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Chain-reaction crash on a highway in high visibility

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HIGHLIGHTS

- We presented the dynamic model of multiple-vehicle collisions in high visibility.
- We studied the chain-reaction crash in high visibility and compared with that in low visibility.
- We explored the dependence of the dynamic transitions from no collisions to the chain reaction crash on visibility.

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ABSTRACT

We study the chain-reaction crash (multiple-vehicle collision) in high-visibility condition on a highway. In the traffic situation, drivers control their vehicles by both gear-changing and braking. Drivers change the gears according to the headway and brake according to taillights of the forward vehicle. We investigate whether or not the first collision induces the chain-reaction crash numerically. It is shown that dynamic transitions occur from no collisions, through a single collision, 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 compare the multiple-vehicle collisions in high-visibility with that in low-visibility. We derive the transition points and the region maps for the chain-reaction crash in high visibility.

1. Introduction

Traffic flow is a typical example of self-driven many-particle system [1–5]. Physicists have studied the traffic flow by applying the concepts and techniques of physics to transportation systems [6–35]. The jamming transitions and dynamic behavior of vehicular traffic have been studied from a point of view of statistical physics and nonlinear dynamics.

Traffic accident is nowadays one of the most significant ingredients of a modern society. The accident prevents the traffic flow, blocks the highway, and induces severe congestions. A single-vehicle 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 and occurs on high-capacity and high-speed routes such as freeways. The most disastrous pile-ups have involved more than a hundred vehicles.

Recently, the multiple-vehicle collision has been investigated by using the optimal velocity model. Sugiyama and Nagatani have studied the multiple-vehicle collision induced by a sudden slowdown [36]. Also, the multiple-vehicle collision induced by lane changing has been investigated by Nagatani and Yonekura [37]. The dynamic transitions from no collision, through a single-vehicle collision, to multiple-vehicle collision have been explored by using the optimal velocity model. Li and Cheng have investigated the multiple-vehicle collision by using the extended optimal velocity model [38].

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

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as soon as the taillights of the forward vehicle switch on. The traffic flow in low visibility is controlled by the taillights. Very recently, the chain-reaction crash in low-visibility conditions has been studied by the friction-force model [39,40]. It has been shown that the traffic behavior in low-visibility conditions is definitely different from that in the normal conditions. The dynamic transition between the infinite chain-reaction crash and finite multiple-vehicle collision has been found by the friction-force model [39].

Only the friction force for braking is taken into account in the friction-force model for the chain-reaction crash in low visibility. While the speed control by changing gears is taken into account in the optimal velocity model. Generally, drivers control their vehicles by both gear changing and braking in high-visibility condition. However, the multiple-vehicle collision in high-visibility conditions has not been studied by using the dynamic models taking into account both gear changing and braking. It is little known how much speed and how long headway are necessary to avoid the multiple-vehicle collision in high and low visibilities. It is necessary and important to study the chain-reaction crash in high-visibility conditions by using the dynamic models. It is important to compare the multiple-vehicle collisions in high visibility with those in low visibility.

In this paper, we present the dynamic model for the chain-reaction crash in high visibility on a highway. We study the multiple-vehicle collisions on a highway in high visibility when the leading vehicle stops suddenly by a blockage. We explore whether or not the chain-reaction crash is induced in high-visibility conditions. We derive a criterion that the 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 in high-visibility condition. 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 numerically. We compare the multiple-vehicle collisions in high visibility with those in low visibility.

2. Model

We consider the situation that many vehicles move ahead on a single-lane highway in high visibility. There exists a blockage on the highway. All vehicles move with the same headway b and speed $v(0)$ initially. We assume that drivers control the vehicle by both gear changing and braking. Drivers change the velocity to the optimal velocity by changing gears according to their headway before braking because drivers can recognize the headway in high-visibility condition. The taillights switch on when the vehicle brakes. Vehicles brake with delay (perception-reaction time) τ after the driver recognizes red taillights of the forward vehicle. The vehicles are numbered from the downstream to the upstream. The leading vehicle is numbered as one.

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. Here, the speed is that just before the braking. 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.

The driver's attribution, the road's conditions and other related factors have significant effects on the traffic flow and collision process. Also, the stopping distance is affected by the factors. In order to focus upon the multiple-vehicle collision, we ignore the individual difference of the driver's perception ability. The effect of the individual difference of the drivers on the traffic flow has been studied by Tang et al. [41,42]. Furthermore, Tang et al. have investigated the effect of the road condition and electric vehicle on the traffic flow [43–51]. Here, we assume that the road condition is homogeneous and all cars have the same characteristic. We use the typical values for the perception-reaction time and the friction coefficient. Those values were obtained from Ref. [52].

We assume that the motion of vehicles is determined by the optimal velocity model before braking. We apply the optimal velocity model to the vehicular motion before braking [1]. The optimal velocity model is described by the following equation of motion of vehicle n:

$$\frac{\mathrm{d}^2 x_n}{\mathrm{d}t^2} = a\left\{V(\Delta x_n) - \frac{\mathrm{d}x_n}{\mathrm{d}t}\right\}, \tag{1}$$

where $V(\Delta x_n)$ is the optimal velocity function, $x_n(t)$ is the position of vehicle n at time t, $\Delta x_n(t)(= x_n(t) - x_{n+1}(t))$ is the headway of vehicle n at time t, and a is the sensitivity (the inverse of the delay time).

Before braking, driver adjusts the vehicular speed to approach the optimal velocity determined by the observed headway. The sensitivity a allows for the time lag $\tau_0 = 1/a$ that it takes the vehicular speed to reach the optimal velocity when the traffic is varying. Generally, it is necessary that the optimal velocity function has the following properties: it is a monotonically increasing function and it has an upper bound (maximal velocity).

$$V(\Delta x_n) = \frac{v_{\max}}{2}\left\{\tanh[(\Delta x_n - x_c)/x_c] + 1\right\}, \tag{2}$$

$$V(\Delta x_n) = \frac{v_{\max}}{2}\left\{\tanh(\Delta x_n - x_c) + \tanh(x_c)\right\}, \tag{2'}$$

where $v_{\max}$ is the maximal speed and x_c the position of turning point.