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Evaluating the effects of automated vehicle technology on the capacity of freeway weaving sections

Gabriel Tilg[b,a], Kaidi Yang[a,*], Monica Menendez[c,d,a]

[a] Traffic Engineering Group, Institute for Transport Planning and Systems, ETH Zurich, Switzerland
[b] Chair of Traffic Engineering and Control, Technical University of Munich, Germany
[c] Division of Engineering, New York University Abu Dhabi, United Arab Emirates
[d] Tandon School of Engineering, New York University, USA

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ABSTRACT

Weaving sections, where a merge and a diverge are in close proximity, are considered as crucial bottlenecks in the highway network. Lane changes happen frequently in such sections, leading to a reduced capacity and the traffic phenomenon known as capacity drop. This paper studies how the emerging automated vehicle technology can improve the operations and increase the capacity of weaving sections. We propose an efficient yet effective multiclass hybrid model that considers two aspects of this technology in scenarios with various penetration rates: (i) the potential to control the desired lane change decisions of automated vehicles, which is represented in a macroscopic manner as the distribution of lane change positions, and (ii) the lower reaction time associated with automated vehicles that can reduce headways and the required gaps for lane changing maneuvers. The proposed model is successfully calibrated and validated with empirical observations from conventional vehicles at a weaving section near the city of Basel, Switzerland. It is able to replicate traffic dynamics in weaving sections including the capacity drop. This model is then applied in a simulation-based optimization framework that searches for the optimal distribution of the desired lane change positions to maximize the capacity of weaving sections. Simulation results show that by optimizing the distribution of the desired lane change positions, the capacity of the studied weaving section can increase up to 15%. The results also indicate that if the reaction time is considered as well, there is an additional combined effect that can further increase the capacity. Overall, the results show the great potential of the automated vehicle technology for increasing the capacity of weaving sections.

1. Introduction

A weaving section is a highway segment where an on-ramp and an off-ramp are in close proximity. The name originates from the vehicle trajectory pattern formed by drivers who change from the auxiliary lane to the highway and vice versa. Weaving sections are considered as typical bottlenecks for highway networks. Therefore, the capacity of weaving sections is of high significance for the system-wide operations of these networks.

Negative impacts on the capacity of weaving sections result from the traffic phenomenon of the capacity drop, which is widely observed and reported throughout the literature. It is defined as the decrease of the discharge flow at bottlenecks once a queue has formed upstream (Hall and Agyemang-Duah, 1991). Numerous reports show different extents of the capacity drop at merges and

* Corresponding author.
E-mail addresses: gabriel.tilg@tum.de (G. Tilg), kaidi.yang@ivt.baug.ethz.ch (K. Yang), monica.menendez@nyu.edu (M. Menendez).

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weaving sections, ranging normally between 3% and 20% (Hall and Agyemang-Duah, 1991; Cassidy and Bertini, 1999; Chung et al., 2007; Majid Sarvi, 2010; Oh and Yeo, 2012), but in some special cases up to 30% (Kerner, 2002; Yuan et al., 2014; Soriguera et al., 2017). The underlying causes for a reduced stable capacity in weaving sections include lane changes, driving behavior, high traffic densities spreading from the shoulder lane onto other freeway lanes, and the speed of vehicles in congestion (Cassidy and Rudjanakanoknad, 2005; Laval and Daganzo, 2006; Laval et al., 2007; Chung et al., 2007; Lee and Cassidy, 2009; Yuan et al., 2014). Overall, it is agreed that the cause for it is related to local traffic conditions and that lane changes are of great significance. Chen and Ahn (2018), for example, identified the two counteracting effects of lane changes that govern capacity drop: persisting voids (wasted space) and utilization of vacancies created by diverging vehicles. Recent empirical observations further suggest that the non-optimal distribution of lane change positions is of great importance for the decrease of the capacity. For example, Menendez and He (2017) and He and Menendez (2016) discovered a strongly right-skewed distribution of lane change positions (early lane change positions) in the city of Basel, Switzerland. Additionally, Lee (2008) and Sulejic et al. (2017) suggest that the concentration of lane changes in the beginning of weaving sections leads to a low capacity.

The emergence of new technologies, such as automated vehicles, facilitates the optimization and control of traffic flow (National Highway Traffic Safety Administration, 2013; Friedrich, 2015; Talebpour and Mahmassani, 2016; Yang et al., 2016, 2018). The automated vehicle technology (AVT) eliminates the influence of human factors such as the reaction time, reducing headways and the required gap for lane changing, thus potentially increasing the highway capacity. Moreover, the information provided by automated vehicles is valuable to identify the traffic states on urban arterials (Yang and Menendez, 2017) and highways (Menendez and Daganzo, 2004), and can be used for more intricate control (Guler et al., 2014). The AVT further provides the flexibility for central traffic managers to control the motion or gap searching decisions of the vehicles and apply adequate measures to improve the operations of traffic systems (Yang et al., 2016). However, the transition from conventional to automated vehicles will not happen abruptly. Depending on the penetration rate of automated vehicles in the overall traffic stream, the effects will supposedly differ. The effects of automated vehicles at several different automation stages and penetration rates, on the capacity of the highway network of Germany were assessed by Hartmann et al. (2017). Chen et al. (2017) studied the effects of automated vehicles and conventional vehicles on highway capacity, specially under different lane policies, such as exclusive automated and/or regular vehicle lanes and mixed-use lanes. However, to the best knowledge of the authors, the specific impact of automated vehicles on weaving sections including lateral effects and considering different penetration rates still remains unknown.

The goal of this paper is to propose a systematic framework to evaluate the effects of automated vehicles on the capacity of weaving sections. The contributions are twofold. First, we propose an efficient yet effective multi-class hybrid model to evaluate how automated vehicles can improve the operation of weaving sections regarding the effects of lane changes. Particularly, we model two aspects of the AVT: (i) the potential to control desired lane change decisions of automated vehicles, and (ii) the lower reaction times associated with automated vehicles which lead to reduced headways and shorter required gaps for lane changing maneuvers. To ensure efficiency, both aspects are characterized by direct macroscopic inputs to the proposed model. The lane changing decisions are depicted as the distribution of desired lane change positions, and the reaction times are represented by the fundamental diagrams. Moreover, we examine different application stages of such technology by considering various penetration rates. Second, the mechanism of the model enables a systematic search for an optimum distribution of desired lane change positions for a given set of input parameters in scenarios with different penetration rates. This is formulated as a simulation-based optimization problem, which is solved for each scenario using a surrogate method that is capable of finding the quasi-global optimum. Such method and the obtained distribution shed light on where to guide drivers regarding their lane changing maneuvers.

The remainder of the paper is structured as follows. Section 2 provides a short review of the related work. Section 3 describes the proposed multi-class hybrid model and shows the validation results. Section 4 explains the incorporation of the considered aspects of automated vehicles including the optimization. Subsequently, a simulation is conducted in Section 5 to show the influences of optimum desired lane change distributions and shorter reaction times on the capacity of weaving sections. Additionally, the effects of the simultaneous consideration of both aspects are analyzed. Finally, Section 6 concludes the paper and outlines possible future research.

2. Related work

Lee (2008) developed a microscopic traffic model for weaving sections based on the lane changing and car following model formulated in Menendez (2006) and validated in Menendez and Daganzo (2007). Their lane changing model distinguishes between three different lane change types, i.e. free, forced, and cooperative lane changes. Inspired by the multi-lane hybrid theory (MHT) and incorporating certain ideas on the modeling of the relaxation phenomenon, Laval and Leclercq (2008) proposed a microscopic model for traffic flow at merges. Still, such microscopic models are typically computationally more complex than macroscopic models. Additionally, they involve too much stochasticity when considering the distribution of lane change positions.

Pan et al. (2016) developed a mesoscopic traffic model which is capable of reproducing traffic characteristics as heterogeneous traffic flow distributions, capacity drop and flow balancing effects. The model incorporates mandatory and discretionary lane change types. Based on the gas-kinematic theory, Ngoduy (2006) proposed a complex macroscopic multi-class model for highway weaving sections. The model is able to reproduce traffic dynamics including the capacity drop. Less intricate macroscopic models are based on the kinematic wave theory (KWT) (Lighthill and Whitham, 1955; Richards, 1956). For example, Jin (2010) introduced a lane-changing intensity parameter to model the impacts of lane changes on the traffic stream. However, this macroscopic model cannot reproduce the traffic dynamics in weaving sections including additional lanes connecting the on- and off-ramp, due to the assumption of same density across all lanes. Leclercq et al. (2011, 2016a,b) built analytical models to study the capacity drop at merges. They