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Modeling chain collisions in vehicular networks with variable penetration rates

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ABSTRACT

The vehicular ad hoc network has great potential in improving traffic safety. One of the most important and interesting issues in the research community is the safety evaluation with limited penetration rates of vehicles equipped with inter-vehicular communications. In this paper, a stochastic model is proposed for analyzing the vehicle chain collisions. It takes into account the influences of different penetration rates, the stochastic nature of inter-vehicular distance distribution, and the different kinematic parameters related to driver and vehicle. The usability and accuracy of this model is tested and proved by comparative experiments with Monte Carlo simulations. The collision outcomes of a platoon in different penetration rates and traffic scenarios are also analyzed based on this model. These results are useful to provide theoretical insights into the safety control of a heterogeneous platoon.

1. Introduction

In recent years, the highly advancement of various wireless communication technologies have accelerated the deployment of the advanced transportation information systems (ATIS). Especially, the ongoing development of dedicated short range communication (DSRC) has made the inter-vehicle communication (IVC) and the road-vehicle communication (RVC) feasible. The vehicular ad-hoc networks (VANETs) can support a variety of onboard active safety applications such as the danger warning systems, the collision avoidance systems, the advanced driver assistance systems and so on Hartenstein and Laberteaux (2008). Many significant research projects relevant to vehicular communication have been subsequently launched over the past dozen years. For examples, the Connected Vehicle project undertaken by the U.S. Department of Transportation and the European projects DRIVE C2X and COMeSafety2 all aim to make the transportation systems benefit from the inter-vehicle communications. One of the main concerns in most of those research projects is improving the performance of disseminating safety messages among neighboring vehicles maintaining low latency and high reliability (Hossain et al., 2010). Although it has been confirmed that inter-vehicle communication is promising to improve

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the safety of vehicles on roads, the inter-vehicle communication systems should be evaluated at full length for different driving parameters, vehicle-related properties as well as different traffic conditions before being deployed in real-life vehicular environments.

As a typical safety application of inter-vehicle communications, vehicle chain cooperative collision avoidance (CCA) systems or cooperative adaptive cruise control (CACC) systems have recently received much attention (Marsden et al., 2001; Vahidi and Eskandarian, 2003; Rajamani, 2012). A CCA system allows the DSRC equipped vehicles to promptly react in time to the abrupt deceleration of their front vehicles, even though the emergency is out of their sights. Some successful and well known testing work related to CCA applications can be linked to California PATH (Misener and Shladover, 2006; Ioannou et al., 2007). Although the U.S. government has announced in February 2014 that new light vehicles should be required to equip V2V (vehicle-to-vehicle) communications (Spangler and Detroit Free Press, 2013), the ubiquitous deployment of inter-vehicle communications onboard is not likely to be achieved within the next few years. The actual situation is that those equipped and unequipped vehicles would co-exist in general traffic flows (Chakravarthy et al., 2009). Therefore, it is meaningful to study the vehicle collisions in platoons where only a fraction of vehicles are equipped with inter-vehicle communications. We will explore the collision in a platoon with different penetration rates of vehicular communication unit.

In this work, we present a stochastic model which removes the assumption that all the vehicles install the wireless vehicular communications units. In the model, the kinematic parameters (e.g., velocity and acceleration) of any vehicle in a platoon are not completely independent but influenced to some extent by the preceding vehicle's kinematics, since the driver would make driving decision partially according to the behavior of its leader, which is called as car-following behavior (Pipes, 1953; Chandler et al., 1958). The driving operation of one vehicle is a function of the kinematic parameters of its preceding vehicle, which is formulated as a car-following model. The model is defined with a linear ordinary differential equation which can closely model the response of manually driven vehicles (Bose and Ioannou, 2003a,b). Furthermore, we investigate the vehicle chain collisions in a given platoon, which considers the influences of different penetration rates of inter-vehicle communication, stochastic nature of inter-vehicle distance distribution, and different kinematic parameters related to driver and vehicle. Similarly to some existing studies (Bose and Ioannou, 2003a,b; Chakravarthy et al., 2009; Garcia-Costa et al., 2012; García-Costa et al., 2013), some basic assumptions are also adopted in this paper to make our work tractable: (1) Each of the vehicles in a given platoon is moving in the same direction and cannot reverse its motion or change its lane even when it will collide with its preceding or rear vehicle; (2) Any potential collisions caused by communication device failures or driver faults are ignored. The model is not limited to the assumption that all the vehicles in a platoon being equipped with vehicular communications. Therefore, our work can be treated as a step toward a deep insight into the safety evaluation of vehicle platoons in general mixed-communication environments, which can help to guide an appropriate implementation of vehicular safety control applications when inter-vehicle communications are not ubiquitously deployed.

The remainder of this paper is organized as follows. A brief review on the related work is presented in Section 2. Section 3 presents the basic computation model for the rear-end collision which takes into account the stochastic nature of inter-vehicular distance distribution and the heterogeneity of vehicle platoon. In Section 4, based on the proposed computation model, we present a Markov chain-based approach for the computation of average collision percentage in a platoon. Section 5 demonstrates the validation and application of our model with different penetration rates, inter-vehicular broadcasting latencies, driver reaction times and kinematic parameters. Finally, concluding remarks are given in Section 6.

2. Related work

As one of specific and typical issues on traffic safety, vehicle chain collision avoidance has attracted a number of research efforts, and the safety control of automatic vehicle platoons has been modeled as inter-connection systems with wireless vehicular communications. Many researchers have investigated the advanced control policies of vehicle platoons with string stability analysis (Godbole and Lygeros, 1994; Swaroop and Hedrick, 1996; Swaroop, 1997; Bose and Ioannou, 2003a,b; Zhou and Peng, 2005). In their control models, the initial velocity and the inter-vehicle distance are almost assumed to be identical. But, in fact, the inter-vehicle distance between any adjacent vehicles always follows a specific stochastic distribution in most traffic scenarios. Namely, the inter-distance in a platoon can be reasonably regarded as a random variable when exploring the potential chain collisions. At this point, deterministic formulations in the form of transfer functions used in the aforementioned string ability analysis will be unsuitable to model chain collisions in terms of the stochastic nature of vehicle collisions.

In terms of the stochastic distribution of vehicles in a platoon, a stochastic model is more effective to describe the potential chain collisions. Recently, the evaluation of chain collisions in vehicular communication environments based on stochastic models can be found in Choi and Swaroop (2001), Choi and Darbha (2001) and Garcia-Costa et al. (2012). Choi and Swaroop (2001) and Choi and Darbha (2001) have considered the random braking in their model. Similarly, Garcia-Costa et al. (2012) has proposed a stochastic model for evaluating all the possibilities of chain collisions that may occur in a platoon. The authors focus on the theoretical computation of the collision probability and the expected collision number. In their stochastic model, a more realistic assumption that the inter-distance between vehicles is a random variable is added as well. In addition, in Garcia-Costa et al. (2012), the kinematic parameters of any one vehicle are assumed to be independent from each other's. Compared to most of the aforementioned work, although we also adopt the stochastic model approach, unlike (Choi and Swaroop, 2001; Choi and Darbha, 2001; Garcia-Costa et al., 2012), our model removes the assumption that