Transportation Research Part C 93 (2018) 292–309

Contents lists available at ScienceDirect

Transportation Research Part C

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

Connectivity's impact on mandatory lane-changing behaviour: Evidences from a driving simulator study

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ARTICLE INFO

Keywords:
Connectivity
Mandatory lane-changing
Gap acceptance
Driving behaviour
Safety

ABSTRACT

The connected environment provides driving aids to help drivers making efficient and safe driving decisions. The literature to date is devoid of conclusive evidences of the connected environment's impact on drivers' mandatory lane-changing (MLC) behaviour. As such, the objective of this study is to examine MLC behaviour through a driving simulator experiment using the CARRS-Q Advanced Driving Simulator. Participants with diverse background performed the experiment in randomised driving conditions: baseline (without the driving aids), connected environment with perfect communication, and connected environment with communication delay. Repeated measure ANOVA in the form of linear mixed model and Generalized Estimation Equation (GEE) are employed to analyse various driving performance indicators during MLC event. We find that drivers in the connected environment tend to wait longer, increase the initial speed, and maintain a larger spacing, compared to when they are driving in the baseline condition. In addition, drivers in the connected environment are likely to reject fewer number of gaps and select relatively bigger gap sizes. Furthermore, post-encroachment time (PET) in the connected environment is higher across different gap sizes, indicating that the connected environment makes MLC safer. The GEE model on gap acceptance suggests that the perfect communication and communication delay has positive and negative impact on the accepted gap size, respectively, and the GEE model on lane-change duration indicates that lane-change duration tends to increase in the connected environment.

1. Introduction

The connected environment is promising in mitigating many transportation issues related to safety, mobility, and environmental impact (Kim, 2015). The connected environment provides information that can assist in driving tasks, particularly in lane-changing (LC) that requires information about surrounding traffic. Since LC is a multistage decision making process, it increases driver's workload and stress, thus the chance for the driver to make errors increases which can create safety hazards (Zheng et al., 2010). LC also causes negative impacts on traffic stream. For example, Cassidy and Rudjanakanoknad (2005) reported LC's impact on traffic breakdowns and capacity drops; Ahn and Cassidy (2007) revealed the linkage between LC and stop-and-go oscillations, which was further confirmed by Zheng et al. (2011b).

In traffic flow theory, LC is mainly divided into two types: mandatory and discretionary. Mandatory LC (MLC) is mainly performed to reach a planned lane position, while discretionary LC (DLC) is for achieving a desired driving condition, e.g., increasing

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https://doi.org/10.1016/j.trc.2018.06.008
Received 26 February 2018; Received in revised form 30 May 2018; Accepted 16 June 2018
0968-090X/

speed. LC modelling endeavours in the literature can be classified into two categories: modelling LC decision-making (LCD), and modelling LC's impact (LCI) on surrounding traffic (Zheng, 2014). This study focuses on LCD in the context of MLC in a connected environment.

In a connected environment, driving aids e.g., information about gap availability in the target lane, the speeds of surrounding vehicles, and the remaining distance (in case of MLC) can change (in most cases benefit) drivers' MLC decision making. More specifically, connectivity's impact on MLC decision making is expected to be more pronounced at the operational stage that includes gap acceptance and duration of MLC's execution (LC duration hereafter). The former has received significant attention in the LCD modelling (Bham and Goswami, 2007; Bham, 2009; Choudhury et al., 2007; Marczak et al., 2013; Toledo et al., 2005; Toledo et al., 2003) while the latter has been rarely studied in the past (Toledo and Zohar, 2007). Note that the gap in this study is defined as the distance from the rear bumper of the leading vehicle to the front bumper of the following vehicle in the target lane, and LC duration is defined as the time taken by the subject vehicle (SV) to execute the LC manoeuvre.

A sound understanding of connectivity's impact on driver's MLC decision making is important for developing more accurate and more realistic MLC models suitable for operating and controlling connected vehicles, and for designing a safer and more efficient connected driving environment. A survey of recent literature reveals that most of the studies focus on measuring the impact of connectivity on macroscopic behaviour using microsimulation (Guériau et al., 2016; Reina and Ahn, 2015), while some studies proposed algorithms for MLC scenarios (i.e., merging behaviour) for the connected environment and tested using simulation data (Letter and Elefteriadou, 2017; Rios-Torres and Malikopoulos, 2017). However, to accurately analyse drivers' MLC behaviour and to model their MLC decision making mechanism, high-quality vehicle trajectories are required along with detailed human factor information. Primarily because of the novelty of the connected environment (and consequently, the scarce of the data), very few studies in the literature focused on the connected environment's impact on drivers' MLC behaviour. To fill this gap, this research aims to investigate the impact of connectivity (or connected environment; note that these two terms are used interchangeably in the rest of the paper) on drivers' MLC behaviour using a driving simulator experiment in a high-fidelity advanced driving simulator. More specifically, we aim to address the following three questions:

i. Does connectivity impact drivers' driving performance related to MLC, e.g., gap selection, initial speed, waiting time, and spacing?
ii. Does connectivity improve the safety margin associated with MLC manoeuvre?
iii. Does connectivity influence the execution of MLC?

The remainder of this paper is organized as follows. Section 2 presents a literature review on gap acceptance behaviour and LC duration modelling. Section 3 introduces the driving simulator experiment design and data collection. Section 4 explains data processing methodology. Section 5 describes data analysis in detail. Section 6 discusses main findings. Finally, Section 7 concludes the study by summarizing major findings, limitations, and pointing out some future research topics.

2. Literature review

This section is divided into two parts: (a) gap acceptance behaviour studies, and (b) studies related to modelling LC duration.

2.1. Gap acceptance behaviour

Gap acceptance, which is an integral part of LCD models, is an important microscopic parameter in traffic control and management. In most of the existing studies, gap acceptance is modelled based on the gap acceptance theory, which assumes driving behaviour as consistent, and implies that the rejected gaps will not be larger than the accepted gaps (Daamen et al., 2010). According to this theory, if drivers do not find a gap larger than the critical gap in case of merging scenario, they would travel to the end of the acceleration lane without merging to the target lane (Marczak et al., 2013). Usually, the length of lag gap increases with increase in relative speed, and drivers tend to accept a smaller gap size as the remaining distance becomes shorter (Ahmed et al., 1996). Meanwhile, drivers are more likely to select a larger gap size with the increase of the speed (Kondyli and Elefteriadou, 2011).

Table 1 summarizes some representative studies on gap acceptance behaviour in MLC. Almost all studies presented in Table 1 considered relative speed, lead and lag gaps, and remaining distance on the acceleration lane. However, only Marczak et al. (2013) considered the rejected gaps while describing gap acceptance behaviour. Further, drivers' gap acceptance behaviour can also be influenced by personality traits (e.g., aggressiveness, sensation seeking, etc.), and urgency of the LC (Bham and Goswami, 2007), which has rarely been incorporated in the existing models. In addition, most of the existing studies did not consider the connected environment, and ignored human factors (e.g., age, gender, and driving experience). Smith et al. (2016) is an exception, which reported that connected vehicle technology benefits drivers' gap acceptance behaviour, and the anticipated benefits from the connected vehicle technologies are a function of driver's compliance, which is affected by factors related to situation and personality traits. However, no model was developed to capture driver's gap acceptance behaviour in a connected environment.

2.2. LC duration modelling

LC behaviour generally consists of LC decision-making and LC execution. LC duration is an important aspect of LC execution. Though LC duration is considered as one factor or characteristics of LC's impact and has a weak relationship with LCD process, LC