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Macroscopic traffic flow modeling with adaptive cruise control: Development and numerical solution

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HIGHLIGHTS

- A novel macroscopic modeling approach for Adaptive Cruise Control (ACC) in traffic flow dynamics.
- The proposed model is incorporated to a gas-kinetic (GKT) traffic flow model.
- A comparison with an alternative approach from the literature is performed.
- A high-resolution relaxation finite volume discretization (in space and time) is implemented.

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ABSTRACT

The incorporation of two macroscopic approaches reflecting Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) traffic dynamics in a gas-kinetic (GKT) traffic flow model is presented. The first approach was recently analyzed in the literature aiming to describe the effects induced by the ACC and CACC systems due to changes of the speed of the leading car(s) by the introduction of an acceleration/deceleration term. The second approach is a novel one and is based on the introduction of a relaxation term that satisfies the time/space-gap principle of ACC or CACC systems. In both approaches, the relaxation time is assigned on multiple leading vehicles in the CACC case; whereas in the ACC case this relaxation time is only assigned to the direct leading vehicle. We numerically approximate the resulting models by an accurate and robust high-resolution finite volume relaxation scheme, where the nonlinear system of partial differential equations is first recast to a diagonalizable semi-linear system and is then discretized by a higher-order WENO scheme. Numerical simulations investigate the effect of the different ACC and CACC approaches to traffic flow macroscopic stability with respect to perturbations introduced in a ring road and to flow characteristics in open freeways with merging flows at an on-ramp. Following from the numerical results, it can be concluded that CACC vehicles increase the stabilization of traffic flow, with respect to both small and large perturbations, compared to ACC ones. Further, the proposed CACC approach can better improve the dynamic equilibrium capacity and traffic dynamics, especially at the on-ramp bottleneck.

1. Introduction

Emerging technologies in the field of Vehicle Automation and Communication Systems (VACS), such as Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) systems, are likely to revolutionize the way traffic flow will be controlled and optimized in the near future. Although such technologies have been developed to increase driver's comfort

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and safety, the continuously increasing use of such systems in the years to come will have a direct impact on the overall traffic flow. The widespread use of such systems can form a potential solution to the continuously increasing problem of traffic congestion, by using advanced control strategies to increase road capacity, stabilize the flow and accomplish an optimal usage of the available infrastructure. As a result, a new generation of Traffic Management (TM) strategies need to be developed and tested, which will allow for the optimal use and exploitation of such systems. To this end, the development of appropriate modeling tools for such systems should be a priority, to allow for the reliable and efficient simulation of their performance and of the effects they have on traffic flow; this would allow to optimize the relevant parameters and explore new strategies for VACS implementation.

An ACC system forces the vehicle to slow down when the leading vehicle has a lower speed and, reversely, allows the vehicle to accelerate to a pre-determined speed when the leading vehicle accelerates. In principle, the pre-specified parameters of an ACC system are the time-gap to the leading vehicle and the desired speed of the vehicle. The main aim of such a system is to liberate the driver from the need to adjust its speed to that of the leader. However, the application of ACC systems, and for certain parameter settings, may also induce negative effects on traffic flow dynamics. Hence, and in order to minimize potential negative effects, it is crucial to evaluate the impact of such systems on traffic flow dynamics in advance. Vehicles equipped with CACC systems have the ability of sharing traffic information via vehicular networks or wireless technologies that allow communication between such vehicles. CACC systems constitute a further development of the ACC technology which provides more accurate and faster real time information sharing among the equipped vehicles. Research has shown that CACC systems can potentially improve safety as well as the traffic dynamics (in terms of capacity, flow, average speed and speed variation), if widely adopted. Compared to ACC, the literature on CACC systems is still very premature and relevant studies, usually, do not explore the effects of CACC in traffic flow quantitatively in terms of throughput, capacity, and congestion reduction but aim on creating design frameworks, to optimize and standardize the use of such technology.

Although much work has been reported for the microscopic simulation of ACC/CACC systems at vehicle level, we refer for example to [1–13], model applications of macroscopic or gas kinetic traffic flow models for the simulation of VACS are relatively rare. However, the development of accurate macroscopic traffic flow models for the simulation of VACS will be of major importance in the future, for real-time prediction and control applications, when the percentage of CACC/ACC vehicles will have significantly increased thus affecting considerably the traffic dynamics. As macroscopic models require less computational resources and simpler calibration effort than microscopic ones, they can be easily and more efficiently combined with optimization algorithms, either for parameter estimation or for optimization purposes. In [14] a design approach for an ACC strategy in an Automated Highway System based on macroscopic traffic flow stability analysis was presented. Using a linearized stability analysis, it was shown that the traffic flow equilibrium state was marginally stable under a constant time headway (CTH) policy. Moreover, in [15] a macroscopic model was presented with velocity saturation for traffic flow where vehicles are controlled with ACC spacing policy. Additionally, a non-linear stability criterion was derived, while the stability results provided sufficient and necessary conditions for ACC traffic flow stability. In [16,17] the macroscopic formulation of a kinetic model to variable speed control was applied using Variable Message Signs (VMS). In the first work a sliding mode controller was applied, being able to eliminate stop-and-go waves, as the controller increases the flow above some density and decreases it for the flow below this density. In the second work a similar approach was adopted, and VMS were used to inform drivers of slower traffic ahead. They assumed that drivers decrease their desired velocity when control is active and applied the variable average desired speed in the macroscopic implementation of the model. As a result, the occurrence of the so-called phantom traffic jams was prevented, as long as the speed adaptation by the drivers was sufficiently large. The impact of ACC concepts on the macroscopic level of traffic flow modeling was also considered in [18]. The simulation results showed that at lower time headways there is an improvement of traffic conditions (higher flow rate, faster dissolution of the congestion), even with small penetration rates; up to a certain penetration rate the traffic flow rate is increasing whereas higher penetration rates do not provide additional benefits.

In [19] a continuum approach to model the dynamics of cooperative traffic flow was presented, where the cooperation is defined in a way that the equipped vehicle can issue and receive a warning message when downstream congestion has been created. To this end, a multi-class gas-kinetic theory was extended to capture the adaptation of the desired speed of the equipped vehicles to the speed at the downstream congested traffic. Numerical tests indicated that the equipped vehicles contribute significantly to the stabilization of traffic flow, while increasing the fraction of equipped vehicles leads to a delay in traffic inflowing to the congested area and consequently results in a reduced shock-wave strength. In [20] the mixed operation of manual and ACC traffic flow was investigated, by deriving macroscopic multi-class traffic equations, obtained from a gas-kinetic model using the method of moments. A gas-kinetic macroscopic traffic flow model was further proposed in [21], based on a car-following one, to describe the dynamics of traffic where vehicles operate in the form of many platoons. A linear stability analysis showed a stabilization of the flow with respect to small perturbations. The analytic results were supported by the numerical simulation of an open freeway with an on-ramp bottleneck. In [22] the derivation of an improved macroscopic model for multi-anticipative driving behavior, using a modified gas-kinetic approach, was presented. Theoretical analysis and numerical simulations of the model were carried out to show the improved performance of the derived model over other existing multi-anticipative macroscopic models. In [23] a macroscopic model is proposed to describe the operations of CACC in the traffic flow. Using linear and nonlinear stability analysis it was found that CACC vehicles enhance the stabilization of traffic flow with respect to both small and large perturbations, compared to ACC vehicles, while numerical simulation supported the analytical findings. Further, from the linear analytical results,