Accident Analysis and Prevention 108 (2017) 74–82

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

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

Jingliang Duan[a,1], Renjie Li[a,1], Lian Hou[a], Wenjun Wang[a,*], Guofa Li[b,*], Shengbo Eben Li[a], Bo Cheng[a], Hongbo Gao[a]

[a] State Key Laboratory of Automotive Safety and Energy, Department of Automotive Engineering, Tsinghua University, Beijing, 100084, China
[b] Institute of Human Factors and Ergonomics, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, 518060, China

ARTICLE INFO

Keywords:
Braking behavior
Vehicle-bicycle conflict
Driving simulator
Autonomous emergency braking

ABSTRACT

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

* Corresponding authors.
E-mail addresses: djl15@mails.tsinghua.edu.cn (J. Duan), lirenaxe@gmail.com (R. Li), houl16@mails.tsinghua.edu.cn (L. Hou), wangxiaowenjun@tsinghua.edu.cn (W. Wang), guofali@szu.edu.cn (G. Li), lishbo@tsinghua.edu.cn (S.E. Li), chengbo@tsinghua.edu.cn (B. Cheng), ghb48@mail.tsinghua.edu.cn (H. Gao).
[1] These authors have equally contributed to this research work.

http://dx.doi.org/10.1016/j.aap.2017.08.022
Received 20 March 2017; Received in revised form 16 August 2017; Accepted 20 August 2017
Available online 06 September 2017
0001-4575/

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

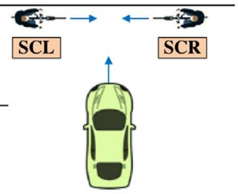
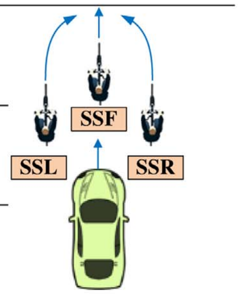
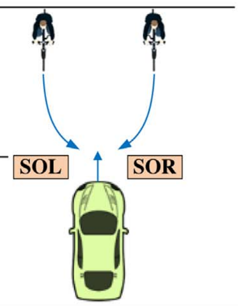
To study the braking behavior of Chinese drivers in V-B conflicts, it is a prerequisite to first summarize the primary conflict scenarios from the above datasets. According to the relative motion of the vehicle and bicycle, the 368 conflicts collected by VDRs were classified into 15 types, as explained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

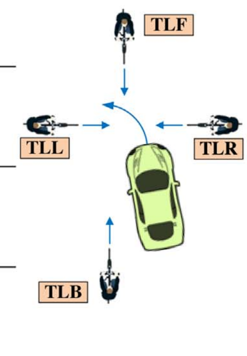
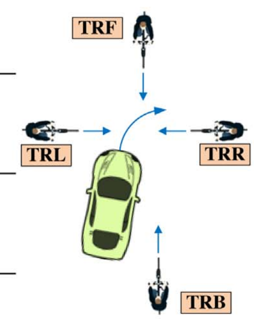
The frequency distribution of the conflict scenarios is shown in Fig. 1. It shows that the top three conflict scenarios were SCL (21.7%), SCR (14.1%), and SSR (14.1%). As shown in Table 1, SCL is defined as a bicycle crossing from the left side while the vehicle is driving straight; SCR is similar to 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"

Table 1
V-B conflict scenarios.

vehicle maneuver	relative motion	relative position	scenario
going straight (S)	cross direction (C)	left (L)	
		right (R)	
	same direction (S)	left (L)	
		front (F)	
		right (R)	
	opposite direction （O）	left (L)	
		right (R)	

vehicle maneuver	relative position	scenario
turning left (TL)	left (L)	
	front (F)	
	right (R)	
	behind (B)	
turning right （TR）	left (L)	
	front (F)	
	right (R)	
	behind (B)	

means the vehicle is starting at an intersection), in an effort to find out whether the vehicle status affects drivers' braking behavior (SSR were not divided because SSR-S conflicts are very rare, i.e., SSR is equivalent to SSR-R in the following sections). To sum up, five conflict types (SCR-R, SCR-S, SCL-R, SCL-S, and SSR) were chosen as the typical V-B conflicts to be studied in the simulator experiment.

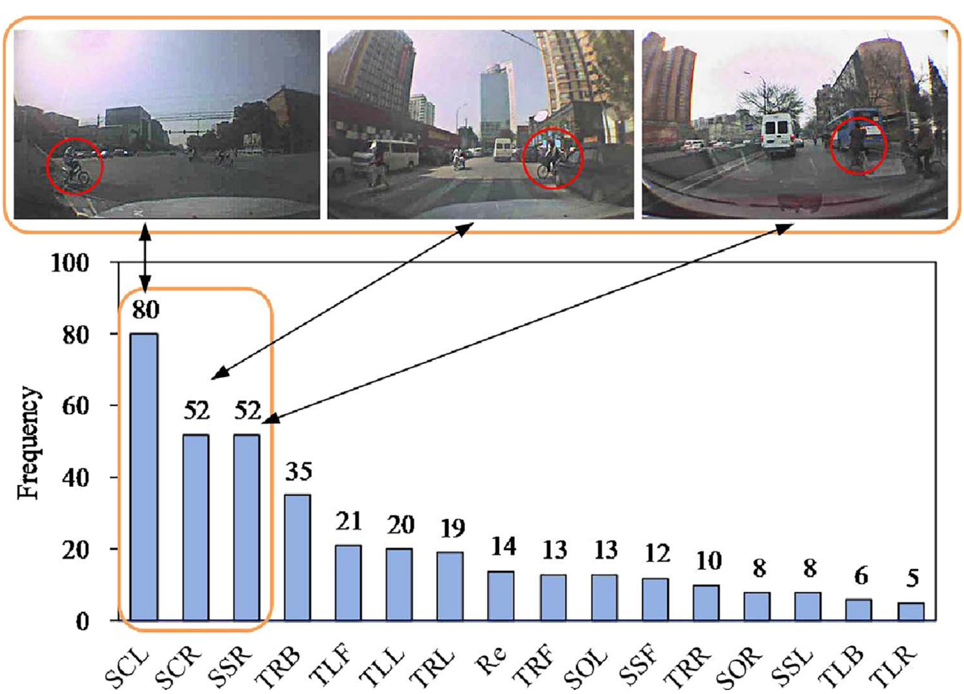


Fig. 1. Frequency distribution of V-B conflict scenarios from VDR dataset (SCL: going straight + cross direction + left; SCR: going straight + cross direction + right; SSR: going straight + same direction + right).

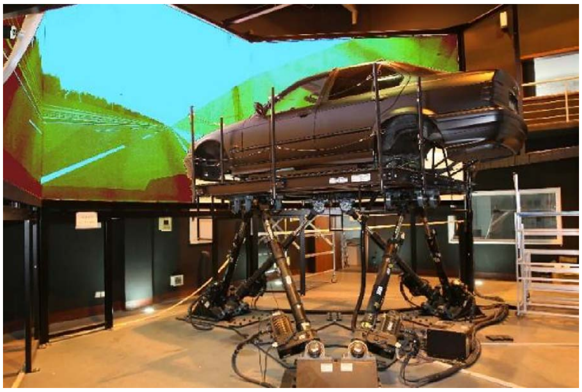


Fig. 2. Driving simulator.

3. Experiment

3.1. Driving simulator

The experiment was conducted in the high-fidelity driving simulator in Tsinghua University, as shown in Fig. 2 (Li et al., 2014; Liao et al., 2016). A passenger car (BMW sedan) is mounted on a six degree-of-freedom motion base, providing realistic driving experience to subjects. The angular and longitudinal moving range of the vehicle is ± 15° and ± 0.4 m, respectively. The simulator functions in the same way as real cars. The audio simulation unit contains a stereo speaker system to simulate the sound of engine, wind and traffic noises as in real driving. The driving scene is projected onto five screens: three for front view with a total of 200° field of view and two for rear view with a total of 55° field of view. Vehicle positions and driving performance data (speed, acceleration/deceleration, steering wheel angle, etc.) are logged at a frequency of 60 Hz.

3.2. Conflict reconstruction

The five types of V-B conflicts (SCR-R, SCR-S, SCL-R, SCL-S and SSR) were reconstructed in the driving simulator. The design of SCR-R conflict is illustrated in Fig. 3(a). A bicycle crosses the road at a speed of V_b = 3.5 m/s from the right side behind a stopped bus while the host vehicle is approaching. V_b is in accordance with the average bicycle speed in China (Liang, 2007). The stopped bus serves as a visual obstruction. The movement of the bicycle will be triggered when the instant TTC is lower than 1.5s. TTC is defined as the time to collision if the host vehicle maintains the current speed. In this scenario, TTC is calculated as $TTC = d/V_c$, where V_c is the instant vehicle speed and d is the longitudinal distance between the bicycle and the vehicle. The threshold was chosen based on the findings that a TTC below 2 s was considered dangerous and would give drivers a feeling of emergency (Minderhoud and Bovy, 2001; Vogel, 2003). In each scenario, the initial position of the bicycle was programmed to ensure that drivers can see the bicycle immediately after it is triggered. Oncoming traffic is presented in the opposite lane to imitate real traffic situations. The reconstruction of SCL-R conflict is similar to SCR-R (see Fig. 3(b)), except that the moving direction of the bicycle is reversed.

The design of SCR-S conflict is shown in Fig. 3(c). The host vehicle is starting at an intersection after the traffic light turns green, while a bicycle suddenly crosses at a speed of V_b = 3.5 m/s from the right front of an adjacent vehicle. The adjacent vehicle also serves as a visual obstruction. The bicycle's movement is triggered when the TTC is lower than 2 s or when the head of the host vehicle passes the stop line. The second condition is to ensure that the bicycle can be properly triggered in case that some drivers enter the intersection at a very low speed. The reconstruction of SCL-S conflict is similar to SCR-S (see Fig. 3(d)), except that the moving direction of the bicycle is reversed.

Fig. 3(e) illustrates the design of SSR conflict. The host vehicle is cruising while a bicyclist is riding along the bicycle path at a speed of V_b = 3.5 m/s. However, the bicycle path is obstructed by a stopped vehicle. The bicycle cuts into the lane of the host vehicle abruptly without noticing the potential danger. The cut-in movement is triggered when the TTC is lower than 2s. In this scenario, the TTC is calculated differently as $TTC = d/(V_c - V_b)$, because the host vehicle and the bicycle move at the same direction. Oncoming traffic in the opposite lane is also presented.

3.3. Subjects

25 drivers (21 men and 4 women) participated in the experiment. Their ages ranged from 21 to 51 (Mean = 32.4, SD = 10.9) with normal or corrected to normal vision. All the subjects had legal driving licenses, and their driving experience ranged from 1 to 25 years (Mean = 7.7, SD = 6.7).

3.4. Procedure

An urban traffic environment with signalized intersections was constructed in the driving simulator (see Fig. 4). The subjects were instructed to keep a cruising speed at around 40 km/h and behave normally at intersections. The distance between each adjacent intersections was 1000 m. The subjects would experience each type of conflict scenarios twice in a 3-trial driving task (10 conflicts in total). In each trial, the traffic environment was identical except for a change of the conflict locations. Besides, 20 similar but conflict-free scenarios were also presented in the three trials, which was to reduce the subjects' learning effects.

4. Data processing

In total, 218 valid samples were collected from the 250 recorded conflicts. The other 32 samples were discarded because the subject felt sick during the experiment. Driving performance data for each sample was collected within a 20 s interval, 10 s before and 10 s after the trigger of the bicycle. Two speed features were extracted to evaluate drivers' pre-decelerating behavior (Bella and Silvestri, 2015; Matsui et al., 2016). In addition, four brake features used in Green's (2000) and Wang et al.'s (2016) researches were extracted to evaluate drivers' emergency braking behavior. The feature definitions are given below:

- Speed features (see Fig. 5(a)):

a) Braking velocity (V_{brk}): the vehicle speed when a driver starts to apply pressure on the brake pedal (brake point).
b) Mean velocity (V_{mean}): the mean vehicle speed from the beginning of a recorded sample to the brake point moment.

- Brake features (see Fig. 5(b)):

a) Brake reaction time (BRT): the time interval from the movement trigger moment to the brake point moment.
b) Perception time (PT): the time interval from the movement trigger moment to the moment a driver releases the gas pedal (release point).
c) Movement time (MT): the time interval from the release point moment to brake point moment.
d) Brake time to 50% maximum brake pressure ($BT_{50\%}$): the time interval from the brake point moment to the moment the brake pressure reaches 50% of the maximum (50% brake pressure point).

For data analysis, the interquartile range (IQR) and boxplots were used to detect and eliminate outliers; mean value imputation was applied to estimate the missing value; repeated-measures general linear

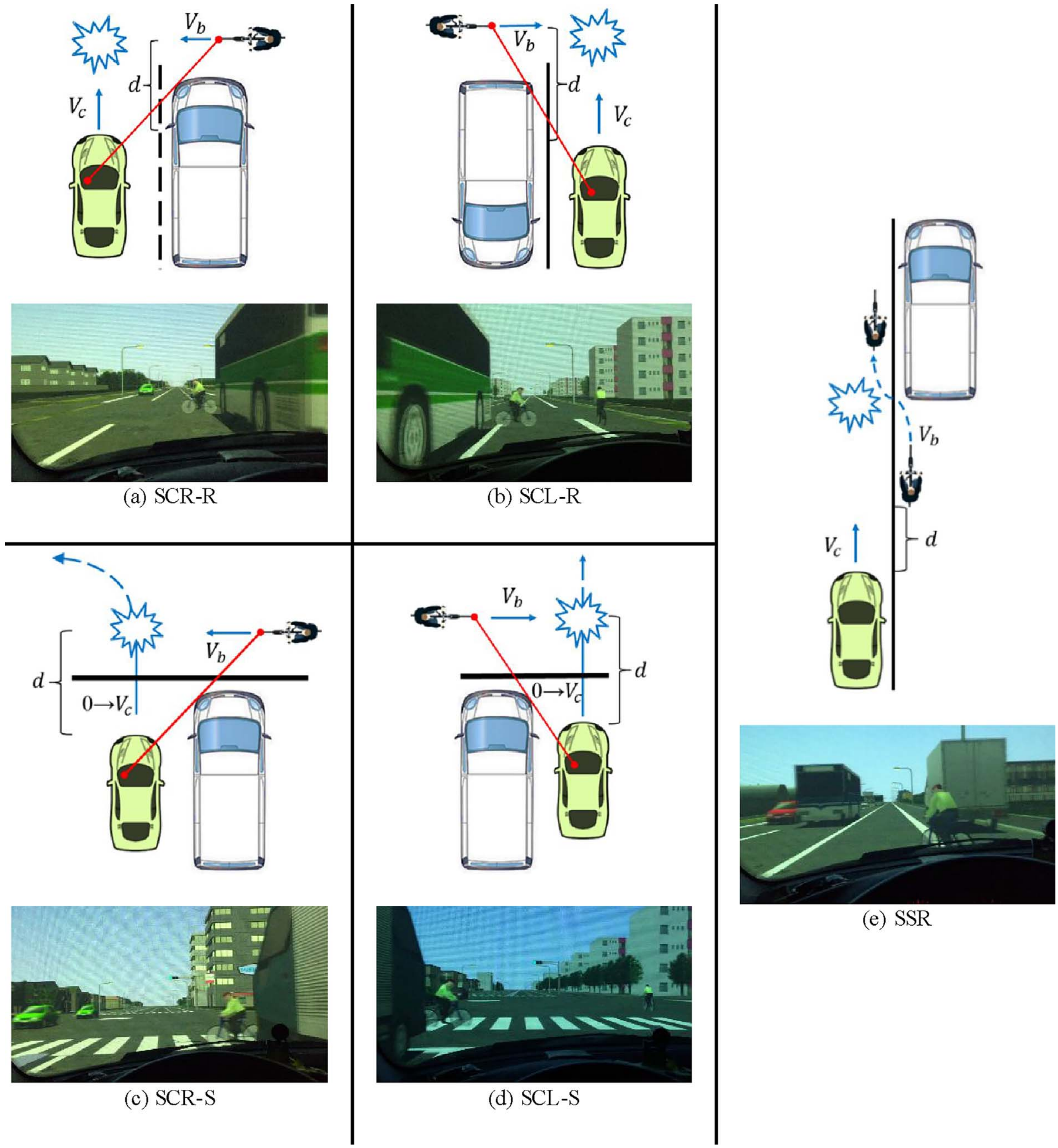


Fig. 3. Reconstruction of typical V-B conflicts (SCL-R/S: going straight + cross direction + left + running/starting; SCR-R/S: going straight + cross direction + right + running/starting; SSR: going straight + same direction + right).

model (GLM) was used to test the statistical significance; Greenhouse-Geisser correction was applied for models that violated the assumption of sphericity; Bonferroni adjustments were used for post hoc pairwise comparisons of means. The statistical significance level was chosen as $\alpha = 0.05$.

5. Results

5.1. Difference between mean velocity and braking velocity

Statistical difference between V_{mean} and V_{brk} was investigated to figure out whether there is a significant difference between the speed features in SCR-R, SCL-R and SSR conflicts. Pairwise comparison results are shown in Fig. 6(a). Results show that V_{mean} is significantly higher than V_{brk} in SCL-R ($p < 0.001$, Δ (mean difference) = 2.59 km/h) and SSR ($p = 0.004$, $\Delta = 2.65$ km/h). V_{mean} is also higher than V_{brk} in SCR-R, whereas the difference is not statistically significant ($p = 0.855$, $\Delta = 0.12$ km/h).

5.2. Brake reaction time (BRT)

Fig. 6(b) shows a significant influence of V-B conflict types on BRT ($F(2.710, 65.031) = 38.120$, $p < 0.001$). Post hoc analysis shows that the BRT in SCR-R (0.75s) is significantly shorter than that in SSR ($p < 0.001$, $\Delta = 0.39$s), but is not significantly different from that in SCL-R ($p = 1.000$, $\Delta < 0.01$s). The BRT in SCR-S (1.07s) is significantly longer than that in SCL-S ($p < 0.001$, $\Delta = 0.30$s). However, the difference of BRT is of no significance between SCL-R and SCL-S ($p = 1.000$, $\Delta = 0.02$s).

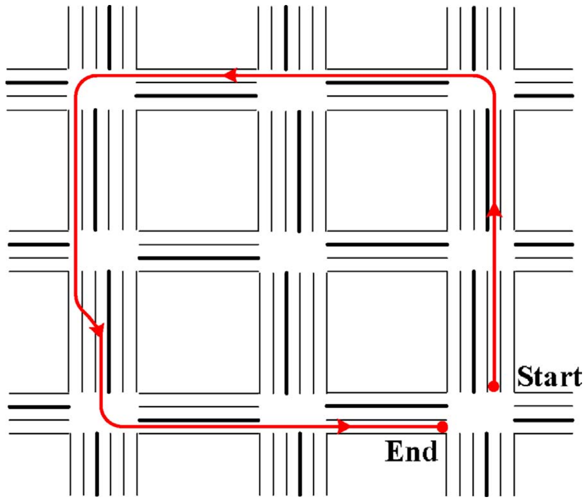


Fig. 4. Constructed road network and experiment route.

5.3. Perception time (PT)

Fig. 6(c) shows a significant influence of V-B conflict types on PT (F (2.293, 55.039) = 16.547, $p < 0.001$). Post hoc analysis shows that the PT in SCR-R (0.54s) is significantly shorter than that in SSR ($p < 0.001$, $\Delta = 0.32$s), but is not significantly different from that in SCL-R ($p = 1.000$, $\Delta = 0.02$s). The PT in SCR-S (0.69s) is significantly higher than that in SCL-S ($p = 0.012$, $\Delta = 0.21$s). However, the difference of PT is of no significance between SCL-R and SCL-S ($p = 0.054$, $\Delta = 0.08$s).

5.4. Movement time (MT)

Fig. 6(d) shows a significant influence of V-B conflict types on MT (F (2.563, 61.513) = 9.566, $p < 0.001$). Post hoc analysis shows that the MT in SCR-R (0.28s) is significantly shorter than that in SSR ($p = 0.010$, $\Delta = 0.09$s), but is not significantly different from that in SCL-R ($p = 1.000$, $\Delta = 0.01$s). In addition, the difference of MT is of no significance between SCR-S and SCL-S ($p = 0.214$, $\Delta = 0.08$s), and between SCL-R and SCL-S ($p = 0.287$, $\Delta = 0.04$s).

5.5. Brake time to 50% maximum pressure ($BT_{50\%}$)

Fig. 6(e) illustrates the significant analysis of $BT_{50\%}$. It shows a significant influence of V-B conflict types on $BT_{50\%}$ (F(2.326, 55.824) = 14.245, $p < 0.001$). Post hoc analysis shows that the $BT_{50\%}$ in SCR-R (0.19s) is significantly shorter than that in SSR ($p < 0.001$, $\Delta = 0.19$s), but is not significantly different from that in SCL-R ($p = 1.000$, $\Delta = 0.02$s). In addition, the difference of $BT_{50\%}$ is of no significance between SCR-S and SCL-S ($p = 0.139$, $\Delta = 0.07$s), and between SCL-R and SCL-S ($p = 0.322$, $\Delta = 0.06$s).

6. Discussion

6.1. Braking behavior and driver reaction time

The difference between V_{mean} and V_{brk} indicates how vigilant the subject was before he/she encountered a V-B conflict (Fuller, 1984; Matsui et al., 2016). If V_{mean} was higher than V_{brk}, it means the subject had intentionally throttled down as he/she anticipated the potential conflict. This pre-decelerating behavior can be regarded as a precautionary measure. As indicated in Section 5.1, pre-decelerating strategy was mostly adopted by the subjects in SCL-R and SSR conflicts. This is reasonable for SCL-R conflicts because a vehicle stopping on the left opposite lane was uncommon, making the subjects more vigilant of the potential dangers. On the contrary, the subjects involving in SCR-R situations would take a stopped vehicle in the rightmost lane as a common situation and a conflict is less expected. Therefore, V_{mean} and V_{brk} would not vary much in SCR-R conflicts. In SSR conflicts, the preceding bicycle was already in the subjects' field of view. Therefore, the subjects might anticipate a potential intrusion of the preceding bicycle and adopt pre-decelerating measures prior to the conflict. Bicycle visibilities may be one of the reasons causing this behavioral difference between SSR and SCR. This result is consistent with the previous findings that driver behavior in risky situations is influenced by their expectation of the potential danger (Summala et al., 1996; Räsänen and Summala, 1998; Werneke and Vollrath, 2012).

Furthermore, the result in Section 5.2 shows that the subjects' expectation would also influence their BRTs in V-B conflicts, but working in a different way as in pre-deceleration. For example, when the subjects were going to be involved in an imminent SSR conflict, they might have an anticipation on the potential cutting in of the preceding bicycle. However, according to their previous driving experience, the bicyclist would usually stop and check before they take a risky cutting-in action. Therefore, the subjects' expectation of a forward conflict was low. Differently in the SCR-R conflict, the subjects would take brake actions immediately after they found the crossing bicycle because their expectation of a collision is very high in such situations. Besides, we found from experiments that a cutting-in action is less perceptible than an abrupt lateral crossing from behind the obstruction. In other words, a lateral bicycle intrusion has a stronger visual impact than a longitudinal intrusion on the subjects. All these factors lead to the longer BRTs in SSR than in SCR-R conflicts. The longer BRT in SCR-S can be also attributed to the subjects' expectation. In SCR-S, the subjects would allocate more attention to the left as they were more aware of the potential risks in their target direction when they were turning (Wang and Abdel-Aty, 2008; Bao and Boyle, 2009; Werneke and Vollrath, 2012). Consequently, they failed to take an immediate response to the sudden intrusive bicycle from the right side. As per SAE J2944 (2015), BRT includes perception time (PT) and movement time (MT). The results in

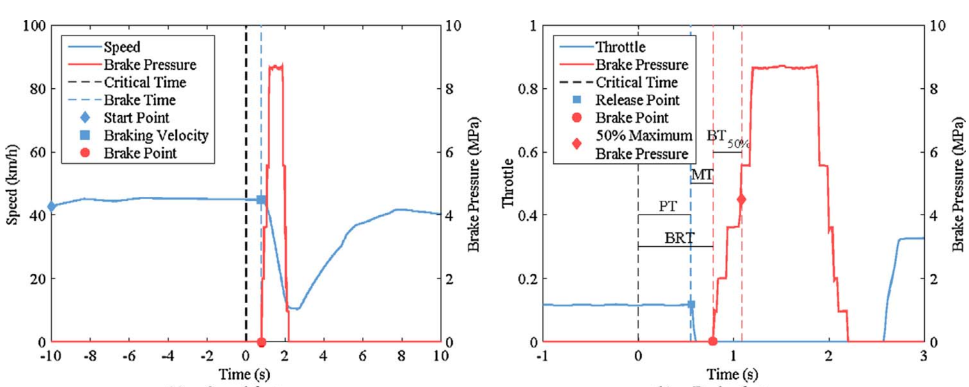


Fig. 5. Extracted features to evaluate drivers' braking behavior.

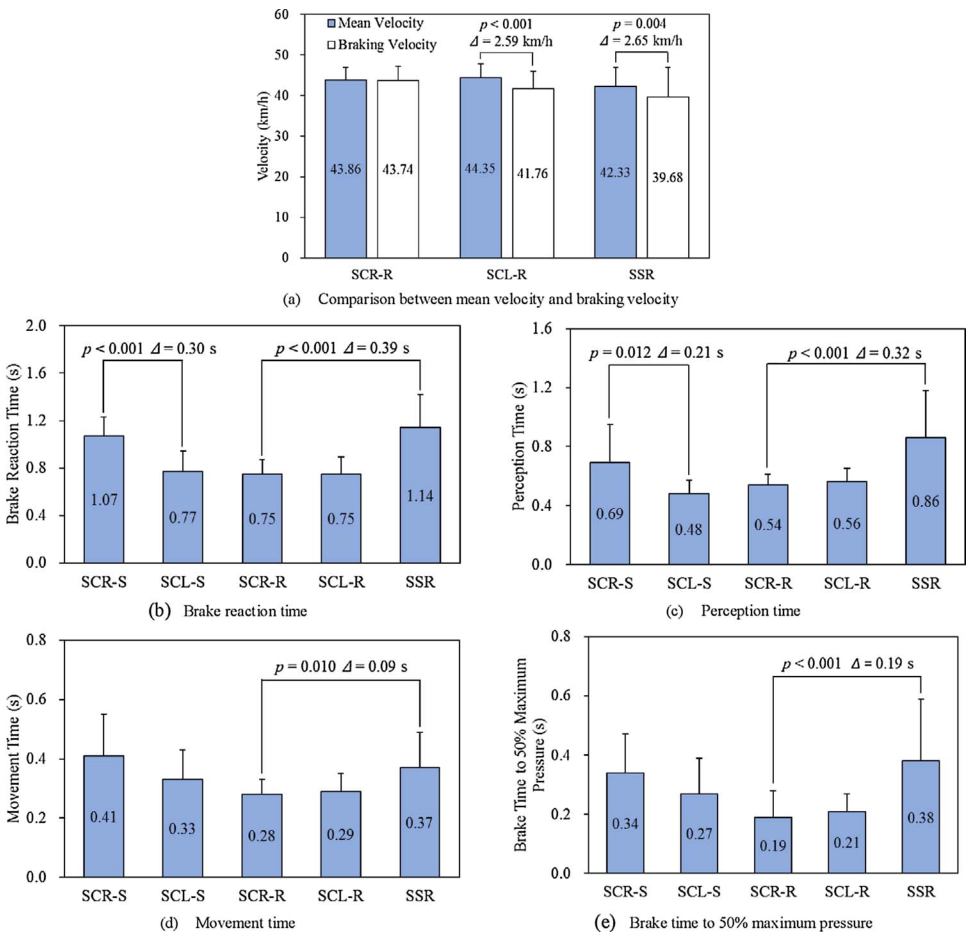


Fig. 6. Significant analysis of the features. (SCL-R/S: going straight + cross direction + left + running/starting; SCR-R/S: going straight + cross direction + right + running/starting; SSR: going straight + same direction + right).

this paper show that the subjects' PT varied much between different situations (0.47s ~ 0.88s, see Section 5.3), whereas MT was much more consistent (0.29s–0.40s, see Section 5.4). This result indicates that danger perception delay is the main contributing factor of the BRT variation in different situations.

$BT_{50\%}$ is a feature indicating how quickly a driver applies the brake pedal, i.e., brake severity (Wang et al., 2016). $BT_{50\%}$ implies drivers' subjective risk assessment of a conflict. According to Section 5.5, the subjects' perceived risk was higher in SCR-R conflicts than SSR conflicts. This suggests that a sudden lateral bicycle intrusion from visual occlusion gives drivers a stronger feeling of emergency. Similar results were also found in Chen et al. (2016)'s work stating that the average braking deceleration was larger when drivers were involved in lateral incidents. Higher relative speed and larger overlapping area may be other contributing factors of the shorter $BT_{50\%}$ in SCR-R (Chen et al., 2016).

6.2. Improvement of Bicyclist-AEB systems

Most conventional AEB systems are activated by comparing the real-time TTC with a predesigned threshold, denoted as TTC_b. It is usually computed by assuming a maximum deceleration under the current relative distance and velocity (Kusano and Gabler, 2012). Therefore, $TTC = TTC_b$ can be regarded as a critical moment to avoid an imminent forward collision. The braking strategy based on such a TTC condition is called conventional auto brake. Without any prior knowledge of the driver braking characteristics, this may be a conservative strategy to avoid collisions and to eliminate driver annoyance. However, if we include drivers' braking characteristics into the activation conditions, the intervention timing of Bicyclist-AEB systems can be advanced and situation-dependent.

Given the results in this paper, a new activation condition is proposed to advance the intervention timing of Bicyclist-AEB systems. The new criterion is denoted as T_b, which is typically chosen as the average (or some percentile of) driver BRT in a specific scenario. The corresponding activation condition is $T \geq T_b$, where T is the time from the beginning of a bicycle intrusion. This means that the Bicyclist-AEB will be activated if the driver does not take actions within the average BRT after an intrusive bicycle appears. A longer T_b indicates a more conservative strategy. Because T_b varies between different V-B conflict types, the automatic braking strategy based on this condition is called adaptive auto brake.

For practical applications on urban roads, a Bicyclist-AEB system would monitor the TTC and T after an intrusive bicycles appears (Li et al., 2018), and compare them with the corresponding TTC_b and T_b, respectively. If the TTC condition is met first, the conventional auto brake is activated (see Fig. 7(a)). Under such a circumstance, the AEB activation is irrelevant to the current conflict type and the prior knowledge of the driver's BRT. However, if $T \geq T_b$ is met first (adaptive auto brake), the activation timing will be earlier than conventional auto brake (see Fig. 7(b)). For adaptive auto brake, the activation timing is dependent on the current situation because T_b is correlated with driver's BRT distribution, which is situation-dependent as suggested by the results of this study. For example, if we use the average BRT from Fig. 6(b) as T_b, the adaptive auto brake activation condition is $T \geq 0.75$ s in SCR-R, $T \geq 1.14$ s in SSR, etc. Under this configuration, Bicyclist-AEB should be activated earlier in SCR-R if the adaptive auto brake works prior to conventional auto brake.

Besides the activation condition, drivers' braking severity and pre-decelerating behavior in different V-B conflicts can also be considered in Bicyclist-AEB design to make the system human-like. Comparatively, the conventional auto brake strategy is usually conservative, which

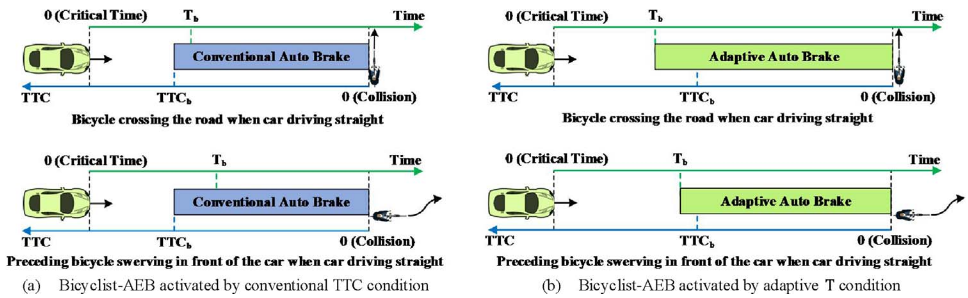


Fig. 7. Activation timing of Bicyclist-AEB systems.

affects its effectiveness and drivers' acceptance. The proposed adaptive auto brake strategy in this study is context-aware and will benefit drivers with timely actions in various V-B situations. In future applications in autonomous driving, driving style preference may also affect the activation timing of Bicyclist-AEB systems (Li et al., 2017).

7. Conclusion

In this paper, the top three scenarios of V-B (vehicle-bicycle) conflicts in China were extracted from naturalistic driving datasets. They were SCR (a bicycle crossing from the right side while the car is running straight), SCL (a bicycle crossing from the left side while the car is running straight) and SSR (a bicycle swerving in front of the car from the right side while the car is driving straight). This finding would provide suggestions for the development of Bicyclist-AEB test protocols in China.

These three scenarios were reconstructed in a driving simulator to investigate Chinese drivers' braking behavior in such situations. Results show that V-B conflict type has a significant influence on drivers' braking behavior. Pre-decelerating behaviors were found in SCL and SSR conflicts, which indicates that drivers are more vigilant in these scenarios as they expect a higher possibility of bicycle intrusion. The brake reaction time in lateral V-B conflicts (bicycle crossing the road) was averagely 0.39 s shorter than in longitudinal conflicts (preceding bicycle swerving in front of the car). This shows that drivers' expectation of a potential collision in lateral conflicts is higher and intrusive crossing bicycles are easier to perceive. The subjects' brake severity in lateral conflicts was higher than in longitudinal conflicts, which suggests that drivers have a stronger feeling of emergency when a bicycle suddenly crosses in front of the car.

Given the results, a method to design an adaptive Bicyclist-AEB system was proposed in this paper. This method integrates the prior knowledge of drivers' BRT in different types of V-B conflicts into the AEB activation conditions, which has the potential to advance the AEB intervention timing adaptively without annoying drivers.

In the future, we will examine whether scenario parameters (such as TTC), driver properties, traffic environment and road alignment would influence the braking behavior in different V-B conflicts. Also, the proposed method for Bicyclist-AEB improvement will be experimentally verified as well.

Acknowledgements

We would like to acknowledge Toyota Motor Corporation for their statistical works of the CIDAS database, and for their funds that made this project possible. This study is also supported by NSF China with U1664263, 51575293, 51577120 and 51622504, Natural Science Foundation of SZU (grant no. 2017033), National Key R & D Program in China with 2016YFB0100906, and International Sci & Tech Cooperation Program of China under 2016YFE0102200.

References

Bíl, M., Bílová, M., Müller, I., 2010. Critical factors in fatal collisions of adult cyclists with automobiles. Accid. Anal. Prev. 42, 1632–1636. http://dx.doi.org/10.1016/j.aap.2010.04.001.

Bao, S., Boyle, L.N., 2009. Age-related differences in visual scanning at median-divided highway intersections in rural areas. Accid. Anal. Prev. 41, 146–152. http://dx.doi.org/10.1016/j.aap.2008.10.007.

Bella, F., Silvestri, M., 2015. Effects of safety measures on driver's speed behavior at pedestrian crossings. Accid. Anal. Prev. 83, 111–124. http://dx.doi.org/10.1016/j.aap.2015.07.016.

Chen, Q., Chen, Y., Bostrom, O., Ma, Y., Liu, E., 2014. A Comparison Study of Car-to-Pedestrian and Car-to-E-Bike Accidents: Data Source: the China In-Depth Accident Study (CIDAS). http://dx.doi.org/10.4271/2014-01-0519.

Chen, M., Zhu, X., Ma, Z., Li, L., 2016. Driver Brake Parameters Analysis Under Risk Scenarios with Pedalcyclist. SAE Technical Paper.

Cheng, B., Lin, Q., Song, T., Cui, Y., Wang, L., Kuzumaki, S., 2011. Analysis of driver brake operation in near-crash situation using naturalistic driving data. Int. J. Automot. Eng. 2, 87–94.

Eichelberger, A.H., McCartt, A.T., 2014. Volvo drivers' experiences with advanced crash avoidance and related technologies. Traffic Inj. Prev. 15, 187–195. http://dx.doi.org/10.1080/15389588.2013.798409.

Fildes, B., Keall, M., Bos, N., Lie, A., Page, Y., Pastor, C., Pennisi, L., Rizzi, M., Thomas, P., Tingvall, C., 2015. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. Accid. Anal. Prev. 81, 24–29. http://dx.doi.org/10.1016/j.aap.2015.03.029.

Fredrikson, R., Fredriksson, K., Strandroth, J., 2014. Pre-crash motion and conditions of bicyclist-to-car crashes in Sweden. International Cycling Safety Conference.

Fuller, R., 1984. A conceptualization of driving behaviour as threat avoidance. Ergonomics 27, 1139–1155. http://dx.doi.org/10.1080/00140138408963596.

Green, M., 2000. How long does it take to stop? methodological analysis of driver perception-brake times. Transp. Hum. Factors 2, 195–216. http://dx.doi.org/10.1207/STHF0203_1.

Heinen, E., Maat, K., 2011. The role of attitudes toward characteristics of bicycle commuting on the choice to cycle to work over various distances. Transp. Res. Part Transp. Environ. 16, 102–109. http://dx.doi.org/10.1016/j.trd.2010.08.010.

Huang, H., Wang, X., Hu, G., 2016. Traffic safety in China: challenges and countermeasures. Accid. Anal. Prev. 305–307. http://dx.doi.org/10.1016/j.aap.2016.07.040.

Kusano, K.D., Gabler, H.C., 2012. Safety benefits of forward collision warning, brake assist, and Autonomous Braking Systems in Rear-End Collisions. IEEE Trans. Intell. Transp. Syst. 13, 1546–1555. http://dx.doi.org/10.1109/TITS.2012.2191542.

Li, G., Wang, W., Li, S.E., Cheng, B., Green, P., 2014. Effectiveness of flashing brake and hazard systems in avoiding rear-end crashes. Adv. Mech. Eng. 6, 792670. http://dx.doi.org/10.1155/2014/792670.

Li, G., Li, S.E., Cheng, B., 2015. Field operational test of advanced driver assistance systems in typical Chinese road conditions: the influence of driver gender, age and aggression. Int. J. Automot. Technol. 16, 739–750. http://dx.doi.org/10.1007/s12239-015-0075-5.

Li, G., Li, S.E., Cheng, B., Green, P., 2017. Estimation of driving style in naturalistic highway traffic using maneuver transition probabilities. Transp. Res. Part C Emerg. Technol. 74, 113–125. http://dx.doi.org/10.1016/j.trc.2016.11.011.

Li, S.E., Li, G., Yu, J., Liu, C., Cheng, B., Wang, J., Li, K., 2018. Kalman filter-based tracking of moving objects using linear ultrasonic sensor array for road vehicles. Mech. Syst. Signal Pr. 98, 173–189. http://dx.doi.org/10.1016/j.ymssp.2017.04.041.

Liang, C., 2007. Study on Characteristic and Application of Bicycle Traffic Flow. Jilin University (in Chinese).

Liao, Y., Li, S.E., Wang, W., Wang, Y., Li, G., Cheng, B., 2016. Detection of driver cognitive distraction: a comparison study of stop-controlled intersection and speed-limited highway. IEEE Trans. Intell. Transp. Syst. 17, 1628–1637. http://dx.doi.org/10.1109/TITS.2015.2506602.

Matsui, Y., Oikawa, S., Hitosugi, M., 2016. Analysis of car-to-bicycle approach patterns for developing active safety devices. Traffic Inj. Prev. 17, 434–439. http://dx.doi.org/10.1080/15389588.2015.1087641.

Minderhoud, M.M., Bovy, P.H.L., 2001. Extended time-to-collision measures for road traffic safety assessment. Accid. Anal. Prev. 33, 89–97. http://dx.doi.org/10.1016/S0001-4575(00)00019-1.

National Bureau of Statistics of China, 2015. China Statistical Year Book 2015. China Stat. Press, Beijing.

Nie, J., Yang, J., 2014. A study of bicyclist kinematics and injuries based on reconstruction of passenger car-bicycle accident in China. Accid. Anal. Prev. 71, 50–59. http://dx.doi.org/10.1016/j.aap.2014.04.021.

Op den Camp, O., Ranjbar, A., Uittenbogaard, J., Rosen, E., Buijssen, S., 2014. Overview of main accident scenarios in car-to-cyclist accidents for use in AEB-system test protocol. Proceedings of International Cycling Safety Conference.

Pucher, J., Buehler, R., Seinen, M., 2011. Bicycling renaissance in North America? An update and re-appraisal of cycling trends and policies. Transp. Res. Part Policy Pract. 45, 451–475. http://dx.doi.org/10.1016/j.tra.2011.03.001.

Räsänen, M., Summala, H., 1998. Attention and expectation problems in bicycle-car collisions: an in-depth study. Accid. Anal. Prev. 30, 657–666. http://dx.doi.org/10.1016/s0001-4575(98)00007-4.

Silvano, A.P., Ma, X., Koutsopoulos, H.N., 2015. When do drivers yield to cyclists at unsignalized roundabouts? Transp. Res. Rec. J. Transp. Res. Board 2520, 25–31. http://dx.doi.org/10.3141/2520-04.

Society of Automotive Engineers,, 2015. Operational Definitions of Driving Performance Measures and Statistics (recommended Practice J2944). Society of Automotive Engineers, Warrendale, PA.

Summala, H., Pasanen, E., Räsänen, M., Sievänen, J., 1996. Bicycle accidents and drivers' visual search at left and right turns. Accid. Anal. Prev. 28, 147–153. http://dx.doi.org/10.1016/0001-4575(95)00041-0.

Summala, H., 2000. Brake reaction times and driver behavior analysis. Transp. Hum. Factors 2, 217–226. http://dx.doi.org/10.1207/STHF0203_2.

Vogel, K., 2003. A comparison of headway and time to collision as safety indicators. Accid. Anal. Prev. 35, 427–433. http://dx.doi.org/10.1016/S0001-4575(02)00022-2.

Wang, X., Abdel-Aty, M., 2008. Modeling left-turn crash occurrence at signalized intersections by conflicting patterns. Accid. Anal. Prev. 40, 76–88. http://dx.doi.org/10.1016/j.aap.2007.04.006.

Wang, X., Zhu, M., Chen, M., Tremont, P., 2016. Drivers' rear end collision avoidance behaviors under different levels of situational urgency. Transp. Res. Part C Emerg. Technol. 71, 419–433. http://dx.doi.org/10.1016/j.trc.2016.08.014.

Werneke, J., Vollrath, M., 2012. What does the driver look at? The influence of intersection characteristics on attention allocation and driving behavior. Accid. Anal. Prev. 45, 610–619. http://dx.doi.org/10.1016/j.aap.2011.09.048.

Wood, J.M., Lacherez, P.F., Marszalek, R.P., King, M.J., 2009. Drivers' and cyclists' experiences of sharing the road: incidents, attitudes and perceptions of visibility. Accid. Anal. Prev. 41, 772–776. http://dx.doi.org/10.1016/j.aap.2009.03.014.

Wu, C., Yao, L., Zhang, K., 2012. The red-light running behavior of electric bike riders and cyclists at urban intersections in China: an observational study. Accid. Anal. Prev. 49, 186–192. http://dx.doi.org/10.1016/j.aap.2011.06.001.

Xu, J., 2015. Getting Back on the Bike. [WWW Document] http://epaper.chinadailyasia.com/asia-weekly/article-4732.html (accessed 10.8.16).

Yan, X., Ma, M., Huang, H., Abdel-Aty, M., Wu, C., 2011. Motor vehicle-bicycle crashes in Beijing: irregular maneuvers, crash patterns, and injury severity. Accid. Anal. Prev. 43, 1751–1758. http://dx.doi.org/10.1016/j.aap.2011.04.006.

Yang, Y., Liu, X., 2017. China's Bike-sharing Boom in Charts. [WWW Document]. https://www.ft.com/content/5efe95f6-0aeb-11e7-97d1-5e720a26771b (Accessed 5.22.17).

Zahabi, S., Strauss, J., Manaugh, K., Miranda-Moreno, L., 2011. Estimating potential effect of speed limits, built environment, and other factors on severity of pedestrian and cyclist injuries in crashes. Transp. Res. Rec. J. Transp. Res. Board 2247, 81–90. http://dx.doi.org/10.3141/2247-10.