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Chain-reaction crash in traffic flow controlled by taillights

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HIGHLIGHTS

- We presented the dynamic model for the chain-reaction crash in low-visibility conditions on a highway.
- We studied whether or not the first collision induces the chain-reaction crash.
- We derived the transition points and region maps for the chain-reaction crash in traffic flow controlled by taillights.

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ABSTRACT

We study the chain-reaction crash (multiple-vehicle collision) in low-visibility condition on a road. In the traffic situation, drivers brake according to taillights of the forward vehicle. The first crash may induce more collisions. We investigate whether or not the first collision induces the chain-reaction crash, numerically and analytically. The dynamic transitions occur from no collisions through a single collision, double collisions and triple collisions, to multiple collisions with decreasing the headway. Also, we find that the dynamic transition occurs from the finite chain reaction to the infinite chain reaction when the headway is less than the critical value. We derive, analytically, the transition points and the region maps for the chain-reaction crash in traffic flow controlled by taillights.

1. Introduction

Traffic flow is a self-driven many-particle system of strongly interacting vehicles [1–5]. The concepts and techniques of physics have been applied to such complex systems as transportation systems [6–35]. The dynamical phase transitions between distinct traffic states have been studied from a point of view of statistical physics and nonlinear dynamics.

Mobility is nowadays one of the most significant ingredients of a modern society. Traffic accident is dangerous and induces severe congestions. The accident prevents the traffic flow and blocks the highway. Frequently, the collisions between vehicles happen by the blockage. The crash may induce more collisions and may result in the chain-reaction crash (multiple-vehicle collision). The chain-reaction crash is a road traffic accident involving many vehicles. Generally occurring on high-capacity and high-speed routes such as freeways, they are one of the deadliest forms of traffic accidents. 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.

Nagatani and Yonekura have studied the multiple-vehicle collision induced by lane changing [36]. The condition of the multiple-vehicle collision has been explored by using the optimal velocity model. Also, the multiple-vehicle collision induced by a sudden slowdown has been investigated by Sugiyama and Nagatani [37]. Frequently, the chain-reaction crash occurs in low-visibility conditions as drivers are sometimes caught out by driving too close to the vehicle in front and not adjusting to the road conditions. In low-visibility conditions, drivers brake to a stop as soon as the taillights of the forward vehicle

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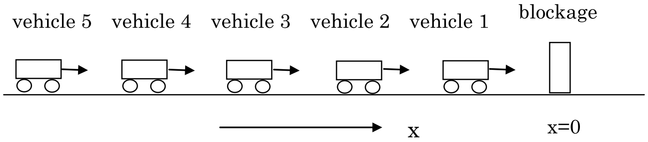

Fig. 1. Schematic illustration of the dynamic model for the vehicular traffic controlled by the taillights on the single-lane highway with the blockage. The vehicles are numbered from the downstream to the upstream. The leading vehicle is numbered as one. The taillights of the leading vehicle switch on after time τ. Then, the taillights of the second vehicle switch on at time 2τ. Successively, the taillights of vehicle n switch on at time $n\tau$.

switch on. Thus, the traffic flow in low visibility is controlled by the taillights. The traffic behavior in low-visibility conditions is definitely different from that in the normal conditions. However, the multiple-vehicle collision in low-visibility conditions has not been studied by using the dynamic models. It is little known how much speed and how long headway between the vehicles ahead or behind is necessary to avoid the multiple-vehicle collision. It is necessary and important to study the chain-reaction crash in low-visibility conditions by using the dynamic models.

In this paper, we present the dynamic model for the traffic flow in low visibility controlled by the taillights. We study the chain-reaction crash on a highway in low visibility when the leading vehicle stops suddenly by a blockage. We investigate whether or not the chain-reaction crash is induced in low-visibility conditions. We derive a criterion that the braking vehicle comes into collision with the vehicles ahead and the crash induces more collisions. We study the dynamic transitions from no collisions to multiple-vehicle collision. 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 analytically.

2. Model

We consider the situation that many vehicles move ahead on a single-lane highway in low visibility. There exists a blockage on the highway. 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 (perception–reaction time) τ until the vehicle brakes after the driver recognizes red taillights of the forward vehicle. The driver of the leading vehicle brakes to a stop after delay τ 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 vehicles are numbered from the downstream to the upstream. The leading vehicle is numbered as one. The taillights of the leading vehicle switch on after time τ. Then, the taillights of the second vehicle switch on at time 2τ. Successively, the taillights of vehicle n switch on at time $n\tau$. The lighting taillights propagate backward (to the upstream) like a red wave.

The total stopping distance consists of two principal 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. A friction coefficient of 0.7 is standard for the purpose of determining a bare baseline.

We take into account only the friction force for braking of the vehicular motion. The dynamics of braking is described by the following equation of motion of vehicle n:

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

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.

If the leading vehicle contacts with the blockage, it comes into collision, its velocity becomes zero, and it stops instantly. The position $x_1(t + \Delta t)$ of the leading vehicle at time $t + \Delta t$ is given by

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

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

where τ is the perception–reaction time, $\theta(t)$ is the step function ($\theta(t) = 1$ for $t \geq 1$ 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 because the vehicle brakes with delay τ. The second term on the right hand side of Eq. (2) represents the velocity when the leading vehicle is braking. For $t \leq \tau$, the velocity of the leading vehicle is v_0. For $t > \tau$, the velocity is $v_0 - \mu g(t - \tau)$. $\theta(b - x_1(t))$ is the step function representing whether or not the leading vehicle collides with the blockage. If the leading vehicle comes into collision, $\theta(b - x_1(t)) = 0$ and otherwise, $\theta(b - x_1(t)) = 1$.

If vehicle n comes into contact with the forward vehicle, it collides with the forward vehicle and stops instantly. The position $x_n(t + \Delta t)$ of vehicle n at time $t + \Delta t$ is given by

$$v_n(t) = [v_0\{1 - \theta(t - \tau n)\} + \{v_0 - (t - \tau n)\mu g\}\theta(t - \tau n)]\,\theta(x_{n-1}(t) - x_n(t)), \tag{4}$$

$$x_n(t + \Delta t) = x_n(t) + v_n(t)\Delta t. \tag{5}$$