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Impact of in-vehicle navigation information on lane-change behavior in urban expressway diverge segments

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ABSTRACT

Lane-changing behaviors frequently occur at upstream of the urban expressway off-ramp, which possibly cause bottleneck or accident. This paper studies how in-vehicle navigation information impacts lane-changing behavior at this urban expressway diverge segments with comparison to the traditional road signs by conducting a series of driving simulator experiments, in consideration of variation of the first provision time point and traffic flow density. Firstly, the driving simulator is validated by comparing data of lane-changing position and merging gap from both field survey and simulator. Then comparison study was performed for twelve scenarios which comprise four information provision design schemes under three different traffic flow density status. Lane-changing characteristics are analyzed by selecting six indicators, which are lane-changing merging gap, lane-changing position, lane change delay, lane-changing steering angle, lane-changing deceleration, and the safe distance of lane-changing. The results show that the impact of in-vehicle navigation information on lane-changing behavior varies with traffic flow density and the time point of the first navigation information provided. The in-vehicle navigation information had significant positive impact on lane-changing safety under medium to high density condition. However, the effect is not significant under light density condition. Moreover, more improvement in operational safety and smooth could be gained when the in-vehicle navigation information is provided earlier within range of 2 km upstream of the exit gore.

1. Introduction

Diverge segments in the vicinity of off-ramps are considered critical elements of urban expressways where intensive lane changing maneuvers may cause the disturbance of traffic operation. Exiting traffic must change to the right-most lane after noticing that it is the exact ramp to get off. This mandatory lane-changing behavior is the primary cause of the majority of conflicts and interactions among vehicles. Therefore, the frequent lane change behavior at diverge segments may produce traffic conflicts and increase the occurrence potentialities, even aggravate the crash injury severity (Wang et al., 2009; Zhang et al., 2011).

Several studies have been conducted to analyze the effect of lane-changing behavior on the operational safety of the diverge segments. Bin et al. (2003) proposed a lane-changing behavior model which was composed by two sub-models. The first model describes the choice behavior between acceleration and deceleration using discriminant analysis. The second model represents the driver's decision on acceleration and deceleration rate. Qi et al. (2015) developed a quantitative model for predicting the safety impact of different types of geometric treatments for a freeway weaving section. The results shown that the number of crashes in the freeway's weaving section was directly related to the number of lane changes that were required for the vehicles to diverge. Moreover, based on the studies of the basic highway segment, the lane-changing behavior will be effected by some external factor, such as the speed limits, curb installation (Yang et al., 2013), drivers' age, cognitive demand (Reimer et al., 2013), and bad weather condition (Zhang et al., 2016).

To improve the operational safety of the urban expressway diverge segments, advanced sign implementation and improvements are recommended to provide more guiding information for drivers in several safety performance evaluation research (Chen et al., 2011; Mergia et al., 2013; Zhang et al., 2015). Moreover, with the development of the Intelligent Transportation System (ITS), Vehicle-to-Infrastructure (V2I) wireless communication technologies were introduced to improve drivers' awareness (Lin et al., 2013). The in-vehicle navigation system is one of such emerging technology which has been used widely. It can offer drivers continuous information by image and sound. The relevant achievements on how in-vehicle navigation effect lane change behavior

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Roelofsen et al. (2010) proposed a lane change assistant design for drivers on the highway by considering both changing circumstances (sudden brake of leading vehicle) and measurement uncertainties (detector error and data missing). The driver interface consists of five LED lights, each operating on a distinct color and guaranteeing a certain safety degree. Hou et al. (2014) developed a lane changing assistance system that advises drivers of safe gaps for making mandatory lane changes at merging area by using simulation data. Some studies proposed a method for inferring driver lane-changing intentions under normal and emergency situations by comparing the collected with the simulated steering angle sequences (Bi et al., 2015). User-related assessment study of a driver assistance system was proposed based on a field trial of twenty-four test drivers which consists of four kinds of warnings including speed limit warning, curve roadline warning, forward collision warning and blind spot warning (Varhelyi et al., 2015). Effects of route guidance variable message signs (VMS) which displays information of alternative routes were investigated in a field study by analyzing route choice, speed and braking behavior (Erke et al., 2007). The existing studies related to lane-changing behavior mainly care about model and method part (Rahman et al., 2013; Butakov and Ioannou 2015; Dang et al., 2015; Joshi et al., 2016; Nilsson et al., 2016). However, the studies exploring how in-vehicle navigation impact lane change behavior compared to road side signs are quite limited.

This paper aims to analyze the difference of lane change behaviors with and without in-vehicle navigation information and its potential benefits in improving lane change safety at the diverge segments. A high fidelity driving simulator is used, which is a cost-effective way in examining driver responses under different traffic conditions, signage, and other design factors without posing any risk to drivers (Lee et al., 2003; Montella et al., 2011).

The driving simulator technology is not new. It has been used in several related studies. Calvi et al. (2015) analyzed the effects of traffic flow and deceleration lane geometries on diverging driving performance. Belanger et al. (2015) examined the crash avoidance behaviors of older and middle-aged drivers in reaction to six simulated challenging road events using two different driving simulator platforms. In many cases, the use of an advanced driving simulator has many advantages over similar real-world or on-road driving research, including experimental control, efficiency, expense, safety, and convenience of data collection (Nilsson, 1993). Moreover, it has been investigated that no significant differences between the road and the simulator for driving errors, lane maintenance, adjustment to stimuli, and visual scanning errors (Shechtman et al., 2009). Therefore, a driving simulator can be an effective tool for studying the driving behavior (Tu et al., 2015).

2. In-vehicle navigation scenarios

In order to understand how in-vehicle navigation information impact lane change behavior compared with road side signs, we designed scenarios considering both static roadside signs and in-vehicle navigation information. Our hypothesis is that lane change behavior is influenced by how early the information is provided. Besides, the influence varies with different traffic flow density. Therefore, we define different scenarios considering different information provision position under low, medium and high traffic density for both in-vehicle navigation information and road side signs.

The scenario of static roadside signs was designed according to the code of traffic signs and markings in China (MOHURD, 2015). There are three provision positions for the road side signs, as illustrated in Fig. 1 and Fig. 2. The first static roadside sign locates at 500 m upstream the off-ramp. The second static sign locates at 250 m upstream the off-ramp. The third static sign locates right at the end of the channel marking of the off-ramp.

In the scenario of in-vehicle navigation, the drivers were guided by dynamic image and sound from in-vehicle screen, as shown in Fig. 3. The guiding image was shown on the top left corner of the screen and the sound command was offered by the audio equipment in the vehicle. The basic hypothesis is that the time of the first provision of the in-vehicle navigation information might influence lane change behavior. Therefore, we design different schemes of in-vehicle navigation by varying the first provision positions.

Based on the lane changing position distribution from field data under static roadside signs, drivers could see roadside sign clearly at 200 m upstream the sign. We set the nearest scenario of in-vehicle information provision at 700 m upstream the off-ramp, so that we can compare how roadside sign differ from in-vehicle information even the drivers see the information at the same position. Since the expressway in the simulator is a real road in Beijing which gives a largest distance of 2000 m of two neighbor ramps. We set the in-vehicle information 2000 m upstream as the earliest provision position. Then take 1500 m upstream as a level in-between. Therefore, the in-vehicle navigation scenario is illustrated in Fig. 4. The navigation information was firstly provided at 2 km, 1.5 km, and 0.7 km upstream of the exit gore under the three schemes, respectively. The dynamic image in the navigation is provided in a way shown in Fig. 3, beginning from the first provision moment until the off-ramp is passed by. The sound is provided first time when the vehicle arrives the certain position shown in Fig. 4., and repetitively provided every 500 m interval. Please note the in-vehicle navigation information is not lane change assistant. Neither the presence of other vehicles in the right lane nor the feasibility of making a lane change maneuver is considered. In the experiment, the drivers themselves need to decide whether to execute lane change.

Overall, the following four information provision design schemes were compared in the following analysis:

(1) Scheme 1: static road sign;
(2) Scheme 2: in-vehicle navigation with the information first provided at 0.7 km upstream of the exit gore;
(3) Scheme 3: in-vehicle navigation with the information first provided at 1.5 km upstream of the exit gore;
(4) Scheme 4: in-vehicle navigation with the information first provided at 2.0 km upstream of the exit gore.

3. Driving simulator experiments

3.1. Goal

This section describes an experimental driving simulator study to evaluate the impact of in-vehicle navigation information on lane-changing behavior. Specific objectives of the study were to address these questions:

- Would drivers follow the in-vehicle navigation information better than the static roadside signs?
- Would safety of lane-changing be improved by using the in-vehicle navigation information?
- Do the impacts vary under different traffic flow density status?

3.2. Driving simulator

The driving simulator in Tongji University is used in this study, as illustrated in Fig. 5. Its dome houses a fully-instrumented Renault Megane III vehicle cab and is mounted on an 8 degree-of-freedom motion system with an X-Y motion range of 20 × 5 m. An immersive 5 projector system provides a front image view of 250° × 40° at 1000 × 1050 resolution refreshed at 60 Hz. LCD monitors provide rear views at the central and side mirror positions. SCANeR™ studio software displays the simulated roadway environment and controls a force feedback system that acquires data from the steering wheel, pedals, and gear shift lever.

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