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Effect of perception irregularity on chain-reaction crash in low visibility

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HIGHLIGHTS

- We presented the dynamic model of the chain-reaction crash to take into account the perception irregularity of drivers.
- We studied the effect of the perception irregularity on the chain-reaction crash in low visibility.
- We derived analytically the transition points and region maps for the chain-reaction crash with the perception irregularity.

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ABSTRACT

We present the dynamic model of the chain-reaction crash to take into account the irregularity of the perception–reaction time. When a driver brakes according to taillights of the forward vehicle, the perception–reaction time varies from driver to driver. We study the effect of the perception irregularity on the chain-reaction crash (multiple-vehicle collision) in low-visibility condition. The first crash may induce more collisions. We investigate how the first collision induces the chain-reaction crash numerically. We derive, analytically, the transition points and the region maps for the chain-reaction crash in traffic flow of vehicles with irregular perception times. We clarify the effect of the perception irregularity on the multiple-vehicle collision.

1. Introduction

Mobility is nowadays one of the most significant ingredients of a modern society. Physics, other sciences, and technologies meet at the frontier area of interdisciplinary research. The development of the modern traffic theories is due to the availability of computer and the concepts of modern physics. The concepts and techniques of physics have been applied to transportation systems [1–35]. Traffic is modeled as a system of interacting vehicles driven far from equilibrium.

Traffic accident is dangerous. The accident prevents the traffic flow, blocks the highway, and induces severe congestions. A crash may induce more collisions. The single collision may result in the chain-reaction crash (multiple-vehicle collision). The chain-reaction crash is a road traffic accident involving many vehicles. Generally, the multiple-vehicle collisions occur on high-capacity and high-speed routes. The most disastrous pile-ups have involved more than a hundred vehicles. The mass of crumpled vehicles depends greatly on the traffic situation and drivers.

The multiple-vehicle collision has been modeled and studied by Sugiyama and Nagatani [36] and Nagatani and Yonekura [37]. The dependence of the multiple-vehicle collision on the traffic situation has been explored by using the optimal velocity model. The traffic behavior in low-visibility conditions is definitely different from that in the normal conditions. The dynamic model for the chain-reaction crash in low-visibility conditions has been proposed and investigated [38].

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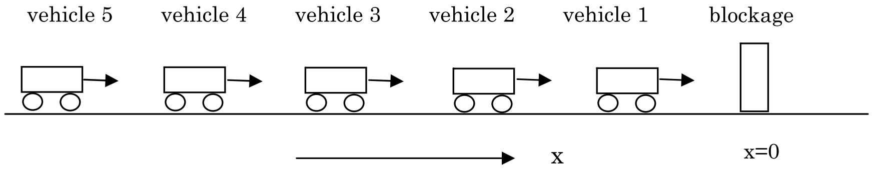

Fig. 1. Schematic illustration of the vehicular traffic controlled by the taillights on the single-lane highway with the blockage. The vehicles are numbered from the downstream to the upstream. The taillights of the leading vehicle switch on after time τ_1. Then, the taillights of the second vehicle switch on at time $\tau_1 + \tau_2$. Successively, the taillights of vehicle n switch on at time $\sum_{i=1}^{n} \tau_i$.

In low-visibility conditions, drivers brake to a stop as soon as the taillights of the forward vehicle switch on. The traffic flow in low visibility is controlled by the taillights. It has been shown that the chain-reaction crash in low visibility depends highly on the perception degree of the driver. If the perception–reaction time is high, the crash occurs easily. In the previous work, the degree of the driver's perception is the same for all drivers. However, the perception degree of a driver is different from that of the other driver. The perception–reaction time varies from driver to driver. It is little known how the perception irregularity has an effect on the chain-reaction crash. It is necessary and important to study the effect of the perception irregularity on the multiple-vehicle collision.

In this paper, we present the dynamic model for the chain-reaction crash in traffic flow of vehicles with irregular perception times. We study the effect of the perception irregularity on the chain-reaction crash on a highway in low visibility when the leading vehicle stops suddenly by a blockage. We investigate how the perception irregularity affects the chain-reaction crash in low-visibility conditions. We study the dynamic transitions from no collisions to multiple-vehicle collision numerically. We derive a criterion that the braking vehicle comes into collision with the vehicles ahead and the crash induces more collisions analytically. We show the dependence of the mass of the crumpled vehicles on the traffic condition. We find the region map for the chain-reaction crash.

2. Model

We consider the situation that many vehicles move ahead in low visibility on the single-lane highway with a single blockage. The vehicles are numbered from the downstream to the upstream. The leading vehicle is numbered as one. We assume that all vehicles move with the same headway b and speed v_0 before braking. The taillights switch on when the vehicle brakes. There is a delay until a vehicle brakes. The delay is called as the perception–reaction time. The perception–reaction time varies from vehicle to vehicle because a driver has an individual perception–reaction time. We define the delay (perception–reaction time) of vehicle n as τ_n. It takes time τ_n until vehicle n brakes after the driver recognizes red taillights of forward vehicle $n-1$. The driver of the leading vehicle brakes to a stop after delay τ_1 when the headway is b at $t = 0$. Fig. 1 shows the schematic illustration of the dynamic model for the vehicular traffic controlled by the taillights on the single-lane highway with the blockage. The taillights of the leading vehicle switch on after time τ_1. Then, the taillights of the second vehicle switch on at time $\tau_1 + \tau_2$. Successively, the taillights of vehicle n switch on at time $\tau_1 + \tau_2 + \cdots + \tau_n$. The lighting taillights propagate backward (to the upstream) like red wave.

The total stopping distance consists of two components: one is the braking distance and the other is the reaction distance. The braking distance refers to the distance that a vehicle will travel from the point when its brake is fully applied to the point when it comes to a complete stop. It is determined by the speed of the vehicle and the friction coefficient between the tires and the road surface. The reaction distance is the product of the speed and the perception–reaction time of the driver. The typical value of a perception–reaction time is 1.5 s. However, the perception–reaction time depends strongly on the driver's response. A friction coefficient of 0.7 is standard for the purpose of determining a bare baseline.

The dynamics of braking is described by the following equation of motion of vehicle n:

$$m \frac{d^2 x_n}{dt^2} = -\mu m g, \tag{1}$$

where $x_n(t)$ is the position of vehicle n at time t, μ is the friction coefficient, and g is gravitational acceleration. The first term on the right-hand side represents the friction force between the tires and the road surface.

We derive the equation of motion for the leading (first) vehicle. For $t \le \tau_1$, the velocity of the leading vehicle is v_0 because the leading vehicle brakes with delay τ_1. For $t > \tau_1$, the velocity is $v_0 - \mu g(t - \tau_1)$ because the leading vehicle brakes after time τ_1. If the leading vehicle contacts with the blockage, it comes into collision, its velocity becomes zero, and it stops instantly. The first collision is represented by step function $\theta(b - x_1(t))$. The position $x_1(t + \Delta t)$ of leading vehicle at time $t + \Delta t$ is given by

$$v_1(t) = [v_0\{1 - \theta(t - \tau_1)\} + \{v_0 - (t - \tau_1)\mu g\}\theta(t - \tau_1)]\,\theta(b - x_1(t)), \tag{2}$$

$$x_1(t + \Delta t) = x_1(t) + v_1(t)\Delta t, \tag{3}$$

where τ_1 is the perception–reaction time of vehicle 1, $\theta(t)$ is the step function ($\theta(t) = 1$ for $t \ge 1$ and $\theta(t) = 0$ for $t < 0$), and Δt is the time interval. The first term on the right hand side of Eq. (2) represents the velocity before braking. The second term on the right hand side of Eq. (2) represents the velocity when the leading vehicle is braking. $\theta(b - x_1(t))$ is the