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# Stability analysis of an extended intelligent driver model and its simulations under open boundary condition

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## HIGHLIGHTS

- We proposed an extended intelligent driver traffic flow model with power cooperation.
- Linear stability analyses have been conducted.
- The effect of power cooperation is examined theoretically as well as numerically.
- We simulated the traffic flow model on a single lane under open boundary condition.

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## ABSTRACT

This paper presents an extended intelligent driver traffic flow model, in which the power of the considered vehicle is strengthened in proportion to that of the immediately preceding vehicle. We analyze the stability against a small perturbation by use of the linear stability method for the proposed traffic flow model on a single lane under open boundary condition, with the finding that the traffic flow stability can be improved by increasing the proportion of the direct power cooperation of the preceding vehicle. The participation of forward power cooperation can help to stabilize the traffic flow and suppress the traffic jams. In addition, the simulations under open boundary single lane are conducted to validate the correctness on theoretical deduction, which shows that numerical results in large-wave and short-wave stability are in good agreement with those of theoretical analysis.

## 1. Introduction

Due to the seriousness of traffic fumes and the great importance of efficient traffic for modern countries, the study of traffic flow theory has been given considerable attention in the past several decades. Many modeling approaches have been applied to describe the complicated dynamics of traffic flow in fields [1–3]. Traditionally, there are two types, microscopic and macroscopic models [4–12] are distinguished for the stability analysis. According to the viewpoint of microscopic approaches, each vehicle is modeled by its own equation of motion. In contrast, macroscopic models represent traffic flow by a continuum approach needing several traffic variables like the spatial traffic density, average speed and traffic flux [13–18].

The intelligent driver model (IDM, for short) is one of the favorable car-following models [19–22], which is described by a second-order differential equation and the motion of a vehicle depends on the velocity, the net distance gap and the velocity difference to the leading vehicle. An increasing number of investigators with different backgrounds and points of view devoted themselves to the study of traffic dynamics by use of the IDM model because of its strong advantages in

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simulation. The effects of some human elements (the finite reaction times, the estimation errors, the spatial anticipation, and so on) on traffic characteristics have been investigated to explore some inherent patterns existing in real traffic. The impacts of traffic stability have been proved to depend on the driver behaviors and different driving habits. In addition, many improvements in the motion equation of the original IDM model have been conducted for a variety of desired purposes, and the string stability analysis is usually implemented in the IDM model for the purpose of verifying the availability of some improvements [23–26].

In recent years, with the boom of information and communication technologies (ICT), the fantasy that driving tasks are shifted from the driver to the intelligent equipped vehicle, has become reality today by integrating the technologies of the sensors, the global positioning system and intelligent control. The rapid development of the connected vehicle has achieved the real "Car Talk"—vehicles that can communicate with each other by using vehicle Dedicated Short Range Communications (DSRC, for short). Many scholars were engaged in the exploration to strengthen the stability of traffic flow by use of the availability of motion information from the preceding vehicles on the same road, such as the headway, velocity and flux [27]. Theoretical analysis results show that some improvements play a great role in avoiding the appearance of traffic density waves (go-and-stop waves). However, most of them were proposed to adjust the acceleration of the considered vehicle by indirectly integrating the acceleration of the vehicle ahead. Moreover, they have conducted the linear stability analysis and traffic simulations to their models under the periodical boundary condition. So it is inevitable that there exist some shortcomings describing the real traffic system in these models.

In view of that, the task of this paper is to deliver a more direct approach of IDM model considering the power cooperation of the nearest vehicle in front. Then an extended model is proposed and is used for simulations, the linear stability analysis will be done for the proposed model to obtain its stability against the small disturbance added into the homogeneous flow under an open boundary condition. The linear stability analysis shows that the improvement in the stability of traffic flow is obtained by taking into account the power cooperation of the immediately preceding vehicle. The phase diagrams are drawn to illustrate the dependency of the traffic flow stability on the intensity of the preceding power cooperation, the reaction time, the desired time gap, and the maximum acceleration. We compare the results of the linear analysis with the numerical simulations for long-wave and short-wave stability.

This paper is organized as follows. In Section 2, the extended intelligent driver model is presented to incorporate the power cooperation of the nearest preceding vehicle. The linear stability analysis of the proposed model is done with the reaction time of drivers in Section 3. In Section 4, the numerical simulations are carried out to the results of the theoretical analysis. Section 5 is devoted to the conclusion.

## 2. Extended intelligent driver model

The greatest strength of car-following models is that one can easily explore the analytical structure of the models. As one of car following models, the intelligent driver model [25–27] can describe the behavior of individual vehicles and drivers by differential equations, in which the acceleration of the $n$th vehicle at time $t$ is determined by the current velocity $v_n(t)$, the headway $s_n(t)$, and the velocity difference (approaching rate) $\Delta v_n(t)$ to the leading vehicle:

$$a_n = \frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = f_n(s_n(t), v_n(t), \Delta v_n(t)) = \alpha \left[ 1 - \left( \frac{v_n(t)}{v^0} \right)^4 - \left( \frac{s\,(t)^*}{s_n\,(t)} \right)^2 \right] \tag{1}$$

where $\alpha$ is the maximum acceleration of vehicle, $v^0$ is a desired velocity in free flow, and $s(t)^*$ is the desired safe headway, which is formulated as the following form [27]:

$$s(t)^* = s^0 + Tv_n(t) + \frac{v_n(t)\Delta v_n(t)}{2\sqrt{\alpha\beta}} \tag{2}$$

where $s^0$ is the minimum space gap for completely stopped traffic, $Tv_n(t)$ is the velocity-dependent distance, where $T$ is the constant desired time gap, and $\beta$ is the desired deceleration. From Eq. (2), one can observe that the last term will work for a case in which there is velocity fluctuation of vehicle $n$ with $\Delta v_n \neq 0$. Note that, the original IDM model is divided into two parts: one is the free-road acceleration strategy $a_n = \alpha[1 - (v_n(t)/v^0)^4]$, which only relates with $v_n(t)$, the other is the deceleration strategy $a_n = -\alpha(s^*/s)^2$ which relates with $v_n(t)$, $s$ and $\Delta v_n(t)$.

In this article, we consider the case in which the power output of the immediately preceding vehicle will be an adjusting term of the power output of the considered vehicle. The considered vehicle pays attention to not only the headway but also the power output of the immediately preceding one. If the power output of the preceding vehicle is great, the considered vehicle assumes that the forward vehicle accelerates, thus it increases the desired velocity even though its headway is short. On the other hand, if the acceleration of the preceding vehicle is negative, the considered vehicle decreases the desire velocity even if its headway is long.

Now, we try to describe this assumption by the mathematical expression. The power output $F_n$ of the vehicle $n$ is given by $F_n = ma_n$, where $m$ is the mass of each vehicle. Then, the power output $F_n$ of the vehicle based on the power cooperation in front is given by:

$$F_n = F_n + \lambda F_{n-1} \tag{3}$$