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Driver braking behavior analysis to improve autonomous emergency braking systems in typical Chinese vehicle-bicycle conflicts

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A B S T R A C T

Bicycling is one of the fundamental modes of transportation especially in developing countries. Because of the lack of effective protection for bicyclists, vehicle-bicycle (V-B) accident has become a primary contributor to traffic fatalities. Although AEB (Autonomous Emergency Braking) systems have been developed to avoid or mitigate collisions, they need to be further adapted in various conflict situations. This paper analyzes the driver's braking behavior in typical V-B conflicts of China to improve the performance of Bicyclist-AEB systems. Naturalistic driving data were collected, from which the top three scenarios of V-B accidents in China were extracted, including SCR (a bicycle crossing the road from right while a car is driving straight), SCL (a bicycle crossing the road from left while a car is driving straight) and SSR (a bicycle swerving in front of the car from right while a car is driving straight). For safety and data reliability, a driving simulator was employed to reconstruct these three scenarios and some 25 licensed drivers were recruited for braking behavior analysis. Results revealed that driver's braking behavior was significantly influenced by V-B conflict types. Pre-decelerating behaviors were found in SCL and SSR conflicts, whereas in SCR the subjects were less vigilant. The brake reaction time and brake severity in lateral V-B conflicts (SCR and SCL) was shorter and higher than that in longitudinal conflicts (SSR). The findings improve their applications in the Bicyclist-AEB and test protocol enactment to enhance the performance of Bicyclist-AEB systems in mixed traffic situations especially for developing countries.

1. Introduction

Bicycling remains a popular means of transport worldwide (Heinen and Maat, 2011; Pucher et al., 2011). In China, bicyclists constitute a considerable portion of road users. Statistics show that the bicycle number in China was over 370 million by the end of 2013 (Xu, 2015). In this year, China has experienced a surge in bicyclist number because of the recent boom of bicycle-sharing schemes (Yang and Liu, 2017). The huge amount of bicyclists contribute to lots of accidents in China every year. In 2015, there were reportedly 1602 bicyclist-involved accidents, including 1298 severe injuries and 304 fatalities (National Bureau of Statistics of China, 2015). However, the actual numbers should be much larger than the official statistics because a certain amount of accidents were not put on record. Some previous researches demonstrated that the leading cause of vehicle-bicycle (V-B) accidents in China is the irregular bicyclist behavior, such as running red lights at intersections (Yan et al., 2011; Wu et al., 2012; Huang et al., 2016).

Continuous efforts have been made to reduce or mitigate V-B accidents. A large amount of previous studies were devoted to investigating the contributing factors of V-B collisions (Yan et al., 2011; Zahabi et al., 2011), or the influential factors of bicyclist injury severity (Bíl et al., 2010; Nie and Yang, 2014). With the advent of vehicle active safety technologies, people have become increasingly interested in preventing accidents by advanced driver assistance systems (Li et al., 2015). A pioneer practice is the Automatic Emergency Braking (AEB) system, which has the authority to actively brake if a forward crash is imminent but the driver fails to respond promptly. To date, however, the AEB system capable of protecting bicyclists (called Bicyclist-AEB) is not yet available.

Conventional AEB systems adopt time-to-collision (TTC) as the criterion to assess forward collision risk (Kusano and Gabler, 2012). If the TTC is lower than a predefined threshold, additional brake pressure will

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be applied to mitigate the collision. The AEB systems based on such a strategy are very conservative, because they are not activated until the situation becomes extremely dangerous. This conservativeness inevitably raises driver distrust and discomfort (Eichelberger and McCartt, 2014), and even limits the actual effectiveness (Fildes et al., 2015). In light of the limitations of conventional AEB design, Bicyclist-AEB can be potentially improved by being adapted to drivers' braking characteristics, which requires a thorough understanding of the driver braking behavior in V-B conflicts.

Räsänen and Summala (1998) first applied attention-expectation theory to explain the driver behavior in V-B collisions. They pointed out that the inattention of drivers and the inappropriate expectation of bicyclists were the leading cause of V-B accidents. Wood et al. (2009) further claimed that V-B accidents were partly due to the disagreement between the drivers and bicyclists' attitudes regarding bicycle visibility. Silvano et al. (2015) found that drivers were more likely to yield to bicyclists at unsignalized roundabouts if the vehicle speed was high. Although these efforts addressed driver behavior in V-B conflicts at a general level, they failed to provide some quantitative features of driver braking behavior, which are directly related to Bicyclist-AEB design. A common metric to characterize driver braking behavior is the brake reaction time (BRT), which is typically defined as the time from the start of a stimulus (e.g., sudden intrusion of bicycles) to the first contact with the brake pedal (SAE J2944, 2015). The intervention timing of Bicyclist-AEB can be advanced by taking the prior knowledge of drivers' BRT into consideration. Green (2000) surveyed the studies on driver BRT, most of which were conducted in rear-end collisions between vehicles. Summala (2000) suggested that driver BRT was largely dependent on sites and questioned the attempts to seek a canonical BRT. Matsui et al. (2016) found that a driver's BRT to bicycles was shorter than that to pedestrians, and ascribed it to the larger visible area and higher moving velocity of bicycles. Although driver's BRT has been explored extensively in previous studies, studies focusing on V-B conflicts are still lacking. Chen et al. (2016) recently studied driver BRT in V-B conflicts based on naturalistic data in China, but the results may not be convincing due to the latent sensor errors introduced in road tests. Besides emergency braking, pre-decelerating behaviors were also observed in a previous study (Bella and Silvestri, 2015), which is deemed as a part of driver braking behavior in this paper.

As suggested by Green (2000) and Summala (2000), driver braking behavior is highly situation-dependent. One reason is that drivers' attention is largely subject to the specific environment (Summala, 2000). Besides, drivers' expectation of potential collisions also significantly influences their braking response (Räsänen and Summala, 1998; Green, 2000). For V-B conflicts, it is reasonable to infer that driver braking behavior should vary in different conflict scenarios. Thus, to study the braking behavior of Chinses drivers in V-B conflicts, it is necessary to 1) summarize the major V-B conflict types in China based on naturalistic driving data, and 2) study the driver braking behavior in corresponding major conflict scenarios. Step 1) requires a comprehensive classification method for the V-B conflicts in China. Op den Camp et al. (2014) categorized the V-B accidents in Europe into 10 groups based on the precrash motion. However, the scenario definition in their study needs to be improved to cover the V-B conflicts in China. For safety and data reliability, in step 2) conducting an experiment on driving simulator is preferable to analyzing naturalistic driving data acquired from road vehicles.

This paper aims to analyze Chinese drivers' braking behavior in V-B conflicts, in an effort to improve the design of Bicyclist-AEB systems. Compared with previous field-test studies, the data in this paper was obtained from simulator experiments which are expected to be more reliable. The main contributions of this paper include: 1) three major V-B conflict scenarios were extracted from naturalistic driving data; 2) the influence of conflict types on the braking behavior of Chinese drivers were figured out; 3) a potential method to design an adaptive Bicyclist-AEB based on driver braking characteristics was proposed.

The remnant of this paper is organized as follows. Section 2 proposes the classification method of V-B conflicts in China, and summarizes the major conflict scenarios. Section 3 introduces the conflict reconstruction method and experiment details on a driving simulator. Section 4 gives the data processing method and Section 5 presents the results. Section 6 discusses the results in Section 5 and explains how they can be used to improve the Bicyclist-AEB design. Section 7 concludes this paper.

2. Classification and summarization of naturalistic driving data

2.1. Database

Two Chinese datasets were used for the preliminary summarization of V-B conflict types. The first one is the naturalistic driving data collected by 50 taxis in Beijing urban area (Cheng et al., 2011). The taxis were equipped with video driving recorders (VDRs) which would be triggered if the longitudinal deceleration reached 0.4 G within 0.5 s or the instantaneous deceleration reached 2 G. The recorded data included forward images, speed, acceleration and brake signal. Each data sample was an 18 s episode (12 s before and 6 s after the trigger). In total, 368 V-B conflict data samples were collected.

The second dataset is the China In-Depth Accident Study (CIDAS) database. The CIDAS project aimed to collect on-site accidents annually in five cities (Beijing, Changchun, Weihai, Ningbo, and Foshan) of China since 2011 (Chen et al., 2014). A specialist team was dispatched to each accident scene to collect the detailed accident information. The recorded information included accident sketches, vehicle damage condition, injuries and road layout. From the CIDAS database, 90 V-B conflicts were available for analysis.

2.2. Conflict type classification

To study the braking behavior of Chinese drivers in V-B conflicts, it is a prerequisite to first summarize the primary conflict scenarios from the above datasets. According to the relative motion of the vehicle and bicycle, the 368 conflicts collected by VDRs were classified into 15 types, as explained in Table 1. The conflicts unable to be categorized into the 15 types were classified as Re (Remaining).

The frequency distribution of the conflict scenarios is shown in Fig. 1. It shows that the top three conflict scenarios were SCL (21.7%), SCR (14.1%), and SSR (14.1%). As shown in Table 1, SCL is defined as a bicycle crossing from the left side while the vehicle is driving straight; SCR is similar to SCL except that the bicycle is crossing from the right side; SSR is defined as a preceding bicycle swerving from the right side while the vehicle is running straight. These three scenarios accounted for approximately 50% of the total V-B conflicts collected by the VDRs.

90 V-B conflicts from the CIDAS dataset were also classified based on the scenario definition in Table 1. However, the on-site description of the CIDAS conflict samples could not clearly distinguish SSR, SSL and SSF. Therefore, these three scenarios were combined as SS when classifying the CIDAS samples. The classification results indicate that SCR (34.3%), SCL (22.2%) and SS (21.1%) were the dominant conflict scenarios in the CIDAS dataset. It indirectly supported the VDR result despite a slight difference in proportions. Thus, SCR, SCL and SSR were selected as the typical V-B conflict scenarios for further study on driver braking behavior. It should be noted that some studies (Op den Camp et al., 2014; Fredrikson et al., 2014) also found that these three scenarios covered the majority of V-B conflicts in Europe.

According to a further investigation of the conflict locations, 14 out of 52 (26.9%) SCR conflicts, 17 out of 80 (21.3%) SCL and 1 out of 52 (1.9%) SSR conflicts happened when the vehicle was starting at intersections, while the others occurred when the vehicle was running along roads. Because the vehicle speed and driver attention are different in these two situations, we subdivided SCR and SCL into SCR-R, SCL-R ("R" means the vehicle is running along a road) and SCR-S, SCL-S ("S"