become difficult to control the vehicle when a pavement with a layer of water fails to offer the required amount of friction, especially at high speed even for a highly skilled and alert driver.[4,5] At the same time low visibility may not guarantee enough safe sight distance when the rainfall intensity is large. This increases the safety risks, e.g., resulting in single or multiple rear-end accidents, or a sideslip accident. It means that the road flux will drop. As is well known, there are many influencing factors on traffic safety, such as road geometric condition, driver character and state, vehicle type, weather, and other traffic states. All these factors interact in complicated ways, making the traffic accident size, e.g., the occurrence of accident and accident rate, have a nonlinear relationship with the factors.[6–10] Now, the point is how to describe the complex dynamic process microscopically by using a model and then providing the effect of rainy weather on road safety?

On the whole, the approaches of road traffic safety in rainy weather can be classified as three categories. Firstly, a number of previous studies were devoted to the effect of rainy weather on road traffic safety by using macro data and statistical methods.[1,4,6,8–13] Some analytic equations or models were used to map the relationships among the rainfall intensity, other variables, and traffic accident size.[6,8,9,11] For example, Keay and Simmonds investigated the effect of weather variables on traffic flow at a site in Melbourne, Australia,in the period 1989–1996.[6] Rainfall was the strongest correlated weather parameter and it had the greatest influence in winter and spring, when traffic volume decreased on wet days. A novel and rigorous approach was presented to analyze the influence of rainfall on road traffic accidents in urban areas by Jaroszweski and McNamara.[8] Cai *et al.* developed a quantitative model to analyze driving risks under rainy weather conditions and built a multi-ordered discrete choice model to analyze those risk factors and their influence degrees.[9] Those studies show that the road factors, driver factors and environment factors are strongly related to the accident size, and some control advice, e.g., variable speed limit (VSL), is provided for the traffic management department. But the complex dynamic process of traffic flow, e.g., the micro-scale driver behavior and the occurrence of traffic accident, are not described. Secondly, some are devoted to the estimation of vehicle sideslip from the angle of vehicle engineering caused by tire force, wheel cornering stiffness, road friction coefficient, etc.[14,15] Traffic flow and its nonlinear evolution in rainy weather have not been discussed. Thirdly, some research focused on the traffic accident avoidance and road safety improvement in adverse weather conditions by using the microscopic simulation models of traffic flow.[3,5,7] Using the car-following model, Wang *et al.* estimated the emergency braking distance of passenger vehicles with respect to the following interval that should be kept as a "gap" between two consecutive vehicles moving in

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the same lane.[7] The theoretical models for lane change and operational risk are used to study the multi-lane freeway at a microscopic level in disaster weather. Wan *et al.* discussed a dynamic speed control strategy to reduce collision risks on freeways by using a car-following model to simulate the traffic operation in adverse weather.[5] An indicator, chosen risk index (CRI), was defined for describing the chosen risk level for drivers in a car-following case by Hjelkrem and Ryeng [3] Obviously, only a car-following model was used to describe the traffic flow process, and the complex time-space evolution in rainy weather has not been discussed.

As an excellent tool, cellular automata (CA) models have been used widely to investigate the traffic flow behaviors. In particular, many researchers have studied the occurrence of car accidents by using the extended CA models,[16–26] e.g., the deterministic NS model proposed firstly by Boccara *et al.*[20] Only the traffic influences of low visibility weather, e.g., foggy weather, on a freeway including the fraction of real vehicle rear-end accidents and road traffic capacity were studied by using the established CA model. The traffic flow model in rainy weather has not been established and the possible traffic accident has not been discussed. In the present work, according to those and symmetric two-lane Nagel–Schreckenberg (STNS) model, we analyze the micro-scale driving behaviors in rainy weather and possible vehicle rear-end and sideslip accidents. An improved CA model of two lanes one-way freeway is presented. The characteristics of traffic flow under different rainfall intensities and traffic demand are discussed and the different effects are analyzed via the simulation experiments by using VSL and incoming flow control. The optimal strategies are provided under different conditions.

2. Analyses of driving behaviors and possible vehicle accidents in rainy weather

2.1. Cause analysis of vehicle rear-end accident

After it rains for some time, the road surface will be covered with rain water. This makes the tyre surface become smooth, for the tire tread gaps are also filled with rain water. There is not enough time to squeeze out the water from the smooth wheel tires especially in a heavy rainstorm or short-time heavy rainfall. The water film will gather in the rotating wheel and form a wedge. For a concrete road, the relationship between the depth of surface water (water film) and rainfall intensity is described as follows:[27]

$$D = 0.046\frac{(60\times WS'Q)^{1/2}}{S^{1/5}}, \tag{1}$$

where D denotes the surface water depth (mm), W the width of pavement (m), Q the rainfall intensity (mm/min), $S' = S/S_c$, and $S = (S_l^2 + S_c^2)^{1/2}$, with S_l being the longitudinal slope (%), and S_c the slope of pavement cross section (%).

The water film leads to the decreasing of contact area between tire and road surface and makes the adhesion coefficient decrease with the increase of wedge length. The reduced friction coefficient (φ) can be fitted by a linear formula as follows:[2]

$$\varphi = 0.6603 - 0.0037v - 0.0057D, \quad (R^2 = 0.8313), \tag{2}$$

where v denotes the speed (km/h).

The decreasing of adhesion coefficient makes the braking distance lengthen, which may occur in single or multiple rear-end accidents. So the the safety distance S_{safe} between a vehicle and its preceding vehicle should increase. By using the classical vehicle safety braking model, S_{safe} can be calculated from formula (3) including adverse weather, e.g., fog, rain, and snow, where the decreasing of sight distance is also considered in rainy weather when rainfall intensity reaches 0.206 mm/min.[7,28]

$$\begin{aligned} S_{safe} &= \frac{v^2(i,t)/v(i-1,t) - v(i-1,t)}{70.56(\varphi \pm S_l)} \\ &\quad + \frac{v(i,t)(t_s + t_w)}{v(i-1,t)} + \frac{3.6\times L_1}{v(i-1,t)}, \end{aligned} \tag{3}$$

where $v(i,t)$ denotes the velocity of vehicle i at time t and the velocity of its predecessor is $v(i-1,t)$. The safe stopping distance L_1 represents the minimum distance between two vehicles when their velocities are zero, where its values are set to be 2 m for a car and 5 m for a truck. The t_s represents the time of normal response for a driver, and t_w refers to the increasing response time on a rainy day.

Obviously, some rear-end accidents will happen if the distance between a vehicle and its predecessor is not larger than S_{safe}, meaning that the safety distances are not met and the drivers cannot brake in time.

2.2. Cause analysis of vehicle sideslip accident

In the driving course, the influence of many forces on the vehicle, e.g., side wind, braking imbalance between left and right wheels of automobile, and steering brake, can cause its lateral displacement even sideslip, which makes the vehicle deviate from the right direction. Considering the fact that the vehicle sideslip in rainy weather is mainly caused by lateral gravity component due to the decrease of friction coefficient, we only study the case of a transverse slope. As shown in Fig. 1, the differential equation of vehicle motion in the early period of braking deceleration is defined as follows:[29]

$$I\dot{r} = Mg\cdot\sin\gamma\cdot b + F_y b + F_x\sin\beta\cdot b - F_z\sin\alpha\cdot L, \tag{4}$$

where I denotes the rotation inertia of the vehicle front wheel vertical axis (kg·m^2), r the vehicle yaw rate (°/s), M the vehicle mass (kg), g the acceleration of gravity, 9.8 m/s^2, γ the pavement transverse slope angle (°), b the distance between front axle and the height of the vehicle center of mass (m), and L the wheel base (m).

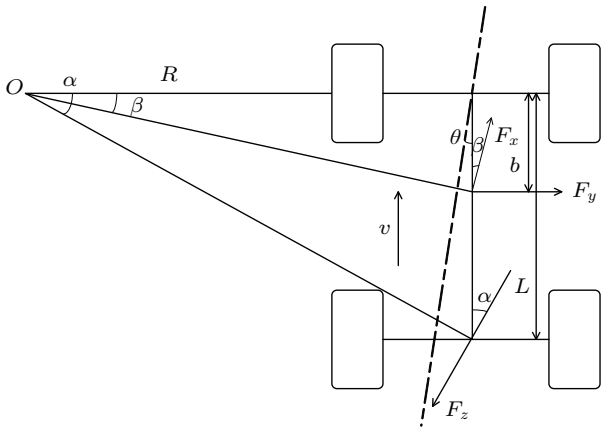


Fig. 1. Movement condition of vehicle rear axle sideslip.

F_y denotes the lateral force acting on the center of mass and is calculated from

$$F_y = Mvr, \tag{5}$$

where v is the instantaneous speed when a vehicle starts to move. F_z denotes the braking force of rear wheel and is calculated from

$$F_z = M\varphi(gb - ah)/L, \tag{6}$$

where a denotes the braking deceleration (m/s^2), h the height of the vehicle center of mass (m), F_x the braking inertia force and is calculated from

$$F_x = Ma, \tag{7}$$

where α denotes the angle of rear wheel lateral displacement. Since they are relatively small at the beginning of the slip, we assume that

$$\sin\alpha = \tan\alpha = \alpha, \quad \sin\beta = \tan\beta = \beta, \tag{8}$$

where β is the angle of mass center.

According to Fig. 1, we can obtain the following formulae

$$r = v/R = v\tan\alpha/L, \tag{9}$$

$$\beta = \tan\beta = b/R = b\tan\alpha/L = b\alpha/L. \tag{10}$$

Then

$$\alpha = Lr/v, \tag{11}$$

$$\beta = br/v. \tag{12}$$

Substituting Eqs. (5)–(12) into Eq. (4), the differential equation of vehicle motion of the slip is transformed into formula (13)

$$\dot{r} = Mg\gamma b/I + M(bv^2 + ab^2 - L\varphi gb + L\varphi ah)r/(vI). \tag{13}$$

If the above formula is integrated, we can derive vehicle yaw rate model as shown in formula (14). Here the changes of instantaneous speed v and deceleration a are ignored when the vehicle starts to slip.

$$r = (\mathrm{e}^{qt} - 1)g\gamma b/(\rho^2 q), \tag{14}$$

where

$$\rho^2 = I/M, \tag{15}$$

$$q = (bv^2 + ab^2 - L\varphi(gb - ah))/(\rho^2 v). \tag{16}$$

If r in formula (14) is integrated, we can obtain the vehicle steering angle θ when it is slipping.

$$\theta = (\mathrm{e}^{qt} - qt - 1)g\gamma b/(\rho q)^2. \tag{17}$$

For a vehicle driving at speed v, lateral gravity component leads to its steering angle θ due to the decrease of friction coefficient. At the same time, the driver makes the vehicle return to normal driving conditions by braking and adjusting the direction after the reaction time T_0. But the longitudinal displacement and lateral displacement will appear.

$$S_x = v \cdot \cos\theta \cdot T_0, \tag{18}$$

$$S_y = v \cdot \sin\theta \cdot T_0, \tag{19}$$

where S_x denotes longitudinal displacement during the driver's reaction time, S_y the lateral displacement, and $T_0 = t_\mathrm{s} + t_\mathrm{w}$.

If S_y is large enough to make the vehicle deviate from the original lane, a sideslip motion occurs and part of sideslip motions form a traffic accident. For only one mainline on a freeway with no ramp as shown in Fig. 2, the road is composed of four parts, named marginal strip, left lane, right lane, and shoulder. Several types of sideslip accidents may occur. (i) S_y for a left lane vehicle with the left sideslip direction is larger than the sum of the width of marginal strip and the width between its left front corner and the lane left line; (ii) S_y for a right lane vehicle with the right sideslip direction is larger than the sum of the shoulder width and the width between its right front corner and the lane right line; (iii) S_y for a left lane vehicle with the right sideslip direction is larger than the distance between its right and the left of right lane vehicle if the position is occupied with a vehicle. (iv) S_y for a right lane vehicle with the left sideslip direction is larger than the distance between its left and the right of left lane vehicle if the position is occupied with a vehicle.

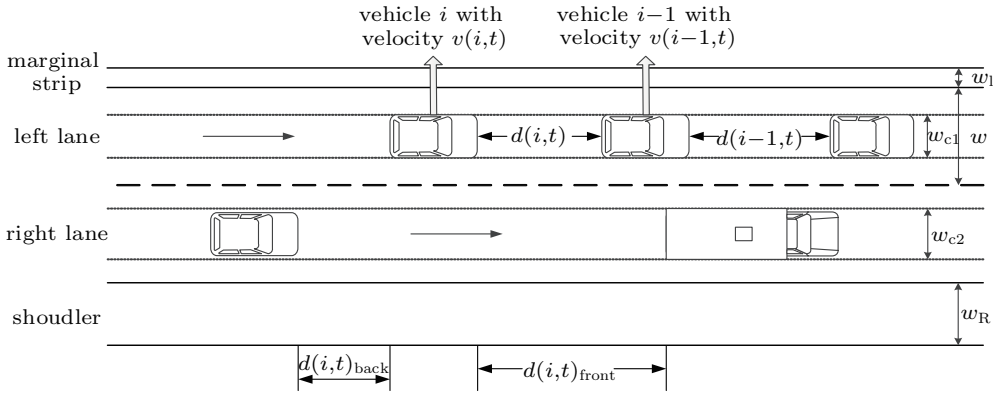


Fig. 2. Studied object.

3. CA model with the occurrence of vehicle accidents

As shown in Fig. 2, only one mainline on a freeway with no ramp, which possesses continuous traffic flow characteristics, is used as the research object to illustrate the problem. The widths of marginal strip, shoulder, and lane are $w_{\rm l}$, $w_{\rm R}$, and w, respectively. The width of a vehicle is $w_{\rm c}$, where we use $w_{\rm c1}$ in place of $w_{\rm c}$ for a car and $w_{\rm c2}$ in place of $w_{\rm c}$ for a truck. As shown in Fig. 3, the roads, named left lane, right lane and shoulder, are divided into discrete cells, where left lane consists of left lane and marginal strip and its width is $w_{\rm c}+w$. The widths of right lane cell and shoulder cell are their original ones, respectively. According to traffic regulations, vehicles are prohibited to drive on the shoulder under normal conditions. But a vehicle may be driven on the shoulder if a sideslip occurs towards the right or a vehicle may be temporarily stopped for some reason. The length of each lane is L_0. The length of each cell is equal to 1 m, which means that the number of cells of each lane is equal to the length of the mainline. We assume that the vehicle is driving on the middle position of the original lane. The lateral distance between a vehicle on the left lane and the road left guardrail is $w_{\rm l}+0.5\times(w-w_{\rm c})$. The lateral distance between a vehicle on the left lane and the road right guardrail is $0.5\times(w-w_{\rm c})+w+w_{\rm R}$. The lateral distance between a vehicle on the left lane and another vehicle on the right lane is $w-w_{\rm c}$. The lateral distance between a vehicle on the right lane and the road left guardrail is $w_{\rm l}+w+0.5\times(w-w_{\rm c})$. The lateral distance between the right front corner of a vehicle on the right lane and the road right guardrail is equal to $0.5\times(w-w_{\rm c})+w_{\rm R}$.

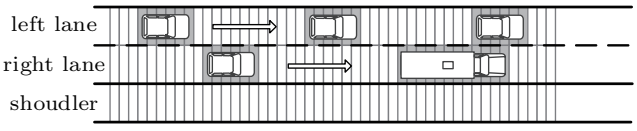


Fig. 3. Cell partition of studied object.

Each cell may be either empty or occupied by one vehicle with an integer velocity v between zero and the maximal speed limit $v_{\max}$, where we use $v_{\max 1}$ in place of $v_{\max}$ for a car and $v_{\max 2}$ in place of $v_{\max}$ for a truck and $P_{\rm car}$ denotes the proportion of car. The $v_{\max}$ is a stable value when no VSL signal is inputted and a variable value when a VSL signal is inputted. Two speed limit values are set for car and truck, respectively. In order to describe the traffic flow processing of the studied object, we establish an extended CA model based on symmetric Nagel–Schreckenberg (NS) model with the occurrence of vehicle accidents in rainy weather. The $x(i,t)$ denotes the position of vehicle i at discrete time step t. The first vehicle is marked as 1, and the following vehicles are marked as 2, 3, ..., i. The $d(i,t)$ denotes the empty cells between vehicle i and its predecessor at time t, $d(i,t)_{\rm front}$ and $d(i,t)_{\rm back}$ refer to the empty cells between vehicle i and its preceding vehicle and between vehicle i and its successor on the adjacent road, respectively. The a denotes the acceleration if it is greater than zero or denotes the deceleration if it is smaller than zero.

3.1. Basic rules

Under normal circumstances, the vehicle evolution rules are as follows.

(i) **Acceleration** $v(i,t+1)=\min(v(i,t)+a,v_{\max})$, indicating that the driver expects to maintain vehicle i at the maximal speed.

(ii) **Deceleration**

Case 1 if $d(i,t)>S_{\rm safe}$, then $v(i,t+1)=v(i,t)$, indicating that it is not necessary to decelerate the vehicle, for the safety distance is met.

Case 2 if $d(i,t)\le S_{\rm safe}$, then $v(i,t+1)=\min(d(i,t)+v(i-1,t+1),\max(v(i,t)-a,0))$, indicating that the driver needs to decelerate the vehicle so as to avoid crashing against the preceding vehicle, for the safety distance is not met.

(iii) **Randomization** $v(i,t+1)=\max(v(i,t)-1,0)$ with probability $p_{\rm r}$, indicating that the vehicle should be decelerated for uncertain factors.

(iv) **Forward motion** $x(i,t+1) = x(i,t) + v(i,t+1)$, indicating that the vehicle should continue to move forward with an updated speed.

The lane-changing rules of mainline vehicle are as follows.

i) **Lane-changing motive**

$$d(i,t) < \min(v(i,t)+a, v_{\max}),$$

indicating that vehicle i cannot travel at an expected speed, and $d(i,t)_{\text{front}} > d(i,t)$, indicating that the driving condition in the neighboring lane is better than that in its lane.

ii) **Safety condition** $d(i,t)_{\text{back}} > d_{\text{safe}}$ and $d(i,t)_{\text{back}} > v_{\max}$, indicating that when changing lanes, vehicle i does not crash against the vehicle immediately behind it.

The vehicle will change lane with probability of p_1 if the above two conditions are satisfied.

3.2. Rules in rainy weather

In rainy weather, the driver sight distance is affected when the rainfall intensity reaches 0.206 mm/min.[28] At the same time, the driver will open the fog lamps in order to find the preceding vehicle, which makes his actual sight distance longer than that for visibility. The actual sight distance is set to be 1.1 times that for visibility in the present study for describing the actual reaction of driver.[24] For each vehicle, S_{safe} in each simulation step is calculated by using formula (3) in Subsection 2.1. The vehicle evolution rules are as follows.

(I) If (a) $Q \geq 0.206$, and $d(i,t) > 1.1 \times$ visibility, or (b) $Q \geq 0.206$, $d(i,t) \leq 1.1 \times$ visibility, and $d(i,t) \geq S_{\text{safe}}$, or (c) $Q < 0.206$, and $d(i,t) \geq S_{\text{safe}}$ are met, vehicle i will travel at an expected speed or accelerate at time $t+1$, e.g., $v(i,t+1) = \min(v(i,t)+a, v_{\max})$.

In condition (a), the first condition indicates that rainfall intensity reaches 0.206 mm/min. The second condition indicates that vehicle i will not decelerate for the driver of vehicle i cannot see the preceding vehicle.

In condition (b), the first condition indicates that rainfall intensity reaches 0.206 mm/min. The second condition indicates that the driver of vehicle i can see the preceding vehicle. The third condition means that the safety distance is met.

In condition (c), the first subcondition indicates that rainfall intensity cannot reach 0.206 mm/min. The second subcondition means that the safety distance is met.

(II) If (a) $Q >= 0.206$, $d(i,t) \leq 1.1 \times$ visibility, $d(i,t) < S_{\text{safe}}$, and rand$\leq p'$, or (b) $Q < 0.206$, $d(i,t) < S_{\text{safe}}$, and rand$\leq p'$, vehicle i will move forward with $v(i,t+T_0) = v(i,t)$ during time T_0. Vehicle i will decelerate at $a_{\max}$ after a certain delayed reaction time T_0. In other words, $v(i,t+T_0+1) = \max(v(i,t) - a_{\max}, 0)$, where the maximal deceleration is $a_{\max} = g(\varphi + S_1)$ and the upper limit is 3.4 m/s^2.[13]

In condition (a), the second subcondition indicates that the driver of vehicle i can see the preceding vehicle. The third subcondition means that the safety distance is not met. The fourth subcondition means that rand is less than p', where p' denotes the probability of driver who has distracted his (or her) attention to driving or has delayed reaction time.

In condition (b), the second subcondition indicates that the safety distance is not met. The third subcondition means that rand is less than p'.

(III) If (a) $Q \geq 0.206$, $d(i,t) \leq 1.1 \times$ visibility, $d(i,t) < S_{\text{safe}}$, and rand$> p'$ or (b) $Q < 0.206$, $d(i,t) \leq S_{\text{safe}}$, and rand$\geq p'$, vehicle i will decelerate at $a_{\max}$ immediately, e.g., $v(i,t+1) = \max(v(i,t) - a_{\max}, 0)$.

In condition (a), the second subcondition indicates that the driver can see the preceding vehicle. The third subcondition means that the safety distance is not met. The fourth subcondition means that rand is larger than p'.

In condition (b), the second subcondition indicates that the safety distance is not met. The third subcondition means that rand is larger than p'.

(IV) Forward motion, if $a < 0$, $x(i,t+1) = x(i,t) + S_x = x(i,t) + v(i,\, t+1) \times \cos\theta$, $y(i,t+1) = y(i,t) + S_y = y(i,t) + v(i,t+1) \times \sin\theta$, otherwise, $x(i,t+1) = x(i,t) + v(i,t+1)$, indicating that the vehicle should continue to move forward at θ degree in the lateral direction when braking deceleration.

3.3. Criterion rules of accident for a vehicle

3.3.1. Criterion rules of rear-end accident for a vehicle

In a basic model, the rule is designed to decelerate to any value immediately for a vehicle in order to keep the safety distance. So a vehicle rear-end accident will not occur. As discussed in Subsection 2.1, the safety distance between a vehicle and its preceding vehicle will increase in rainy weather. Some rear-end accidents may happen because the safety distances are not met and the drivers do not brake in time either. Thus, the criteria of a rear-end accident are as follows (we name the criterion of rear-end accident as CRA).

CRA 1 $T_0 \times v(i,t) > S_{\text{safe}}$, indicating that vehicle i can reach the position of his predecessor during his delayed reaction time T_0 and a rear-end accident occurs.

CRA 2 $v(i,t+T_0+1) > S_{\text{safe}}$, indicating that vehicle i still can reach the position of his preceding vehicle even with a maximal deceleration at $a_{\max}$ after his delayed reaction time T_0, and an accident occurs.

CRA 3 $v(i,t) - a_{\max} > S_{\text{safe}}$, indicating that vehicle i will reach the position of his preceding vehicle even with a maximal deceleration at $a_{\max}$ immediately, and an accident occurs.

If one of the above conditions is met, a rear-end accident occurs once during or after time T_0. The number of the rear-end accident occurrences N_{1ac} is increased by 1 under the assumption of neglecting time correlations proposed by Boccara *et al.*[20] The vehicle rear-end accident does not really occur in the simulation. These dangerous situations are calculated and considered to be the signal of the occurrence of accidents. The rear-end accident probability P_{1ac} is defined as N_{1ac}/N, where N is the total number of vehicles.

3.3.2. Criterion rules of sideslip and probably accident for a vehicle

As discussed in Subsection 2.1, a sideslip motion may happen and partially form sideslip accident if S_y is large enough to make the vehicle deviate from the original lane. The criteria of a sideslip accident are as follows (we name criterion of sideslip accident as CSA).

CSA 1 For a vehicle driving on left lane

Case 1 if rand1<0.5 and $S_y < w_l + 0.5\times(w-w_c)$, no sideslip accident occurs, indicating that the vehicle does not reach the road left guardrail although it slides slightly in the left lateral direction.

Case 2 if rand1<0.5 and $S_y \geq w_l + 0.5\times(w-w_c)$, a sideslip accident shown in Fig. 4 occurs, indicating that the vehicle slides in the left lateral direction and reaches the position of the road left guardrail.

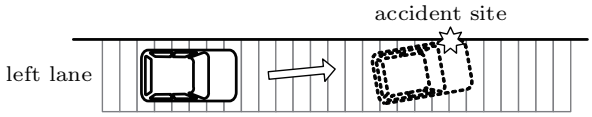


Fig. 4. Sideslip accident for a vehicle with left guardrail.

Case 3 if rand1≥ 0.5, and $S_y < w-w_c$, no accident occurs, indicating that the vehicle slides slightly in the right lateral direction and does not touch the probable vehicle of right lane.

Case 4 if rand1≥ 0.5, $S_y \geq w-w_c$, $S_y \leq 0.5\times(w-w_c)+w$, and $S_x < d(i,t)_{\text{front}}$, the vehicle slides into the right lane and no accident occurs, and $x(i,t+1) = x(i,t) + S_x$, for it cannot reach the position of his preceding vehicle on right lane.

Case 5 if rand1≥ 0.5, $S_y \geq 0.5\times(w-w_c)+w$, $S_y \leq 0.5\times(w-w_c)+w+w_R$, and $S_x < d(i,t)_{\text{front}}$, the vehicle slides to the shoulder and no accident occurs, and $x(i,t+1) = x(i,t) + S_x$, for it cannot reach the position of his preceding vehicle on the right lane.

Case 6 if rand1≥ 0.5, $S_y \geq w-w_c$, $S_y \leq 0.5\times(w-w_c)+w$, and $S_x \geq d(i,t)_{\text{front}}$, a sideslip accident shown in Fig. 5 occurs, indicating that the vehicle slides in the right lateral direction and reaches the position of his preceding vehicle on the right lane.

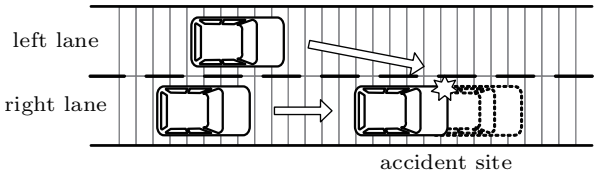


Fig. 5. Sideslip accident for a vehicle with another one on its right lane.

Case 7 if rand1≥ 0.5, and $S_y \geq 0.5\times(w-w_c)+w+w_R$, a sideslip accident shown in Fig. 6 occurs, indicating that the vehicle slides in the right lateral direction and reaches the position of the road right guardrail.

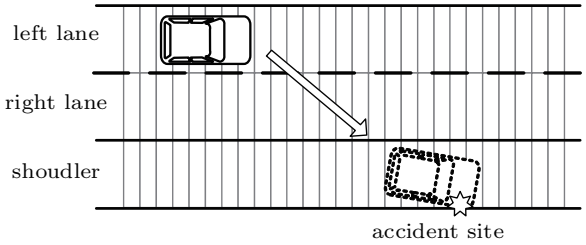


Fig. 6. Sideslip accident for a vehicle with right guardrail.

CSA 2 For a vehicle driving on right lane

Case 8 if rand1<0.5 and $S_y < w-w_c$, no accident occurs, indicating that the vehicle slides slightly in the left lateral direction and does not touch the probable vehicle of left lane.

Case 9 if rand1<0.5, $S_y \geq w-w_c$, $S_y \leq 0.5\times(w-w_c)+w+w_l$, and $S_x < d(i,t)_{\text{front}}$, the vehicle slides into the left lane and no accident occurs, and $x(i,t+1) = x(i,t) + S_x$, for it cannot reach the position of his preceding vehicle on the left lane.

Case 10 if rand1<0.5, $S_y \geq w-w_c$, $S_y \leq 0.5\times(w-w_c)+w+w_l$, and $S_x \geq d(i,t)_{\text{front}}$, a sideslip accident shown in Fig. 7 occurs, indicating that the vehicle slides in the left lateral direction and reaches the position of his preceding vehicle on the left lane.

Case 11 if rand1<0.5, and $S_y \geq 0.5\times(w-w_c)+w+w_l$, a sideslip accident shown in Fig. 8 occurs, indicating that the vehicle slides in the left lateral direction and reaches the position of the road left guardrail.

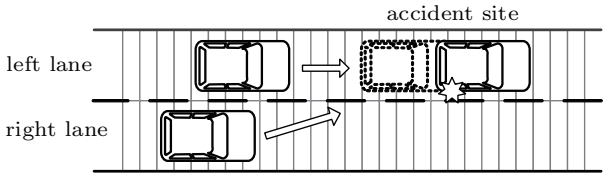


Fig. 7. Sideslip accident for a vehicle with another one on its left lane.

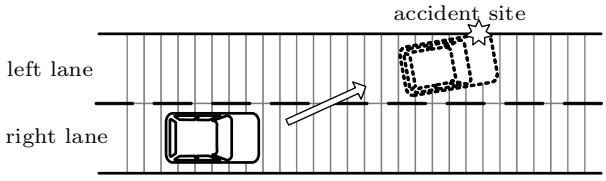


Fig. 8. Sideslip accident for a vehicle with left guardrail.

Case 12 if rand1≥ 0.5, $S_y \leq 0.5\times(w-w_c)+w+w_R$, the vehicle slides to the shoulder and no accident occurs, and $x(i,t+1)=x(i,t)+S_x$, for it cannot reach the position of the road right guardrail.

Case 13 if rand1≥ 0.5, $S_y \geq 0.5\times(w-w_c)+w+w_R$, a sideslip accident shown in Fig. 9 occurs, indicating that the vehicle slides in the right lateral direction and reaches the position of the road right guardrail.

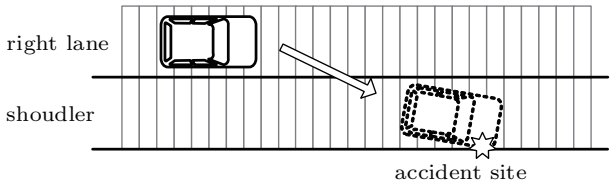


Fig. 9. Sideslip accident for a vehicle with right guardrail.

If one of the Cases 2, 6, 7, 10, 11, and 13 occurs, the number of the sideslip accident occurrences N_{2ac} is increased by 1 under the assumption of neglecting time correlations proposed by Boccara *et al.*[20] The sideslip accident probability P_{2ac} is defined as N_{2ac}/N, where N is the total number of vehicles.

3.4. Total vehicle accident statistics

The total number of vehicles N_{ac} is equal to N_{1ac} plus N_{2ac}. The total accident probability P_{ac} is defined as N_{ac}/N and also equal to P_{1ac} plus P_{2ac}.

3.5. Boundary conditions

The boundary conditions are open. In each time step, when the update of vehicles on the freeway is finished, the position x_{last} of the last vehicle on each lane is checked. If $x_{last} > v_{max}$, a vehicle with velocity v_{max} is injected with the entering probability P_e at the cell $\min\{v_{max}, x_{last}-v_{max}\}$. If rand2 $> P_{car}$, the injected vehicle is a truck, otherwise it is a car. The leading vehicle on each lane is removed, if its position $x_{first} > L_0$ and its following vehicle becomes the new leader.

4. Simulation results and discussion

The freeway section described in Section 3 is simulated, where the length of the two-lane mainline is 5000 m. The length of each cell is 1 m. A car is considered to be six-cell-long, a truck is considered to be twelve-cell-long, and each time step is 1 s. The value of v_{max1} is 33 for a car and v_{max2} is 25 for a truck. The proportion of car P_{car} is 0.8 and randomization probability p_r is 0.03. The maximum acceleration a_{max} is 3 cells for a car and 2 cells for a truck according to vehicle dynamic behavior and based on the driving comfort degree. Considering that the value of maximum deceleration restriction is 3.4 m/s^2 in the parking stadia model,[13] the maximum deceleration a_{max} is set to be 3 cells for a car and 2 cells for a truck. According to the survey that about 1.9% drivers always have distracted their driving attention, p' is set to be 1.9%. Although a driver reaction time may vary with traffic condition and the action of his preceding vehicle, its value T_0 is still set to be 1 s, considering that the average reaction time of drivers is 3/4 second presented by the National Safety Council.[24,30] According to Technical Standard of Highway Engineering (JTG B01-2014), w is 3.75 m.[31] The other parameters are set as follows: $w_l = 0.75$ m, $w_R = 3$ m, $w_{c1} = 1.8$ m, $w_{c2} = 2.5$ m, $w_1 = 1.725$ m, $w_2 = 1.95$ m, $w_3 = 7.725$ m, $w_4 = 1.6$ m, $w_5 = 7.375$ m, $w_6 = 1.25$ m, $w_7 = 1.375$ m, $w_8 = 5.475$ m, $w_9 = 3.975$ m, $w_{10} = 5.125$ m, and $w_{11} = 3.625$ m. The total simulation time for each experiment is 9000 s. The first 2000 time steps are discarded to avoid transient behavior. The flux is obtained by counting the vehicles in the later 7000 time steps. Meanwhile, each result shown here is the value averaged over 20 experimental data in order to reduce stochastic influence.

According to actual statistics in traffic engineering, the values of accident rate AH under different rainfall intensities are in a range from 0.76 to 160 number/billion vehicle·km.[32] It means that comparable accident rate AH1 is transformed due to unity of units varies from 0.0532 to 11.2 (‰) number/vehicle·5 km·7000 s. The simulated accident probabilities in rainy weather is in a range from 0.5 to 8.5 (‰) number/vehicle·5 km·7000 s. Obviously the accident probability of the simulated CA model is in a range of the actual statistics. The validity is preliminarily proved.

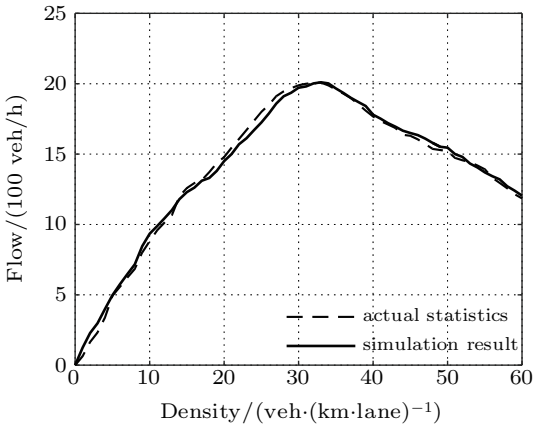


Fig. 10. Comparison of phase diagram between the actual statistics and the simulation result.

Figure 10 shows a comparison of phase diagram between the actual statistics data and the simulation results, where the rainfall intensity is 0.007 mm/min and the inlet traffic volume is 2000 veh/h and the corresponding upper speed limits are 100 km/h and 70 km/h, respectively. The two fitting curves are basically the same. The validity of the proposed CA model is proved again.

4.1. Effect of rainfall

Figure 11 shows a comparison among flow-density plots, and figure 12 shows a comparison among speed-density plots. Figure 13 shows a comparison among the rainfall-intensity-dependent accident probabilities, where the inlet traffic volumes are 2000, 1500, 1000, and 500 veh/h, respectively. No VSL signal is input which means that the stable upper speed limit $v_{\max 1}$ is used, where $v_{\max 1}$=33 cells is corresponding to 120 km/h and $v_{\max 2} = 25$ cells is corresponding to 90 km/h. The achieved findings are as follows.

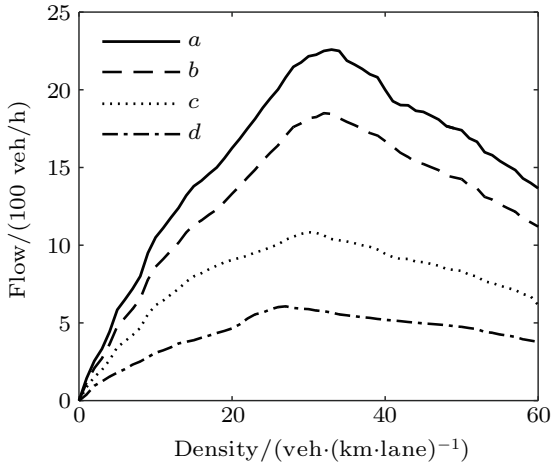


Fig. 11. Comparison of flow-density plots.

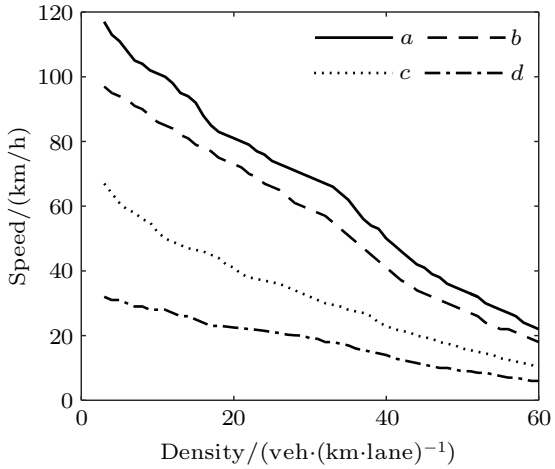


Fig. 12. Comparison among speed-density plots. In Figs. 11 and 12, the curves "*a*", "*b*", "*c*", "*d*" correspond to the rainfall intensities of 0, 0.04 mm/min, 0.2 mm/min, and 0.66 mm/min, respectively.

I) The flux increases and the speed decreases with the increase of density until it reaches a saturated value for each rainfall intensity. Then the flux and the speed decrease with the increase of density after it has exceeded the saturated value. The characteristics of traffic flow are tested by the phase diagrams under different rainfall intensities.

II) The maximal flux, where the density reaches a critical value, will decline with the increase of rainfall intensity, especially when rainfall intensities are 0.2 mm/min and 0.66 mm/min, meaning heavy rainstorm or short-time heavy rainfall. The road actual traffic volume and speed will decline. The critical density decreases with rainfall increasing. The larger the rainfall intensity, the smaller the flux is. So the rainfall is one of the main factors influencing the traffic flow under adverse weather especially when heavy rainstorm or short-time heavy rainfall happens.

III) From Fig. 13, we can see that the three indices of accident probability increases with rainfall increasing, respectively. The conclusion that the rainfall is one of the main factors influencing road traffic safety is proved again. At the same time, the figure is divided into two parts. When the rainfall intensity is smaller than 0.2 mm/min, which means light rain or moderate rain, the accident probability is very small. When the rainfall intensity is larger than 0.2 mm/min, which means heavy rain or rainstorm, the accident probability is very high. Especially when there is a heavy rainstorm or short-time heavy rainfall, the road becomes dangerous.

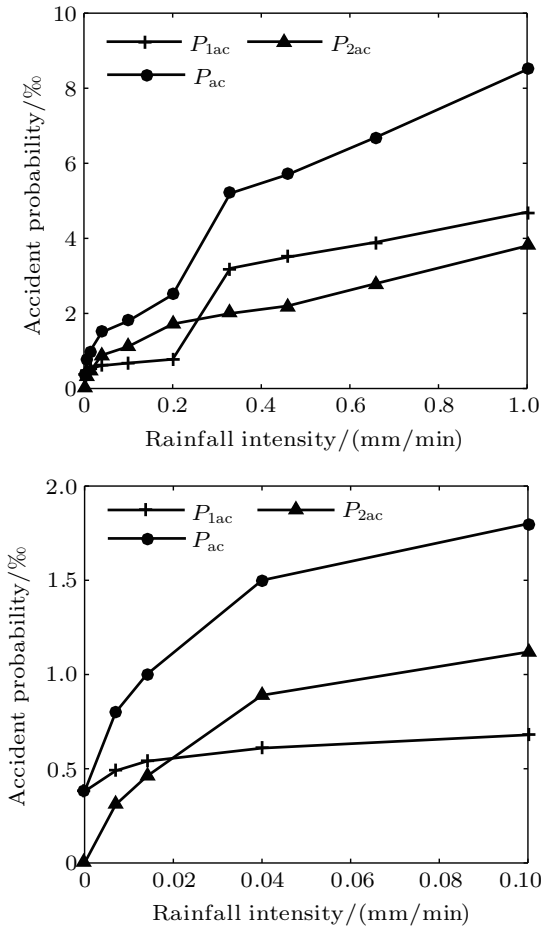


Fig. 13. Wrecked vehicles fraction N_{ac}/N as a function of rainfall intensity.

IV) The probability of sideslip accident P_{2ac} increases rapidly with the increase of rainfall intensity. This is because the friction coefficient will decrease markedly with the increase of rainfall intensity. It becomes very difficult for a driver to overcome vehicle lateral force, which means that the

probability of deviating from the original lane will decrease markedly. This makes the rate of sideslip accident increase rapidly.

V) The probability of rear-end accident P_{1ac} increases slightly with the increase of rainfall intensity when it is smaller than 0.2 mm/min. But it is not obvious. This is because the driver becomes more careful although the friction coefficient will decrease remarkably with rainfall increasing. The distance between two vehicles will be increased consciously for the drivers. This does not make the rear-end accident increase obviously. But when rainfall intensity is larger than 0.2 mm/min, meaning heavy rainstorm or short-time heavy rainfall, the increase of rear-end accident rate is very obvious. This is because it may become difficult to control the vehicle with very small adhesion coefficient in the weather although the driver, even a highly skilled and alert driver, becomes very careful. At the same time very low visibility cannot guarantee enough safe sight distance. With the decreasing of the braking distance lengthening, the increase of rear-end accident probability is very obvious.

4.2. Analysis of VSL

Figure 14 shows comparisons among rainfall-intensity-dependent accident probabilities obtained by using the different speed limit upper values. The inlet traffic volumes are 2000 veh/h for Fig. 14(a), 1500 veh/h for Fig. 14(b), 1000 veh/h for Fig. 14(c), and 500 veh/h for Fig. 14(d), respectively. The achieved findings are as follows.

1) The increasing trends of accident probability are basically the same under the inlet volume of 500 veh/h, 1000 veh/h, 1500 veh/h, and 2000 veh/h, which are increased with rainfall intensity increasing. The larger the speed limit upper value, the larger the accident probability is. This proves again that inputting the signal of VSL is very effective in reducing the accident rate and enhancing road safety in rainy weather.

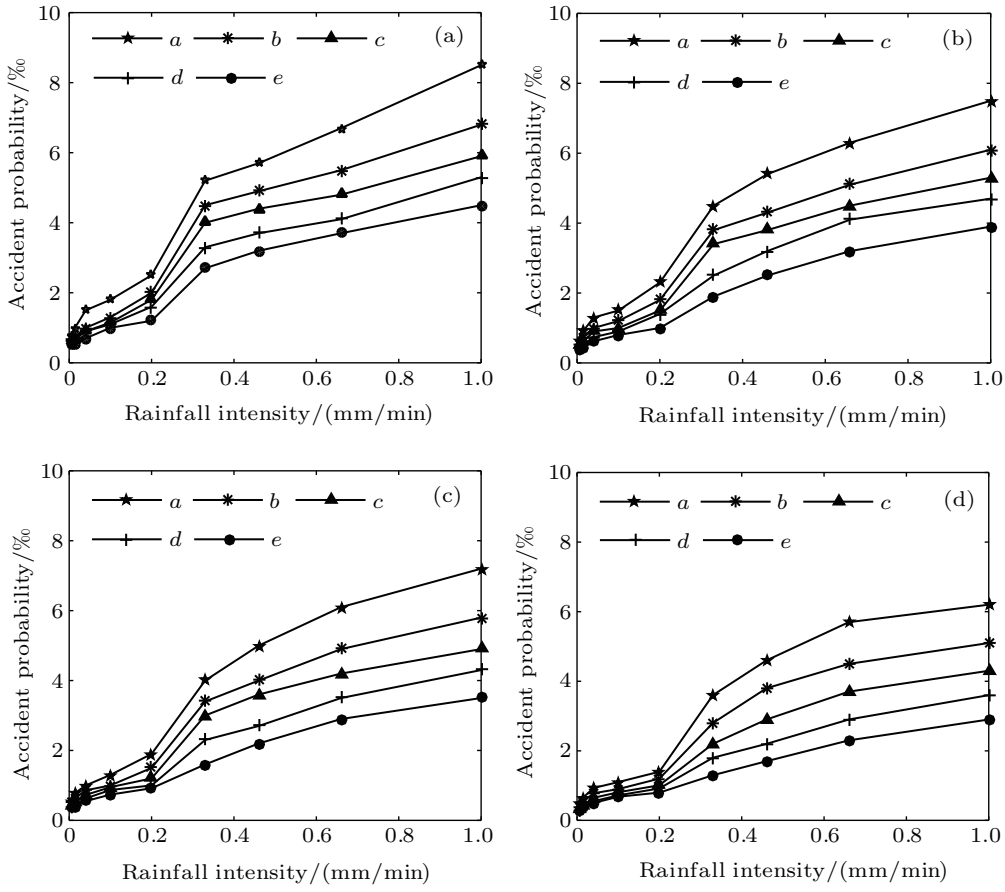


Fig. 14. Rainfall intensity dependent accident probabilities with VSLs of (a) 2000 veh/h, (b) 1500 veh/h, (c) 1000 veh/h, and (d) 500 veh/h. The curve "*a*" indicates the results of N_{ac}/N which experimented with $v_{max1} = 120$ km/h and $v_{max2} = 90$ km/h, "*b*" indicates the results with $v_{max1} = 100$ km/h and $v_{max2} = 70$ km/h, "*c*" indicates the results with $v_{max1} = 80$ km/h and $v_{max2} = 50$ km/h, "*d*" indicates the results with $v_{max1} = 60$ km/h and $v_{max2} = 40$ km/h, "*e*" indicates the results with $v_{max1} = 40$ km/h and $v_{max2} = 30$ km/h.

2) Figure 14 can be divided into two parts. The first part is the comparison of accident probability, where the rainfall intensity is less than 0.206 mm/min. The accident probability of this part is small, even though the speed limit is different. The change of accident probability is not obvious. This is because the rainfall is relatively small and the water can be squeezed from the smooth wheel tires in time. The change of friction coefficient of pavement is not obvious and the influence on the

driver's sight distance is not big. Most of the drivers can still find the front vehicle and control their vehicles to avoid an accident. Although low speed upper limit value can reduce the accident rate, the flux of road will decrease. So it is the best way to slightly reduce the upper speed limit value in this part. The second part in Fig. 14 is the comparison of accident probability, where the rainfall intensity is between 0.206 mm/min and 1 mm/min. The accident probability of this part increases rapidly with rainfall intensity increasing. The changes of accident probability are very obvious by inputting the different speed limit values. This is because the rainfall intensity is large when a heavy rainstorm or short-time heavy rainfall happens and there is not enough time to squeeze out the water from the smooth wheel tires. The change of friction coefficient of pavement is very obvious and the influence on the driver's sight distance is also large. It is difficult for some drivers to find the front vehicle and control their vehicle to avoid an accident. So it is the best way to reduce dramatically the upper speed limit value in this part.

3) The accident probabilities are different by using the different inlet traffic volumes. The larger the incoming flow, the larger the accident probability is. So incoming flow control is also an important measure to reduce traffic accident.

4.3. Analysis of incoming flow control

Figure 15 shows comparisons among the rainfall-intensity-dependent accident probabilities obtained by using the different inlet traffic volumes. The upper speed limit values are 100(70) km/h for Fig. 15(a), 80(50) km/h for Fig. 15(b), 60(40) km/h for Fig. 15(c), and 40(30) km/h for Fig. 15(d), respectively. The achieved findings are as follows.

a) The increasing trends of accident probability are basically the same, obtained by using the upper speed limit values of 100(70) km/h for Fig. 15(a), 80(50) km/h for Fig. 15(b), 60(40) km/h for 15(c), and 40(30) km/h for 15(d), which increase with rainfall intensity increasing. The larger the incoming flow, the larger the accident probability is. This proves that reducing the inlet volume is very effective in reducing the accident rate and enhancing the road safety in rainy weather.

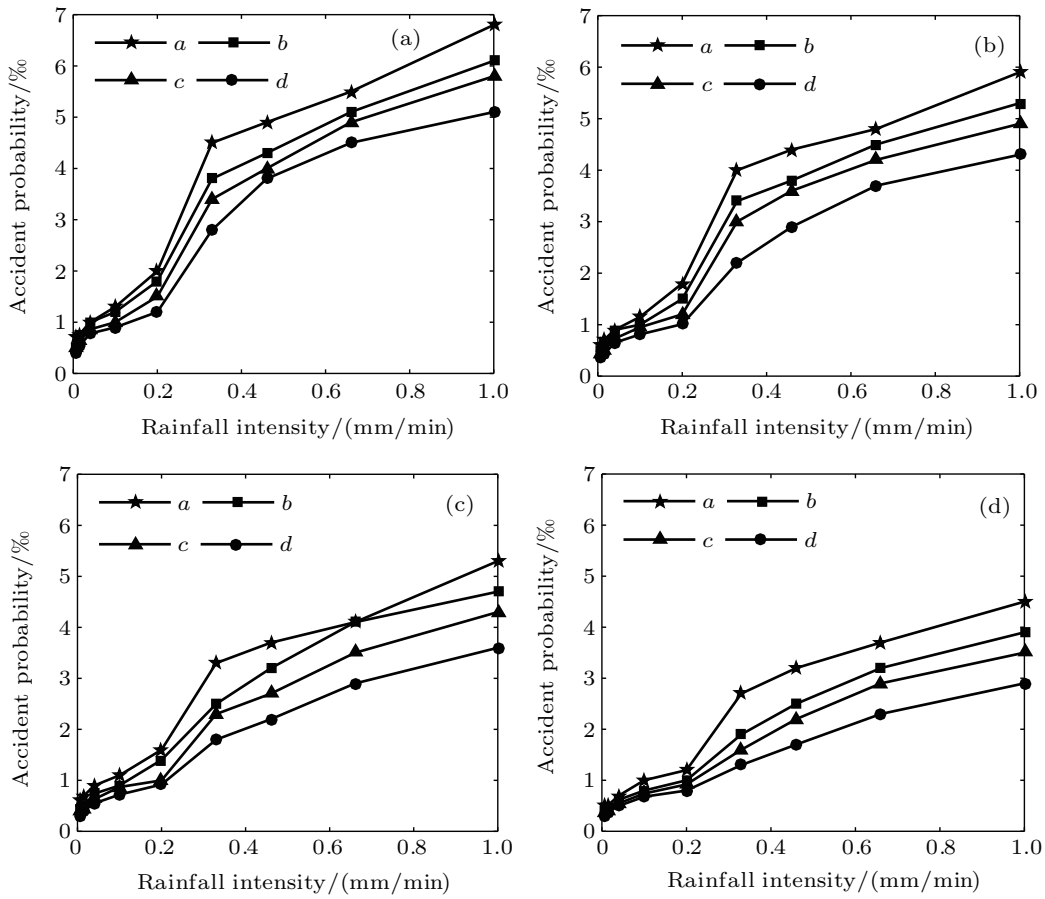


Fig. 15. Rainfall-intensity-dependent accident probabilities at (a) $v_{max1} = 100$ km/h and $v_{max2} = 70$ km/h, (b) $v_{max1} = 80$ km/h and $v_{max2} = 50$ km/h,(c)$v_{max1} = 60$ km/h and $v_{max2} = 40$ km/h, and (d) $v_{max1} = 40$ km/h and $v_{max2} = 30$ km/h. Curves "*a*", "*b*", "*c*", and "*d*" indicate the results at inlet traffic volumes of 2500 veh/h, 1500 veh/h, 1000 veh/h, and 500 veh/h.

b) Figure 15 can be divided into two parts. The first part is the comparison of accident probability, where the rainfall intensity is less than 0.206 mm/min. The accident probability of this part is small, even though the inlet volume is different. The change of accident probability is not obvious. The reason is the same as that in Subsections 4.1 or 4.2. So it is the best way to slightly reduce the inlet volume in this part. The second part in Fig. 15 is the comparison of accident prob-

ability, where the rainfall intensity is between 0.206 mm/min and 1 mm/min. The accident probability of this part increases rapidly with rainfall intensity increasing. The change of accident probability is very obvious with inputting the different inlet volume. So it is the best way to dramatically reduce the inlet volume or close the way in this part.

c) The accident probabilities are different by inputting the different VSL signals. The larger the VSL, the larger the accident probability is. So incoming flow control and inputting the different VSL signals are considered synthetically.

4.4. Analysis of control mode

Figure 16 shows the simulation results of the phase diagram in (inflow, rainfall intensity) space. The space can be divided into five regions. The traffic flow is free in region I and region II, while it is congested in region III, region IV, and region V. We can obtain the optimal strategy under different conditions.

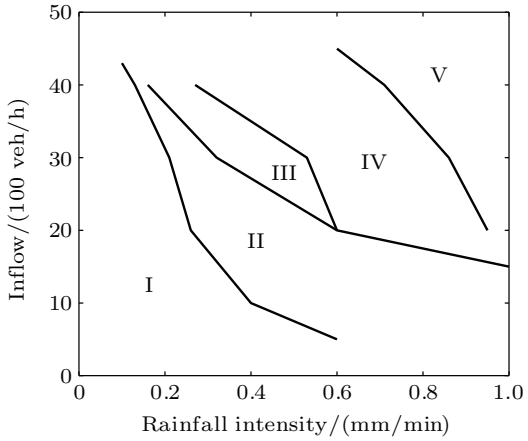


Fig. 16. Phase diagram in (inflow, rainfall intensity) space.

Condition 1 In region I, the rainfall intensity is small and the inflow is not large, or rainfall intensity is medium and inflow is small. The traffic flow on the road is free and the number of accidents is fewer. The best mode is not to input any control signal, which means that the wrecked vehicles fraction is in a rational range. If some control signals are inputted, e.g., VSL or incoming flow control, the flux would decline.

Condition 2 In region II, rainfall intensity is medium and traffic demand is not very large, or rainfall intensity is very large and traffic demand is small. The traffic flow on the road is free and the number of accidents can be controlled. We can get a maximal flux and a low wrecked vehicles fraction by inputting VSL signal.

Condition 3 In region III, rainfall intensity is medium but traffic demand is high. The congested state of the traffic flow on the road cannot be avoided. We can obtain a low wrecked vehicles fraction by controlling the incoming flow. In other words, if the traffic demand and rainfall intensity are located in this region, the wrecked vehicles fraction can be ensured in a rational range.

Condition 4 In region IV, rainfall intensity and traffic demand are large. The best mode is to input VSL signal and reduce the inlet traffic volume, which can ensure that the wrecked vehicles fraction is in a rational range.

Condition 5 In region V, rainfall intensity and traffic demand are very high. The best mode is to close the freeway. This is because inputting VSL signal or reducing the upstream traffic volume has little effect on reducing N_{ac}/N, nor have even both of them.

5. Conclusions and perspectives

The micro-scale driving behaviors in rainy weather and possible vehicle rear-end and sideslip accidents are analyzed. The influences of traffic accident in rainy weather and the management strategies are studied by using an improved CA model for a two-lane freeway mainline. The simulation results indicate that controlling the incoming flow and inputting VSL signal are effective especially when there is a heavy rainstorm or short-time heavy rainfall. According to different rainfall and traffic demand, the appropriate control strategies should be adopted in order to reduce the probability of vehicle accidents and enhance traffic flux as well. These findings may provide reference values for freeway management and control.

The formula for the micro-scale driving behaviors in rainy weather is still relatively simple and realistic. Vehicle accidents do not really occur in the simulation and these dangerous situations are only calculated and considered to be the signal of the occurrence of accidents. These problems will be further studied in future.

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