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# Evaluation of the impacts of cooperative adaptive cruise control on reducing rear-end collision risks on freeways

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ABSTRACT

Although plenty of studies have been conducted recently about the impacts of cooperative adaptive cruise control (CACC) system on traffic efficiency, there are few researches analyzing the safety effects of this advanced driving-assistant system. Thus, the primary objective of this study is to evaluate the impacts of the CACC system on reducing rear-end collision risks on freeways. The CACC model is firstly developed, which is based on the Intelligent Driver Model (IDM). Then, two surrogated safety measures, derived from the time-to-collision (TTC), denoting time exposed time-to-collision (TET) and time integrated time-to-collision (TIT), are introduced for quantifying the collision risks. And the safety effects are analyzed both theoretically and experimentally, by the linear stability analysis and simulations.

The theoretical and simulation results conformably indicate that the CACC system brings dramatic benefits for reducing rear-end collision risks (TET and TIT are reduced more than 90%, respectively), when the desired time headway and time delay are set properly. The sensitivity analysis indicates there are few differences among different values of the threshold of TTC and the length of a CACC platoon. The results also show that the safety improvements weaken with the decrease of the penetration rates of CACC on the market and the increase of time delay between platoons. We also evaluate the traffic efficiency of the CACC system with different desired time headway.



## 1. Introduction

Traffic congestion and safety, as well as pollution, have been the severe global problems, which have considerable negative influence on peoples' lives and environment. Traditional countermeasures, such as construction of more transport infrastructures, however, prove to be impractical in many countries. In order to solve these rigorous traffic issues, various novel methods based on the intelligent transportation technologies have been proposed accordingly in recent years. The primary purpose of these techniques is to increase traffic supply, not physically by building new roads but innovatively by vehicular and infrastructural improvements.

One crucially improved technique is the driving-assistant system, which is aimed to comfort drivers by releasing driving tasks and benefit to traffic efficiency and safety as well. The most representative one is the adaptive cruise control (ACC) system, which has been developed for more than one decade and even on the market in some countries. The ACC system has been extensively investigated for its impacts on improving road capacity (Bose and Ioannou 2003; Kesting et al., 2007, 2008) and safety (Kikuchi et al., 2003; Li et al., 2016) previously. Although this system was considered very favorable for reducing collision risks and increasing efficiency, some recent studies based on real vehicular experiments indicated that the ACC techniques exert drawbacks on traffic stability (Milanés et al., 2014; Milanés and Shladover, 2014). In that case, a more advanced driving-assistant system derived from the ACC is developed, which is called the cooperative adaptive cruise control (CACC) system.

The CACC system is an improved technique that adds vehicle-to-vehicle wireless communication to the ACC system to obtain enhanced performances, including traffic flow, fuel consumption and safety. Previous studies related to the CACC system can be classified into three major aspects: 1) its impact on increasing road capacity (Shladover et al., 2012; Milanés et al., 2014; Horiguchi and Oguchi, 2014; Milanés and Shladover, 2014), 2) effects of the CACC system on traffic flow stability (Schakel et al., 2010; Yu and Shi, 2015; Monteil et al., 2014; Jin and Orosz, 2014; Li et al., 2015), and 3)

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impacts on improving traffic safety (Farah and Koutsopoulos, 2014; Shladover et al., 2015). However, the research focuses are not balanced, for the former two points have been analyzed extensively while few studies are conducted about the safety influence of the CACC, especially about the impact on reducing rear-end collision risks on freeways.

Furthermore, researches of the CACC system are mainly based on either simulations or experiments with production cars. Undeniably, the real filed experiments with the CACC vehicles are one of the most effective and accurate methods for analyzing performances of this advanced system. Several vehicle models or controllers have been proposed depended on data from these experiments (Milanés et al., 2014; Milanés and Shladover, 2014). Nevertheless, there are some downsides that real vehicular experiments cannot avoid. The first one is the high cost of the experiment, especially with the wireless communication system, as well as the consideration for safety on freeways. Moreover, these vehicle models or controllers derived from the experimental data are relatively complicated. And there are no concrete meanings of some parameters, which will lead to the difficulties of describing traffic dynamics (Fernandes and Nunes, 2015; Milanés et al., 2014; Milanés and Shladover, 2014). Last, the experimental data are limited and simplex, which may vary greatly from the CACC system of one manufacturer to another one and affect the universality. Thus, the traditional traffic flow models are still an indispensable alternative for investigation of the CACC technology based on simulations.

Indeed, the traffic flow models, such as car-following model, have been developed for modeling the advanced longitudinal driving-assistant systems for a long term (Kesting et al., 2007, 2008; Farah and Koutsopoulos, 2014; Li et al., 2016). A common concern is that whichever the technique is, it has to take into consideration human drivers' behaviors, which is related with comforts and driving habits. In that case, the traffic flow model is prioritized for which has been proved to be able to model driving behaviors precisely (Treiber et al., 2000; Hoogendoorn and Hoogendoorn, 2010; Wang et al., 2010). Another point argued by some researchers is the reality of simulation of traffic flow models considering different values of these parameters. Although these parameters cannot be calibrated accurately based on a large number of experimental data, there are several methods can be used to reduce the unreality. In this study, all the parameters used are classified firstly, and then values of some key factors are set according the existing experimental data, and other parameters are also valued reasonably based on plenty of related researches to ensure the authenticity.

Therefore, the primary objective of this paper is to evaluate the impacts of the CACC system on reducing rear-end collision risks. The CACC model developed from the traditional traffic model, the IDM, was firstly introduced. Then, two surrogate safety measures derived from the TTC were used to quantify the rear-end collision risk on freeways. Moreover, the theoretical analysis of safety based on both TTC notion and linear stability were conducted, and the simulation experimental design was introduced. Finally, the simulation results were presented and discussed, and the paper ended with brief concluding remarks as well as discussion of future work.

## 2. Development of CACC model

Previously, two methods were mainly considered for modeling the CACC vehicles: 1) simulating based on modified traffic flow models (Farah and Koutsopoulos, 2014; Yu and Shi, 2015; Li et al., 2015), and 2) modeling based on vehicle models or controllers with experimental data (Fernandes and Nunes, 2015; Milanés et al., 2014; Milanés and Shladover, 2014). It is undeniable that the experimental data in real traffic situations is more realistic and more reliable for study. However, due to the high cost for CACC experiments, as well as the consideration for safety in road, testing the CACC vehicles' performances in the large scale is impractical. In that case, the traditional traffic flow models are coming in handy, which are mainly on the basis of simulations instead of real tests, thus safe and saving for money.

The traditional traffic flow models, generally divided into macroscopic and microscopic models separately, have dramatically been modified for simulating the CACC operating conditions (Han et al., 2015; Farah and Koutsopoulos, 2014; Yu and Shi, 2015; Li et al., 2015). The macroscopic models, which are mostly used for analyzing the traffic efficiency and capacity as a whole, are not proper for investigating rear-end collision related to interactions of the leading and following vehicles at the microscopic level. To this end, the car-following model, one of the major branch of the microscopic models, is prioritized in the paper.

Indeed, car-following models have been developed for more than half century, and numerous models have been proposed to model the longitudinal behaviors of human drivers (May, 1990; Brackstone and McDonald, 1999; Treiber et al., 2000; Wang et al., 2005). Recently, as the advancement of driving-assistant systems, several eminent models have also been modified to model the ACC and CACC vehicles. One of them is the IDM, which is also applied as the basic model in this study. The IDM is chosen mainly due to the following reasons. Firstly, the IDM, having only six parameters with concrete meanings, has been proven to be able to model car-following behaviors precisely (Treiber et al., 2000; Wang et al., 2010). Secondly, there are many studies using the IDM to model ACC and CACC vehicles, which also indicates the ability of the model to reflect operations of driving-assistant systems (Kesting et al., 2007, 2008; Yu and Shi, 2015; Li et al., 2015, 2016). Therefore, the IDM is firstly introduced and then modified for the ACC and CACC vehicles in the following section.

The IDM, introduced by Treiber et al. (2000), is a non-linear car-following model for which the acceleration $f$ is calculated by the speed differences and the dynamic desired gap distance. The acceleration $f$ is determined by:

$$f(t+t_a) = a[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*}{s}\right)^2] \tag{1}$$

$$s^* = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{2}$$

where $t_a$ = the perception-reaction time, $a$ = the maximum acceleration, $v$ = the speed of the following vehicle, $v_0$ = the desired speed, $s$ = the gap distance between two vehicles, $s_0$ = the minimum gap distance at standstill, $T$ = the safe time headway, $\Delta v$ = the speed difference between two vehicles, and $b$ = the desired deceleration.

Derived from the IDM, one ACC model is also proposed by Kesting et al., which provides alternative parameters to directly simulate ACC vehicle's performance. More details were specified in previous studies (Kesting et al., 2007, 2008).

The CACC is the advanced driving-assistant system that adds vehicle-to-vehicle wireless communication to the ACC system to obtain enhanced performance. With the smaller communicating delay and the shorter time headway, this elaborated system has promising prospect of increasing road capacity and improving traffic safety. According to definitions on CACC by Shladover et al. (2015), the key component of that is the communication system, which provides relevant vehicles' information, including the leader of a string of vehicles and the immediate predecessor. The communicated data contains speed, location and acceleration or deceleration. Based on the typical definition, the CACC model in this paper is proposed as:

$$F_n(t+t_d) = f_n + \lambda_1 F_1 + \lambda_{n-1} F_{n-1} \tag{3}$$