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Evaluating impacts of different longitudinal driver assistance systems on reducing multi-vehicle rear-end crashes during small-scale inclement weather

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ABSTRACT

Multi-vehicle rear-end (MVRE) crashes during small-scale inclement (SSI) weather cause high fatality rates on freeways, which cannot be solved by traditional speed limit strategies. This study aimed to reduce MVRE crash risks during SSI weather using different longitudinal driver assistance systems (LDAS). The impact factors on MVRE crashes during SSI weather were firstly analyzed. Then, four LDAS, including Forward collision warning (FCW), Autonomous emergency braking (AEB), Adaptive cruise control (ACC) and Cooperative ACC (CACC), were modeled based on a unified platform, the Intelligent Driver Model (IDM). Simulation experiments were designed and a large number of simulations were then conducted to evaluate safety effects of different LDAS. Results indicate that the FCW and ACC system have poor performance on reducing MVRE crashes during SSI weather. The slight improvement of sight distance of FCW and the limitation of perception-reaction time of ACC lead the failure of avoiding MVRE crashes in most scenarios. The AEB system has the better effect due to automatic perception and reaction, as well as performing the full brake when encountering SSI weather. The CACC system has the best performance because wireless communication provides a larger sight distance and a shorter time delay at the sub-second level. Sensitivity analyses also indicated that the larger number of vehicles and speed changes after encountering SSI weather have negative impacts on safety performances. Results of this study provide useful information for accident prevention during SSI weather.

1. Introduction

An increasing number of vehicles travel on freeways in many countries, resulting in not only congestions but also accidents. Freeway crashes cause heavy losses of life and property. Among these accidents, one type of crash, rear-end crash, accounts for a large proportion. According to reports (Wang et al., 2016a), around 32% of all crashes belong to rear-end crashes in the US (Traffic Safety Facts, 2013). In other countries, this type of crash also accounts for a tremendous proportion, such as 35% in Japan (Watanabe and Ito, 2007a,b) and about 20% in Shanghai, China (Wang et al., 2011). Rear-end crashes usually occur when the following vehicle's speed is higher than that of the leading one. Besides speed differences, headway between two successive vehicles, perception-reaction time and brake force of the following vehicles are also crucial factors (Winsum and Heino, 1996; Abdel-Aty and Abdelwahab, 2003; Wang et al., 2016a).

In inclement weather, vehicles have the higher possibility to involve rear-end crashes. The inclement weather has significant impacts on car-following behaviors, which has been extensively studied. Asamer et al. (2013) introduced car-following behaviors change significantly on snowy road conditions, such as accelerating more slowly, increasing following distance and driving with lower speeds. Hamdar et al. (2016) utilized a driving simulator to conduct 76 driving experiments for analyzing impacts of weather and road geometry on longitudinal driving behavior. Wu et al. (2017) utilized real-time traffic and weather data and a general algorithm to investigate impact of car-following behaviors under fog conditions and shown a higher probability. Gao et al. (2017) investigated impacts of low visibility under hazy weather condition on different car-following stages by using a high fidelity driving simulator. All of these studies indicated a negative impact of inclement weather on car-following behavior. Inclement weather, such as fog, heavy rain and snow, cause insufficient visibility and terrible road surface condition. Drivers cannot detect preceding vehicles timely and need more perception-reaction time under adverse weather. When

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they perceive crash risks, crashes cannot be avoided due to the weak braking forces caused by wet road surfaces. Thus, rear-end crash risks are higher under various inclement weather (Khattak et al., 1998; Khattak and Knapp, 2001; Strong et al., 2010; Theofilatos and Yannis, 2014; Li et al., 2014).

Up to now, speed limit is the major countermeasure to reduce rear-end crashes under inclement weather. Through limiting maximum speeds on the whole roadways, drivers have to maintain low velocities and thus have enough distances to react and brake. In addition to speed limit, a more dynamic control method, variable speed limit (VSL) strategy, has also been extensively applied. The VSL control makes a proactive intervention by adjusting maximum speed limit and gradually reduces vehicles' speeds in the upstream road. A variety of VSL control strategies have been proposed to deal with safety problems under inclement weather (FHWA, 2012; Li et al., 2014; Choi and Oh, 2016). And these strategies are also applied all over the world, such as the US, the Australia and Netherland (see a detailed summary in the study of Li et al., 2014).

Although traffic safety under adverse weather have been effectively improved with various speed controls, the multi-vehicle rear-end (MVRE) crashes during small-scale inclement (SSI) weather have been unsolved. The SSI weather is the adverse weather occurs in a local area, such as the agglomerate fog. On the one hand, it is impossible to forecast these weather' location and occurrence time precisely. Hence, the speed limit controls used for the large-scale adverse weather cannot be applied for that condition. It is unreasonable to limit all vehicles' velocities in the entire freeway all the time to avoid a SSI weather related crash occurring in a random time and location. On the other hand, if the SSI weather occurs suddenly, the visibilities and road surface conditions in a local area often severely deteriorate in a short period. The poor driving environment can lead to an initial accident with high possibility. And due to the poor visibilities and road surface conditions, vehicles in the upstream road cannot be warned the initial accident and react timely, which always causes the more severe MVRE crashes. Therefore, the MVRE crashes are catastrophic with very high fatality rates, as illustrated in a summary of a part of MVRE crashes under SSI weather in recent five years in China (see Table 1) (BaiduBaike, 2016; CHINA GOV, 2016).

Under the SSI weather, the traditional speed control strategies, including VSL control, may not avoid MVRE crashes effectively. It is because the MVRE crashes often occur suddenly in a normal traffic condition that the VSL control is not activated until. Therefore, new countermeasures should be applied to solve this problem. Recently, with rapid development of the advanced sensor and automatic control technologies, the longitudinal driver assistance systems (LDAS) have drawn attentions of researchers. The LDAS use radars, lasers or wireless communications to detect traffic information of the preceding vehicles and automatically react at the different level to improve longitudinal car-following process. Almost all the previous safety studies about LDAS are focused on system effectiveness, in which two major methods are included. The first one is to evaluate safety effectiveness of LDAS by models or simulators, when the real-world data of these systems are not available. For instance, Touran et al. (1999) proposed a general framework to evaluate effects of autonomous intelligent cruise control on rear-end crashes. Results indicated it could significantly reduce collision probability given the model assumptions. The similar modeling and simulation methods were used by Li et al. (2017a,c) to analyze safety effects of adaptive cruise control (ACC) systems and cooperative ACC (CACC) systems. Bálint et al. (2013) established a test-based method to assess the effectiveness of pre-crash warning and braking systems. Jeong et al. (2017) used VISSIM software to analyze safety effects of automated driving with different market penetration rates and demonstrated the signification improvement of the system. Jeong and Oh (2017) proposed that strategies considering both traffic conditions and market penetration rate (MPR) are necessary to fully exploit the effectiveness of active vehicle safety systems. Ehlers et al. (2017) proposed a useful tool for safety estimation of cooperative intelligent system called bowtie analysis. On the other hand, Ho et al. (2006) demonstrated the effectiveness of a vibrotactile warning signal in reducing front-to-rear-end crashes by comparing responses of participants in a driving simulator. Schleicher and Gelau (2011) used a simulator driven by twenty-two participants to analyze influence of ACC system on driving behavior. Results in their study indicated the system could lead to a better compliance of speed limits. Schwarz and Fastenmeier (2017) investigated effects of modality and specificity on warning effectiveness by a driving simulator.

Table 1
Summary of a part of MVRE crashes during SSI weather in recent five years in China.

Date	Location	Number of vehicles In crashes	Casualty
2/11/2012	NingHang Freeway	30	8
4/15/2012	ShenHai Freeway	–	16
5/28/2012	JingZhu Freeway	–	21
6/3/2012	ShenHai Freeway	60	41
10/20/2012	TangJin Freeway	60	20
6/4/2013	JingGang Freeway	56	14
11/29/2015	DaYung Freeway	47	10
4/2/2016	HuNing Freeway	50	34
11/3/2016	XingFeng Freeway	21	8
11/21/2016	JingKun Freeway	56	54

'–' represents for no precise data provided.

The second method is using real-world data, such as reported-crash data associated with LDAS to evaluate effectiveness. Jermakian (2011) estimated potential crash reductions of forward collision warning (FCW) using crash records and shown a great potential effectiveness of this system. Wege et al. (2013) investigated eye movement reactions of drivers using natural driving data from the Volvo euroFOT database, which showed the brake-capacity FCW system could lead to drivers' immediate attention allocation toward the roadway event. Cicchino (2017) investigated effectiveness of FCW and autonomous emergency braking (AEB) systems by comparing rates of police-reported crash involvements per insured vehicle year in 22 U.S. states during 2010–2014, finding reductions of 27%, 43% and 50% of rear-end striking crash involvement rates of FCW, low-speed AEB and FCW with AEB, respectively. Fildes et al. (2015) evaluated the effectiveness of low speed AEB system using real-world crash experience, supplying an indication on a 38% overall reduction in rear-end crashes compared to similar vehicles without this system. There are likewise several studies investigating factors or conditions affecting the safety effectiveness of LDAS (Staubach, 2009; Rosén et al., 2010; Huth and Gelau, 2013; Lenard et al., 2014; Searson et al., 2014; Ruscio et al., 2015, 2017).

Although safety effects of different LDAS have been extensively researched, to our best knowledge, there has not been any studies about using LDAS to reduce MVRE crashes during SSI weather. Due to the lesser impact on radars or wireless communications by SSI weather, the LDAS may improve the visibility of vehicles (not of drivers). More importantly, the automatic reactions of these systems can reduce perception-reaction time significantly, which is also beneficial for safety. Thus, it is possible to use these advanced technologies to avoid MVRE crashes during SSI weather. Two crucial questions are supposed to be investigated before the application: 1) how does the SSI weather affect MVRE crashes; 2) how does different LDAS affect MVRE crashes during SSI weather? The first question focuses on the impact factors of the MVRE crashes during SSI weather. And the second one focuses on impacts of designs and parameters of different LDAS on improving safety. These investigations will provide useful information for LDAS technologies' developments and applications on reducing MVRE crashes in the future. It is also significant for developing policies related to LDAS, such as popularizing or standardizing applications of these LDAS in the areas with recurrent SSI weather.

Thus, the primary objective of this study is to evaluate impacts of