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A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method

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ABSTRACT

The projected rapid growth of the market penetration of connected and autonomous vehicle technologies (CAV) highlights the need for preparing sufficient highway capacity for a mixed traffic environment where a portion of vehicles are CAVs and the remaining are human-driven vehicles (HVs). This study proposes an analytical capacity model for highway mixed traffic based on a Markov chain representation of spatial distribution of heterogeneous and stochastic headways. This model captures not only the full spectrum of CAV market penetration rates but also all possible values of CAV platooning intensities that largely affect the spatial distribution of different headway types. Numerical experiments verify that this analytical model accurately quantifies the corresponding mixed traffic capacity at various settings. This analytical model allows for examination of the impact of different CAV technology scenarios on mixed traffic capacity. We identify sufficient and necessary conditions for the mixed traffic capacity to increase (or decrease) with CAV market penetration rate and platooning intensity. These theoretical results caution scholars not to take CAVs as a sure means of increasing highway capacity for granted but rather to quantitatively analyze the actual headway settings before drawing any qualitative conclusion. This analytical framework further enables us to build a compact lane management model to efficiently determine the optimal number of dedicated CAV lanes to maximize mixed traffic throughput of a multi-lane highway segment. This optimization model addresses varying demand levels, market penetration rates, platooning intensities and technology scenarios. The model structure is examined from a theoretical perspective and an analytical approach is identified to solve the optimal CAV lane number at certain common headway settings. Numerical analyses illustrate the application of this lane management model and draw insights into how the key parameters affect the optimal CAV lane solution and the corresponding optimal capacity. This model can serve as a useful and simple decision tool for near future CAV lane management.

1. Introduction

Connected and autonomous vehicles (CAVs) are expected to improve highway traffic efficiency, safety, and environment through sensing local environment, sharing information, and applying appropriate control measures (Ghiasi et al., 2017; Li et al., 2017; Kamrani et al., 2017). All these benefits are linked to the expectation that CAVs can largely improve highway

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traffic capacity by reducing time headways between consecutive vehicles through communication and automated control technologies (e.g., platooning). With CAV platooning, a pair of CAVs are similar to two concatenated cars in a train and thus shall have much less time headway compared with a pair of disconnected human-driven vehicles (HVs). Therefore, we envision that highway capacity will be maximized in the far future when all vehicles are platooned CAVs, as predicted by a number of studies on pure automated traffic with computer simulation (Ioannou and Chien, 1993) and analytical models (Kanaris et al., 1997; Swaroop et al., 1994; Fernandes and Nunes, 2012; Amoozadeh et al., 2015).

Besides the consensus on pure automated traffic, it is not yet completely clear how highway capacity is affected by CAVs in mixed traffic containing both CAVs and HVs, which expects to last for a relatively long transitional period. A number of studies conducted capacity analyses for mixed traffic, most of them relying on computer simulation (e.g., Van Arem et al., 1997; Shladover et al., 2001; Vander Werf et al., 2002; Van Arem et al., 2006; Kesting et al., 2008; 2010; Shladover et al., 2012; Krause et al., 2017). There are only a limited number of studies attempting building analytical models to characterize capacity of mixed traffic (e.g., Tientrakool et al., 2011; Levin and Boyles, 2015; 2016; Chen et al., 2017). While these studies provide valuable quantitative results and insights into the benefits of CAVs in improving mixed traffic capacity, most of them consider deterministic time headways in a specific technology scenario. However, in reality, time headways between consecutive vehicles are highly stochastic. The effect of headway stochasticity on highway capacity is not captured in studies assuming deterministic headways. Further, headway distributions in mixed traffic highly depend on CAV technologies that are yet to be fully developed and thus may have quite some uncertainties. From the literature, we see quite some discrepancies in describing CAV headway values ranging from 0.3 to 2.6 s (please refer to Section 2 for a comprehensive review of headway distributions in the literature). How different CAV technology outcomes would affect highway capacity is yet to be investigated. For example, if future CAV technologies are conservative, headways between vehicles will increase, and as a result, capacity may not increase as much as some optimistic models predicted, or may even decrease. On the other hand, more aggressive CAV technologies could result in higher highway capacity.

Existing studies also point out that the CAV market penetration is a critical factor that affects the highway capacity in mixed traffic. Results from both simulation (Kesting et al., 2008; Shladover et al., 2012; Arnaout and Arnaout, 2014; Ntousakis et al., 2015) and analytical modeling (Levin and Boyles, 2015; van den Berg and Verhoef, 2016) show that highway capacity increases significantly with market penetration rate. However, another important factor that also largely affects traffic capacity yet receives less attention is the CAV platooning intensities. CAV platooning refers to the technology that reduces the headway between consecutive CAVs with vehicle-to-vehicle (V2V) communications and automated control (e.g., Stevens et al. 1996; Zhao and Sun 2013; Amoozadeh et al. 2015). Even at the same market penetration rate, different CAV platooning intensities may result in quite different traffic capacities. For example, if CAVs are more scattered across the highway, there will be fewer long platoons of CAVs with reduced headways and thus the improvement of traffic capacity becomes less salient. On the other hand, if CAVs are better clustered, highway capacity will increase as a result of longer CAV platoons with reduced headways. Only limited studies investigated the impact of vehicle platooning on traffic capacity in mixed traffic with simulation and claimed that a higher platooning intensity ensures a higher capacity (e.g., Rao and Varaiya, 1993; Zhao and Sun, 2013; Harwood and Reed, 2014). It remains a challenge to reveal analytical insights into how both market penetration and CAV platooning intensity jointly affect mixed traffic capacity. Recently, Chen et al. (2017) proposes analytical formulations for mixed traffic highway capacity that takes autonomous vehicle (AV) market penetration rate and platoon sizes into account. Despite their analytical breakthrough, this study only considers deterministic periodic platoons with a fixed number of AVs. Moreover, like most relevant efforts, it only considers deterministic time headways in a specific AV technology scenario.

The lack of analytical results on CAV traffic capacity actually restricts us from transferring traditional lane management into CAV traffic. Lane management has been widely applied to highway practices and have made great success in improving capacity of traditional HV traffic. Several studies have been conducted to investigate managed lanes for different types of vehicles and management measures, including high-occupancy vehicles (HOV) (e.g., Dahlgren 2002; Menendez and Daganzo 2007; Kwon and Varaiya 2008; Chu et al. 2012), buses (e.g., Cherry et al. 2005; Xu et al. 2013), trucks (e.g., Rakha et al. 2005; Abdelgawad et al. 2010; Cherry and Adelakun 2012; Rudra and Roorda 2014), and high-occupancy toll (HOT) (e.g., Dahlgren 2002; Sallach et al. 2010; Liu et al. 2011; Hadi et al. 2016). These successes largely benefited from analytical modeling of traffic capacity under different lane management strategies (e.g., Dahlgren 2002; Chu et al. 2012). However, due to the lack of analytical models of mixed CAV traffic capacity, it is difficult to reproduce these successes of traditional lane management modeling in emerging mixed CAV traffic. Therefore, studies on CAV lane management are relatively scarce in the literature. Chen et al. (2016) proposes a deployment model to determine the locations of AV lanes on a general transportation network and provides elegant insights into network infrastructure design decisions. Fakharian Qom et al. (2016) performs a simulation analysis to evaluate the performance of Managed Lanes (ML) with Cooperative Adaptive Cruise Control (CACC) vehicles. Talebpour et al. (2017) examines the effects of reserving one lane for AVs on a two-way and a four-lane highway with computer simulations. Their results show potential benefits at above certain market penetration rates. Chen et al. (2017) evaluates specific lane management policies for mixed traffic with AVs and offers the best policy among the considered ones. Despite these limited efforts, stochastic headways and vehicle platooning intensities in the context of lane management have yet not been investigated.

To bridge these research gaps, this paper proposes an analytical formulation to highway capacity in a mixed traffic environments with CAVs. Furthermore, it presents a lane management framework to determine the optimal number of lanes to be allocated to CAVs to maximize the highway capacity. This study makes the following contributions. First, we provide