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Towards vehicle automation: Roadway capacity formulation for traffic mixed with regular and automated vehicles

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ABSTRACT

This paper provides formulations of traffic operational capacity in mixed traffic, consisting of automated vehicles (AVs) and regular vehicles, when traffic is in equilibrium. The capacity formulations take into account (1) AV penetration rate, (2) micro/mesoscopic characteristics of regular and automated vehicles (e.g., platoon size, spacing characteristics), and (3) different lane policies to accommodate AVs such as exclusive AV and/or RV lanes and mixed-use lanes. A general formulation is developed to determine the valid domains of different lane policies and more generally, AV distributions across lanes with respect to demand, as well as optimal solutions to accommodate AVs.

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List of Variables

AV	automated vehicle;
RV	regular vehicle that is at level 0 automation;
s_0	critical spacing of a RV following another RV;
β^A	spacing coefficient for the lead vehicle in an AV platoon (with a RV or AV ahead);
γ	spacing coefficient for other AVs in the platoon (i.e., with another AV ahead);
β^R	spacing coefficient for the first RV following an AV platoon;
n	AV platoon size;
m	number of RVs between two platoons;
$\bar{s}$	mean critical spacing per cycle;
α	AV proportion in the traffic stream;
u	free-flow speed;
ε	average gain of critical spacing per AV, named "AV gain";
ε_i	AV gain on lane i;
C_0	lane capacity with only RVs;
C_i	capacity on lane i, with potential RVs and AVs;
$f(\alpha,\ \varepsilon)$	capacity function;
p	AV penetration rate;
q_i	flow on lane i;

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α_i^*	AV proportion of lane i in the capacity state;
Q_{policy}	flow corresponding to a policy, (A, R), (M, R) or (A,M);
Q_{policy}^{max}	maximum flow (i.e., capacity) for a given p for a policy;
Q_{case}^*	maximum capacity among the possible p for a policy;
p_{cric}	critical AV penetration rate;
Q_K	total flow for a K-lane highway;
Q_K^{max}	maximum flow (i.e., capacity) for a given p for a K-lane highway.
$E_i(\alpha_i)$	AV gain for lane i as a function of AV proportion α_i.

1. Introduction

Emerging automated vehicle (AV) technologies have the potential to fundamentally change driver interactions and provide tremendous opportunities to drastically improve traffic efficiency, stability and safety. Among different types of AV technologies, vehicle platooning is particularly advantageous due to its unique high performance feature: doubled (or higher) roadway capacity and significantly improved flow stability (Milanes et al., 2014; Milanés and Shladover, 2014; Shladover et al., 2012, 2010). A few pioneering field tests conducted recently have provided the very first understanding of vehicle platooning realized through cooperative adaptive cruise control and suggested very promising improvement in roadway efficiency (Bu et al., 2010; Milanes et al., 2014; Ploeg et al., 2011). Particularly, the latest experiment at the California PATH showed that vehicles in platoons can maintain a time gap as small as 0.6 s, compared to 1.5 s for conventional non-automated vehicles, which implies a substantial increase of roadway capacity and drastic congestion mitigation (Milanés and Shladover, 2014; Shladover et al., 2012).

In traffic flow research, one important problem has received much attention: how the improvement in roadway capacity will evolve as the AV technologies mature and the penetration rate gradually increases? Understanding this problem is critical for applying the emerging technologies for traffic control and transportation planning in the era of AVs (Lin and Wang, 2013; Litman, 2015; Williams, 2013; Zhou et al., 2015). Some existing studies provide valuable insights on this issue. From the perspective of vehicle mechanics, Swaroop et al. (1994) examined the impacts of platooning policy (constant time gap vs. constant space) on traffic flow instability and evaluated lane capacity with different platoon sizes and headway settings. However, the formulation of lane capacity was overly simplified. For example, they did not consider the interaction between platoons and the distribution of AVs across different lanes. Later, using simulations, a number of studies investigated changes in microscopic driving behavior in AVs, such as reaction time and acceleration/deceleration, and platoon size, and their impacts on capacity (e.g., Jerath and Brennan, 2012; Kesting et al., 2010, 2008; Talebpour et al., 2016; Talebpour and Mahmassani, 2014; Talebpour et al., 2017; Treiber et al., 2007; van Arem et al., 2006; Zhao and Sun, 2013). For example, van Arem et al. (2006) used a microscopic simulator, MIXIC, to study the impacts of vehicle platoons on the flow instability and capacity on a freeway with a lane drop. Talebpour and Mahmassani (2016) explicitly considered traffic flow with different compositions of connected and automated vehicles and found that AVs are superior in terms of improving string stability. A large proportion of these studies found that a substantial capacity improvement can be achieved with medium (or even low) penetration rates (e.g., Jerath and Brennan, 2012; Kesting et al., 2008, 2007; Treiber and Kesting, 2013). In contrast, Shladover et al. (2012) calibrated simulations using field experiments and found that a capacity increase is marginal until the penetration rate reaches a moderate to high level (e.g., above 50%), which is consistent with the simulation outcome of van Arem et al. (2006). Using simulations, Talebpour et al. (2017) examined the impacts of reserving one lane of a four-lane highway for AVs on traffic flow dynamics and travel time reliability. It was found that throughput can be improved significantly if the AV penetration rate is greater than 30%. However, the mechanisms of the throughput improvement are unclear because complex car-following and lane-changing dynamics were assumed in the simulations.

To date, most evaluation efforts have used simulations, and very limited theoretical research has been conducted to provide a systematic formulation. To fill this gap, this paper provides a general theoretical framework to shed light on how traffic operational capacity will change with the introduction of AVs. The operational capacity (hereafter capacity to be succinct) is defined as the maximum sustainable flow on a segment, given an AV penetration rate, when demand is sufficiently high. Particularly, this paper focuses on deriving the base macroscopic capacity for mixed traffic when traffic is in equilibrium. This is a very important and necessary step toward establishing a benchmark to meaningfully understand the effects of bottlenecks and various microscopic features. This is not trivial because the base equilibrium capacity is not a fixed number but varies (dynamically) by a number of factors, which presents complexity in understanding the capacity. Our formulations take into account (1) AV penetration rate, (2) micro/mesoscopic characteristics of regular (i.e., conventional non-automated) and automated vehicles, and (3) different lane policies to accommodate AVs such as exclusive AV and/or RV lanes and mixed-use lanes, which has received very little attention in the previous research. The micro/mesoscopic vehicle characteristics (e.g., platoon size, spacing characteristics) are expressed by a single parameter, average gain in critical spacing with AVs, thereby establishing a clear connection to the macroscopic capacity. We further develop a general formulation, inclusive of all the lane policies considered in this study, to determine how AVs should be distributed across lanes, given traffic demand, AV penetration rate, and spacing characteristics of automated and regular vehicles. The analytical formulations offer important insights into valid domains of different lane policies and more generally, AV distributions across lanes with respect to demand, as well as optimal solutions to accommodate AVs.