Accident Analysis and Prevention 104 (2017) 137–145

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Evaluating the safety impact of adaptive cruise control in traffic oscillations on freeways

Ye Li, Zhibin Li*, Hao Wang, Wei Wang, Lu Xing

School of Transportation, Southeast University, 2 Si pai lou, Nanjing, 210096, PR China

ARTICLE INFO

Keywords:
Adaptive cruise control
Rear-end collision
Penetration rate
Safety
Parameter

ABSTRACT

Adaptive cruise control (ACC) has been considered one of the critical components of automated driving. ACC adjusts vehicle speeds automatically by measuring the status of the ego-vehicle and leading vehicle. Current commercial ACCs are designed to be comfortable and convenient driving systems. Little attention is paid to the safety impacts of ACC, especially in traffic oscillations when crash risks are the highest. The primary objective of this study was to evaluate the impacts of ACC parameter settings on rear-end collisions on freeways. First, the occurrence of a rear-end collision in a stop-and-go wave was analyzed. A car-following model in an integrated ACC was developed for a simulation analysis. The time-to-collision based factors were calculated as surrogate safety measures of the collision risk. We also evaluated different market penetration rates considering that the application of ACC will be a gradual process. The results showed that the safety impacts of ACC were largely affected by the parameters. Smaller time delays and larger time gaps improved safety performance, but inappropriate parameter settings increased the collision risks and caused traffic disturbances. A higher reduction of the collision risk was achieved as the ACC vehicle penetration rate increased, especially in the initial stage with penetration rates of less than 30%. This study also showed that in the initial stage, the combination of ACC and a variable speed limit achieved better safety improvements on congested freeways than each single technique.

1. Introduction

As traffic has continuously increased on freeways, more congestion has occurred resulting in increased traffic oscillations and higher crash risks (Abdel-Aty and Abdelwahab, 2003; Golob et al., 2004; Kim et al., 2007). Previously, advanced traffic control techniques have been proposed to improve freeway safety. Some techniques have used infrastructure-based control devices at fixed locations to improve traffic operations and safety, including variable speed limits (VSL) (Papageorgiou et al., 1997; Abdel-Aty et al., 2006; Lee et al., 2006; Li et al., 2014b), ramp metering (Papageorgiou et al., 1997; Papageorgiou and Kotsialos, 2000), and lane management (Shewmake and Jarvis, 2014). Recently, some novel in-vehicle driving assistance systems have been developed, such as advanced vehicle-to-vehicle and vehicle-to-infrastructure communication (Van Nunen et al., 2012; Harigovindan et al., 2014), collision warning (Bueno et al., 2014; Aust et al., 2013), and automated driving (De Diego et al., 2013; Zeeb et al., 2015). Automated driving has drawn the attention of both transportation professionals and automobile manufacturers. It consists of several levels depending on how strong the system intervenes in the longitudinal and lateral control of vehicles (Nowakowski et al., 2010; Milanés and Shladover, 2014; Milanés et al., 2014; Shladover et al., 2015).

Although complete automation is not currently applicable, some automated driving techniques, such as vehicle adaptive cruise control (ACC), have already been on the market and are likely to expand their applications in the near future (Marsden et al., 2001; Bose and Ioannou, 2003; Kikuchi et al., 2003; Kesting et al., 2008; Kesting et al., 2010; Tapani, 2012). ACC is an intelligent form of cruise control that controls a vehicle's acceleration and deceleration to keep pace with the car in front. Current commercial ACC is designed to be a comfortable and convenient driving system. The car will typically slow under ACC, braking at up to half its maximum braking potential to ensure comfort. However, such systems may not prevent the occurrence of crashes in emergency conditions with slow traffic ahead of the ACC-enabled car. Some techniques, such as automatic emergence braking, could be paired with ACC systems, but those techniques only consider the ego-vehicle, and their impact on other vehicles was not fully considered. As the performance of ACC in stop-and-go traffic has not been fully evaluated, users were recommended to deactivate ACC control and use manual driving in congested traffic (Shladover et al., 2015). Those

---

* Corresponding author.
E-mail addresses: yeli@seu.edu.cn (Y. Li), lizhibin@seu.edu.cn (Z. Li), haowang@seu.edu.cn (H. Wang), wangwei_transtar@163.com (W. Wang), luxing@seu.edu.cn (L. Xing).

http://dx.doi.org/10.1016/j.aap.2017.04.025
Received 20 January 2017; Received in revised form 23 March 2017; Accepted 29 April 2017

limitations largely affect the future promotion and commercialization of ACC technology.

Previous studies have evaluated the operation of vehicles equipped with ACC in car-following scenarios. Some debates existed regarding the impacts of ACC on traffic flow. In earlier studies, researchers claimed that ACC techniques can reduce the variation of vehicle acceleration (Marsden et al., 2001; Tapani, 2012; Li et al., 2016), increase flow (Bose and Ioannou, 2003; Kesting et al., 2010), and stabilize traffic (Kesting et al., 2008; Kesting et al., 2010). However, some recent field tests of commercial ACC systems currently on the market showed that the strings of ACC vehicles might not be stable; speed oscillation was amplified from the initial vehicle to the following vehicles (Milanés and Shladover, 2014; Milanés et al., 2014). In field experiments, the parameters of the commercial ACC systems were allowed to adjust only within a small range. A larger adjustable range of parameters could be achieved in the future with improvements in the radar detection quality, processing and communication speed, and inherent feedback controllers, which may affect the operation of vehicle strings. However, the impacts of the parameters in ACC systems on traffic operation have not been fully tested.

A literature review suggested that no particular attention has been paid to the safety impact of ACC system parameters in traffic oscillations on congested freeways where crash risks are the highest (Abdel-Aty and Abdelwahab, 2003; Kim et al., 2007). It was assumed by the authors that the safety impact was largely affected by the parameter setting of the ACC system. In addition, as the application of commercial ACC systems is a gradual process, a long period will exist when traffic flow contains mixed ACC and non-ACC vehicles. Thus, studies that consider different market penetration rates of ACC vehicles are necessary. Targeting the above issues, the objective of this study is to evaluate the impacts of the ACC parameters on rear-end collision risks in oscillatory traffic under different market penetration rates. The findings of the study are expected to be useful to policy makers or transport agencies regarding the development, improvement and application of ACC technologies in the future.

The remainder of the paper is organized as follows. In the next section, the occurrence conditions of a rear-end collision are analyzed. In Section 3, a simulation model for simulating vehicle movements equipped with ACC is developed. In Section 4, a surrogate safety measure is proposed to evaluate the collision risks. Section 5 introduces the experimental design. The simulation results are discussed in Section 6. The paper concludes with brief concluding remarks and future research tasks in Section 7.

2. Rear-end collision risk in stop-and-go traffic

Previous studies have evaluated crashes in different traffic states and have found that collision risks are the highest in stop-and-go traffic (Abdel-Aty and Abdelwahab, 2003; Kim et al., 2007; Oh and Kim 2010). In stop-and-go traffic, rear-end collisions are the major collision type due to the frequent vehicle deceleration and acceleration caused by the propagation of kinematic waves (Abdel-Aty and Abdelwahab, 2003; Golob et al., 2004; Kim et al., 2007). Thus, in this section, a rear-end collision near a stop-and-go wave was considered an example to illustrate the occurrence condition of collisions.

Fig. 1(a) shows the stop-and-go wave that causes obvious vehicle deceleration and acceleration in congested traffic flow. Previous studies have found that the most dangerous situation was when the leading vehicle has decelerated while the following vehicle remains high speed (Abdel-Aty et al., 2005; Zheng et al., 2010; Xu et al., 2012; Li et al., 2013, 2014d). The situation is illustrated in Fig. 1(b)–(d). Fig. 1(b) shows the trajectories of two consecutive vehicles near a deceleration wave. The following vehicle $n + 1$ (see the gray box in Fig. 1(b)) traveling at a high speed v_2 observed the low speed v_1 of the leading vehicle n (see the black box in Fig. 1(b)) at time t. After a perception-reaction time t_a, the following vehicle began to decelerate (see Fig. 1(c)). The following vehicle reduced its speed from v_2 to v_1 within t_{de} (see Fig. 1(d)).

A rear-end collision occurred if:

$$d_a(n) + d_{de}(n) + d < d_a(n+1) + d_{de}(n+1) \tag{1}$$

where$d_a(n)$ = traveling distance of leading vehicle n in time t_a,

$d_a(n+1)$ = traveling distance of following vehicle $n+1$ in time t_a,

$d_{de}(n)$ = traveling distance of leading vehicle n in time t_{de},

$d_{de}(n+1)$ = deceleration distance of following vehicle $n+1$ in time t_{de},

d = distance between the two vehicles when the following vehicle observed the low speed of the leading vehicle, measured between the rear of one vehicle and the front of the next,

$d_a(n) + d_{De}(n) + d$ = location of the leading vehicle rear at time $t + t_a + t_{de}$ with respect to location x,

$d_a(n+1) + d_{De}(n+1)$ = location of the following vehicle front at time $t + t_a + t_{de}$ with respect to location x.

Using the variables shown in Fig. 1(b)–(d), the occurrence condition for the rear-end collision can be described as (Li et al., 2014b):

$$v_1 t_a + v_1\left(\frac{v_2 - v_1}{b_m}\right) + d < v_2 t_a + \frac{(v_2)^2 - (v_1)^2}{2b_m} \tag{2}$$

$$\Rightarrow v_1 t_a + v_1\left(\frac{v_2 - v_1}{b_m}\right) + d - v_2 t_a - \frac{(v_2 + v_1)(v_2 - v_1)}{2b_m} < 0 \tag{3}$$

$$\Rightarrow (v_2 - v_1)t_a + \frac{(v_2 - v_1)^2}{2b_m} - d > 0 \tag{4}$$

$$\Rightarrow t_a + \frac{(v_2 - v_1)}{2b_m} - \frac{d}{(v_2 - v_1)} > 0 \tag{5}$$

where b_m is the maximum deceleration rate of vehicle $n + 1$.

Assuming the speed of the vehicles before and after the deceleration was fixed, an indicator of the risk of a rear-end collision for the following vehicle $i + 1$ can be estimated as:

$$R = t_a + \frac{\beta}{b_m} - \alpha d \tag{6}$$

where R is the risk indicator and α and β are positive constants. When R increases, a rear-end collision is more likely to occur. The derivation showed three variables were related to the rear-end collision risk in stop-and-go traffic, i.e., perception-reaction time, initial gap between vehicles, and deceleration ability. Thus, those variables were considered the key parameters of ACC system to be tested in the simulation analyses in later sections.

3. Development of a simulation model

Although some premium vehicles have been equipped with full speed range ACC, currently, commercial ACC systems are usually not recommended for stop-and-go traffic conditions. It is quite difficult to obtain field experimental data for evaluating the safety impacts of ACC in stop-and-go traffic under different market penetration rates. In this study, the simulation technique was adopted. Data from previous small-scale field tests were used to determine the parameters. Previously, both macroscopic and microscopic simulation models were used to study ACC techniques (Bose and Ioannou, 2003; Kesting et al., 2008, 2010). Macroscopic models simulate traffic dynamic by considering cumulative traffic characteristics, such as speed, flow, and density and their relationships. However, macroscopic models cannot capture individual vehicle maneuvers and their interactions. Considering that ACC mainly affects individual vehicle movements, we decided to use a microscopic simulation model for our study purpose.

Microscopic simulations are the dynamic and stochastic modeling of individual vehicle movements on a second or sub-second basis within transportation facilities. A microscopic model determines vehicle