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Longitudinal safety evaluation of electric vehicles with the partial wireless charging lane on freeways

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ABSTRACT

As an environment friendly transportation mode, the electric vehicle (EV) has drawn an increasing amount of attention from governments, vehicle manufactories and researchers recently. One of the biggest issue impeding EV's popularization associates with the charging process. The wireless charging lane (WCL) has been proposed as a convenient charging facility for EVs. Due to the high costs, the application of WCL on the entire freeways is impractical in the near future, while the partial WCL (PWCL) may be a feasible solution. This study aims to evaluate longitudinal safety of EVs with PWCL on freeways based on simulations. The simulation experiments are firstly designed, including deployment of PWCL on freeways and distribution of state of charge (SOC) of EVs. Then, a vehicle behavior model for EVs is proposed based on the intelligent driver model (IDM). Two surrogate safety measures, derived from time-to-collision (TTC), are utilized as indicators for safety evaluations. Sensitivity analysis is also conducted for related factors. Results show that the distribution of EVs' SOC significantly affect longitudinal safety when the PWCL is utilized. The low SOC in traffic consisting of EVs has the negative effect on longitudinal safety. The randomness and incompliance of EV drivers worsens the safety performance. The sensitivity analysis indicates that the larger maximum deceleration rate results in the higher longitudinal crash risks of EVs, while the length of PWCL has no monotonous effect. Different TTC thresholds also show no impact on results. A case study shows the consistent results. Based on the findings, several suggestions are discussed for EVs' safety improvement. Results of this study provide useful information for freeway safety when EVs are applied in the future.

1. Introduction

Transportation is one of the largest sectors in energy consumption and emission production, which consumes 29% of the total energy and generates 47% of CO_2 in the US (BTS, 2013). A large proportion of these traffic volumes occur on freeways, which plays a role as high-speed operation facility. In order to reduce fuel consumption and emissions, governments, vehicle manufactories and researchers have been advocating the electric vehicle (EV). For example, Tesla Inc., an American automaker, has been producing various types of EVs since 2003, and aims to offer EVs at affordable prices to the average consumer (Wikipedia, 2017).

The advantage of EVs is using electricity as energy instead of gas which as a result generates no pollutants. However, the EV has some shortcomings that may limit its applications. For example, some studies have investigated the potential dangers caused by low noise emission of EVs on pedestrians. Fleury et al. (2016) asked blindfolded pedestrians to detect an approaching EV with or without warning sounds, who found that the addition of external sounds improved the quiet EV detection by pedestrians. Cocron et al. (2014) introduced a hazard detection task to test whether EV drivers had faster responses to incidents due to low noise emission. Their results suggested that experience and sensitization to low noise had little impact on detecting hazards. Cocron and Krems (2013) conducted a survey from 70 drivers about their perceptions of safety after using quiet EVs for several months. Their results indicated that dangers associated with low noise emission of EVs might be less significant than previously expected.

Another shortcoming associates with the charging process. Unlike the rapid filling up with gas, the charging process of EVs is very time-consuming and may be longer than 4 h for a light duty vehicle, so drivers will not choose to wait at a charging station. To deal with this problem, a novel charging facility, the wireless charging lane (WCL), has been proposed recently (He et al., 2013, 2017; Bansal, 2015; Riemann et al., 2015; Chen et al., 2016, 2017; Koh et al., 2016; Fuller, 2016; Deflorio and Castello, 2017; Liu and Song, 2017). The WCL utilizes wireless facilities on the lane to realize vehicle rapid charging. The

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EVs can charge when traveling on freeways at the same time. The dynamic charging saves time and reduces the requirement of EVs' battery capacity. The first 15 miles of WCL has been constructed in Gumi, South Korea, which provides recharging for buses (Bansal, 2015). The British government has also conducted a feasibility analysis of powering EVs on major roads (England, 2015). A number of related researches have also been studied about deployment and pricing issues of WCL. For instance, He et al. (2013) investigated integrated pricing of electricity and roads enabled by WCL. The optimal prices of charging on WCL were analyzed to maximize social welfare, based on the consideration that the prices affected EVs' route choices. Riemann et al. (2015) analyzed the optimal number and locations of wireless charging facilities for EVs with stochastic user equilibrium model. The study of Fuller (2016) assessed the potential for WCL to address range and charging issues of EVs via considering travel to regional destinations in California, which indicated the dynamic charging might be a more cost effective approach to extending range than increasing battery capacity. Liu and Song (2017) investigated the robust planning problem of dynamic wireless charging facilities for electric buses.

Nevertheless, it is still be difficult to utilize WCL at the large-scale level. The cost of WCL per lane mile reaches 4 million dollars (Fuller, 2016), which is approximately 3 times higher than that of non-WCL. One method to reduce the cost is to utilize improved charging material with a low price, but it needs the innovation of material and may be impractical in the near future. Another countermeasure is to partially deploy WCL on freeways (He et al., 2017). As shown in Fig. 1, the partial wireless charging lane (PWCL) refers to the interval-setting of WCL segment on freeways, which provides energy for EVs intermittently. By reasonable deployments, the PWCL can meet both requirements of dynamic charging and economic feasibility.

The PWCL saves money but increases unsafety of EVs. Unlike traveling on the entire WCL, an EV has to reduce its speed to ensure sufficient time for charging on the PWCL. With the low state of charge (SOC), i.e. with less electricity, the EV will decelerate to a lower speed and spend more time on a PWCL for recharging. The speed reduction results in a traffic bottleneck, which may cause shock waves recurrently. The propagated shock waves negatively affect the longitudinal safety, such as increasing the rear-end crashes. However, to our best knowledge, there is no research investigating safety performances of EVs with the PWCL yet.

Thus, this study aims to evaluate longitudinal safety of EVs with PWCL on freeways. The simulation experiments were firstly designed, including deployment of PWCL on freeways and three distribution scenarios of SOC. Then, a vehicle behavior model for EVs was proposed based on the car-following model and two surrogate safety measures, derived from time-to-collision (TTC), were utilized as indicators for safety evaluations. Sensitivity analysis was also conducted for the maximum deceleration rate, the length of PWCL as well as TTC threshold. Based on the findings, several suggestions were also discussed for EVs' safety improvement. Results of this study provide useful information for freeway safety when EVs are applied in the near future.

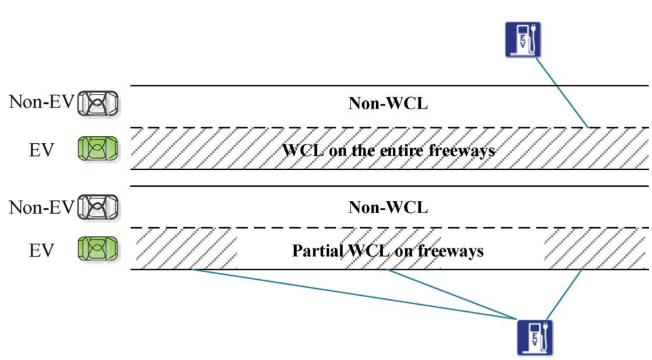

Fig. 1. Illustration of WCL and PWCL on freeways.

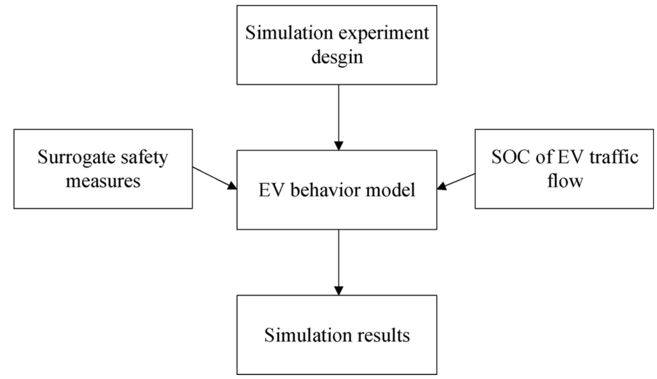

Fig. 2. A Flowchart of the entire methodology.

2. Methodology

2.1. Overview of methodology

The overview of the whole methodology is expressed in Fig. 2. The PWCL is deployed on the freeway as the charging facility for EVs. The traffic flow consists of EVs with various SOC (He et al., 2017). The EVs with high SOC do not need charging so they can maintain the initial speeds to travel on PWCL, while EVs with low SOC have to reduce their speeds to obtain sufficient time for charging. The charging time is dependent on the SOC of EVs, which consequently determines the reduced speed before entering PWCL. All the EVs are controlled by a behavior model derived from a car-following model. The outputs of the EV behavior model are microscopic traffic data, such as position, speed and acceleration. Based on surrogate safety measures, a relation can be established between these microscopic data and longitudinal safety. Finally, with various designed scenarios in simulation experiments, different results can be obtained for analysis with various impact factors.

2.2. Simulation experiment design

Due to the partial design of wireless charging lane on freeways, the entire freeway can be divided into many basic segments, as shown in Fig. 3. The whole length is assumed as 4 km, with the first 1 km without PWCL. Note that, only one single lane is analyzed because the objective of this study is to investigate longitudinal safety. And it is also more reasonable for all EVs to travel on a single lane in the initial stage of popularization. The reason is the application of PWCL on multi-lanes may cause more frequent lane-changings for charging and result in more accidents. EVs can complete their decelerations when needed before entering the PWCL part. Due to deceleration of the leading vehicles, the following vehicles make reactions with a time delay and result in declines of time-to-collision (TTC) (to be defined later). The length of PWCL is set to be variable factor which is tested in simulation experiments. After finishing charging process on PWCL, all the EVs

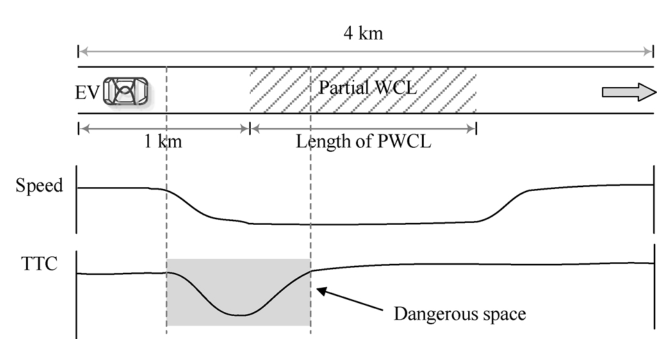

Fig. 3. A basic segment with the PWCL on freeways.