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Longitudinal safety evaluation of connected vehicles' platooning on expressways

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ABSTRACT

Connected vehicles (CV) technology has recently drawn an increasing attention from governments, vehicle manufacturers, and researchers. One of the biggest issues facing CVs popularization associates it with the market penetration rate (MPR). The full market penetration of CVs might not be accomplished recently. Therefore, traffic flow will likely be composed of a mixture of conventional vehicles and CVs. In this context, the study of CV MPR is worthwhile in the CV transition period. The overarching goal of this study was to evaluate longitudinal safety of CV platoons by comparing the implementation of managed-lane CV platoons and all lanes CV platoons (with same MPR) over non-CV scenario. This study applied the CV concept on a congested expressway (SR408) in Florida to improve traffic safety. The Intelligent Driver Model (IDM) along with the platooning concept were used to regulate the driving behavior of CV platoons with an assumption that the CVs would follow this behavior in real-world. A high-level control algorithm of CVs in a managed-lane was proposed in order to form platoons with three joining strategies: rear join, front join, and cut-in joint. Five surrogate safety measures, standard deviation of speed, time exposed time-to-collision (TET), time integrated time-to-collision (TIT), time exposed rear-end crash risk index (TERCRI), and sideswipe crash risk (SSCR) were utilized as indicators for safety evaluation. The results showed that both CV approaches (i.e., managed-lane CV platoons, and all lanes CV platoons) significantly improved the longitudinal safety in the studied expressway compared to the non-CV scenario. In terms of surrogate safety measures, the managed-lane CV platoons significantly outperformed all lanes CV platoons with the same MPR. Different time-to-collision (TTC) thresholds were also tested and showed similar results on traffic safety. Results of this study provide useful insight for the management of CV MPR as managed-lane CV platoons.

1. Introduction

The development of information and communication technologies have facilitated connected vehicle (CV) technologies, in which vehicles communicate with other vehicles (V2V), roadway infrastructure (V2I), and pedestrians (V2P) in real-time. CV is regarded as one of the most promising methods to improve traffic safety. According to the National Highway Traffic Safety Administration (NHTSA), at a full V2V adoption, CV technology will annually prevent 439,000–615,000 crashes (NHTSA, 2016). Nevertheless, the full market penetration rate (MPR) of CV will not be accomplished recently (NHTSA, 2016). Hence, traffic flow will be a mixture of conventional vehicles and CVs. Some studies have found that the efficiency of CV technologies is heavily decided by the CV MPR (Lee et al., 2013; Paikari et al., 2014; Talebpour and Mahmassani, 2016; Yang et al., 2016). Thus, in the CV transition period, studying the MPR on the safety impact of CV technology is needed.

Vehicle platooning with CV technology is another key element of the future transportation systems which help us to enhance traffic operations and safety simultaneously. Recent research (Tian et al., 2016) proposed a stochastic model to evaluate the collision probability for the heterogeneous vehicle platooning which can deal with the inter-vehicle distance distribution. The results showed great potential in decreasing the chain collisions and alleviating the severity of chain collisions in the platoon at the same time. The platoon-based driving may significantly improve traffic safety and efficiency because a platoon has closer headways and lower speed variations compared to traditional traffic flow. The platoon-based cooperative driving system has been widely studied. However, there have not been enough studies that allocate managed-lane CV platoons which is highly related to CV MPR. The safety benefits of managed-lane CV platoons are expected to be positive because of the dissociation of conventional vehicles and CVs in the

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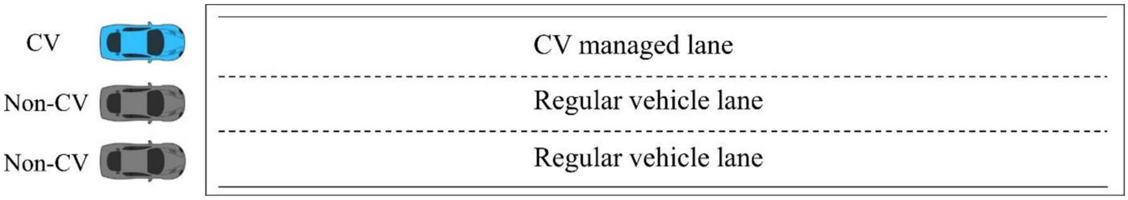

Fig. 1. Illustration of CV managed lane and regular vehicle lane.

same lane. Most of the research in CV technology were related to the implementation of CV in all the lanes of the entire roadway with different MPRs. However, until this point, no researcher has potentially analyzed the managed-lane CV platoons which are expected to decrease the crash risk. Fig. 1 illustrates the managed-lane CV concept along with the regular vehicles' lanes.

The overarching goal of this study was to evaluate the longitudinal safety evaluation of managed-lane CV platoons on a congested expressway. To have better understanding of managed-lane CV effectiveness, this study selected a congested expressway SR408 which has 17 weaving segments. The simulation experiments are first designed, including deployment of both CV platoons as managed-lane and all lanes in this expressway. Then, a driving behavior model for CVs along with the platooning concept were used with an assumption that the CVs would follow this driving behavior in real-world. Five surrogate safety measures, standard deviation of speed, time exposed time-to-collision (TET), time integrated time-to-collision (TIT), time exposed rear-end crash risk index (TERCRI), and sideswipe crash risk (SSCR) were utilized as indicators for safety evaluation. Sensitivity analysis were also conducted for the different time-to-collision (TTC) thresholds. Results of this study provide useful information for expressway safety when CVs are applied as managed-lane concept for the management of CV MPR in the near future.

2. Data preparation

A congested expressway Holland East-West Expressway (SR408) in Orlando, Florida was selected as a testbed for this study. The testbed was a 22-miles section of SR408 with 17 weaving segments from West Colonial Drive, Orlando to Challenger Parkway, Orlando. This expressway is monitored by Microwave Vehicle Detection System (MVDS), and almost all ramps have an MVDS detector to provide ramp traffic information. MVDS indicates the basic traffic characteristics of the selected road segment. The study area along with the MVDS detectors is shown in Fig. 2.

The collected traffic dataset contains seven important variables including volume, speed, and lane occupancy for each lane at 1 min interval, and also categorizes vehicles into four types according to their length; type 1: vehicles 0 to 3 m in length, type 2: vehicles 3–7.5 m in length, type 3: vehicles 7.5–16.5 m in length, type 4: vehicles over 16.5 m in length. In this study, vehicles were classified into two categories: (1) passenger car (PC) and (2) heavy goods vehicle (HGV). A vehicle was considered as a passenger car (PC) if its length is equal to or less than 7.5 m (type 1 and type 2). The traffic data were collected from MVDS detectors installed in the above-mentioned areas (Fig. 2).

3. VISSIM simulation model and calibration

A well calibrated and validated VISSIM network replicating the field condition is the prerequisite of microsimulation based study. Simulations were conducted in PTV VISSIM, version 9.0. The testbed was around 22-miles section of SR 408. The traffic information on the simulation network including, traffic volume aggregated into 5 min intervals, PC and HGV percentages, and desired speed distribution were obtained from the MVDS detectors. The simulation time was set from 6:30 A.M. to 9:30 A.M in VISSIM. After excluding first 30 min of VISSIM warm up time and last 30 min of cool-down time, 180 min VISSIM data was used for calibration and validation. Geoffrey E. Heavers (GEH) statistic was used to compare the field volumes with simulation volumes. The GEH statistic is a modified Chi-square statistic that takes into account both the absolute difference and the percentage difference between the modelled and the observed flows. The definition of GEH is as follows,

$$GEH = \sqrt{\frac{2 \times (M_{obs}(n) - M_{sim}(n))^2}{(M_{obs}(n) + M_{sim}(n))}} \tag{1}$$

Where $M_{obs}(n)$ is the observed volume from field detectors and $M_{sim}(n)$ is the simulated

$M_{obs}(n) M_{sim}(n)$volume obtained from the simulation network. The simulated volume would precisely reflect the field volume if more than 85% of the measurement locations GEH values are less than five (Wang et al., 2017; Yu and Abdel-Aty, 2014). It is worth mentioning that, for GEH $<$ 5, flows can be considered a good fit; for 5 $<$ GEH $<$ 10, flow may require further investigation; and for 10 $<$ GEH, flow cannot be considered a good fit. To validate the simulation network, average speeds from the field and simulation have been utilized. Mean, minimum, and maximum values of the average speeds from in-field detectors were calculated. As for speed, the absolute speed difference between simulated speeds and field speeds should be within five mph for more than 85% of the checkpoints (Nezamuddin et al., 2011). The simulated traffic volumes and speeds were aggregated to 5 min intervals and then compared with the corresponding field traffic data. Ten simulation runs with different random seeds worth of results showed that 93.23% of observed GEHs were less than five, and 92.92% of the aggregated speeds in the simulation were within five mph of field speeds. The results above proved that the traffic calibration and validation satisfy the requirements, and indicate that the network was consistent with that of the field traffic conditions.

Traffic safety deteriorated significantly in weaving segments compared to non-weaving segments which increase crash risk in weaving segments (Glad, 2001; Golob et al., 2004; Kim and Park, 2016; Pulugurtha and Bhatt, 2010). So, there was a need to revalidate the weaving segment VISSIM network with respect to both traffic and safety. To simplify the further validation process, a sensitivity analysis was conducted on VISSIM driver behavior parameters in simulation models to reflect the weaving segments condition. Based on the literature review, six parameters were chosen for VISSIM calibration and validation for weaving segments (Jolovic and Stevanovic, 2012; Koppula, 2002; Woody, 2006; Wu et al., 2005). They were DLCD (desired lane change distance), CC0 (standstill distance), CC1 (headway time), CC2 (following variation), waiting time per diffusion, and safety distance reduction factor. For each parameter, a range of values (9 values), which includes the default, was determined based on previous study and engineering judgment (Habtemichael and Picado-Santos, 2013). A total of 490 simulation runs [(1 base-models + 6 × 8 car-following parameters) times 10 random seeds] were conducted. Toward this end, the standard deviation of speed was selected in order to compare the field and simulated values with two-sample *t*-test at the 5% significance level. For sensitivity analysis, standard deviation of speed was calculated in 5 min of each run and compared it with the corresponding field standard deviation of speed in 5 min by two sample *t*-test. For each value of parameters, the results of *t*-test with 10 different