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Influence of connected and autonomous vehicles on traffic flow stability and throughput

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ABSTRACT

The introduction of connected and autonomous vehicles will bring changes to the highway driving environment. Connected vehicle technology provides real-time information about the surrounding traffic condition and the traffic management center's decisions. Such information is expected to improve drivers' efficiency, response, and comfort while enhancing safety and mobility. Connected vehicle technology can also further increase efficiency and reliability of autonomous vehicles, though these vehicles could be operated solely with their on-board sensors, without communication. While several studies have examined the possible effects of connected and autonomous vehicles on the driving environment, most of the modeling approaches in the literature do not distinguish between connectivity and automation, leaving many questions unanswered regarding the implications of different contemplated deployment scenarios. There is need for a comprehensive acceleration framework that distinguishes between these two technologies while modeling the new connected environment. This study presents a framework that utilizes different models with technology-appropriate assumptions to simulate different vehicle types with distinct communication capabilities. The stability analysis of the resulting traffic stream behavior using this framework is presented for different market penetration rates of connected and autonomous vehicles. The analysis reveals that connected and autonomous vehicles can improve string stability. Moreover, automation is found to be more effective in preventing shockwave formation and propagation under the model's assumptions. In addition to stability, the effects of these technologies on throughput are explored, suggesting substantial potential throughput increases under certain penetration scenarios.

1. Introduction

Cities have gone through numerous transformations through time. Transportation systems and technologies have been an integral part of these transformations. The past two decades have seen substantial integration of advances in wireless communication, processing power, and sensing technologies into traffic management systems, with the goal of enhancing mobility, sustainability, safety, and reliability of these systems. The next major wave of technological innovation is seeking to impact the system through vehicle-based innovation. In particular, autonomous vehicles have been prototyped with substantial advances in sensing technologies and associated pattern recognition and control intelligence, while pervasive

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wireless communication technologies provide the opportunity to create an internet of vehicles where individual vehicles can communicate with other vehicles (through Vehicle-to-Vehicle communications) and infrastructure (through Vehicle-to-Infrastructure communications). Consequently, virtually all aspects of drivers' decision making, from strategic to operational decisions, would be impacted and generally enhanced. At the operational level, these technologies are intended to help drivers and vehicles make safe and reliable decisions about acceleration choice and executing lane-changing maneuvers. It is important to note that these two types of communications (Vehicle-to-Vehicle and Vehicle-to-Infrastructure communications) can also improve the efficiency and reliability of operating autonomous vehicles.

The driving environment and associated driver-vehicle behavior are expected to change with the introduction of connected and autonomous vehicles. Human-driven vehicles and autonomous vehicles have different driving logics. Humans have higher reaction time compared to robots; and therefore, to overcome the uncertainty associated with human decisions, they should consider more decision variables (Treiber et al., 2007). In the context of driving, a human driver not only takes into account the behavior of the immediate leader, but he/she also monitors the behavior of several vehicles ahead (possibly the entire traffic stream ahead) (Treiber et al., 2007). This method can result in a more stable car-following behavior (Treiber et al., 2007).

From the modeling standpoint, capturing the effects of these technologies on driving and car-following stability is a challenging task. A major part of driving-related decisions correspond to the acceleration choice. Consequently, acceleration behavior has been studied extensively in the literature and several models with different levels of complexity have been introduced to capture the underlying processes of acceleration decision making (Chandler et al., 1958; Gazis et al., 1959; Gipps, 1981; Hamdar and Mahmassani, 2009; Herman et al., 1959; Talebpour et al., 2011; Yang and Koutsopoulos, 1996). However, previous studies did not clearly present the role of communication in operating connected and autonomous vehicles, and most of the efforts focused on specific applications of connected and autonomous vehicles technologies (e.g. Cooperative Adaptive Cruise Control or Automated Highway Systems). Moreover, these studies did not investigate the interactions between autonomous vehicles, human-driven vehicles with connectivity (these vehicle are called "connected vehicles" in this paper), and human-driven vehicles without connectivity (these vehicle are called "regular vehicles" in this paper) in detail. Therefore, there is a need for a comprehensive acceleration framework to model this new driving environment and capture the interactions between different vehicle types. This study presents such a comprehensive acceleration framework to model this driving environment with regular, connected, and autonomous vehicles. This framework uses different acceleration models with different assumptions to model regular, connected, and autonomous vehicles. A reliable acceleration modeling framework should offer stability. Two types of car-following stability has been identified in the literature (Treiber and Kesting, 2013; Wilson and Ward, 2010): local stability and string stability. Local stability refers to the vehicle's response to its leader's acceleration decisions. It is achieved if a (following) vehicle recovers from a perturbation and retains the original steady-state speed and spacing after deviating from it (this deviation, for instance, can be caused by the leader's sudden break). String stability is defined for a platoon of vehicles and investigates the behavior of the entire platoon in response to its leader's sudden break. If the perturbation decays as it propagates upstream within the platoon, the car-following behavior is called string stable. Since this acceleration framework is based on well-established car-following models, local stability is expected to hold for this framework. Consequently, the main focus of the present study is to investigate the string stability of traffic flow under different market penetration rates of connected and autonomous vehicles. Accordingly, both analytical and simulation-based analyses of string stability of this acceleration framework are performed.

Moreover, through an extensive simulation effort and by investigating the effects of autonomous and connected vehicles on throughput, and on the scatter in the fundamental diagram of traffic flow, this study shows that this framework is capable of capturing the interactions between different vehicle types. These simulations explore possible changes in throughput and structure of the fundamental diagram under different market penetration rates of connected and autonomous vehicles. Consequently, the main contribution of the present study is to utilize these findings to investigate the possible impacts of connected and automated vehicles on traffic flow and string stability.

The remainder of this paper is organized as follows: Section 2 presents a review of the efforts to model connected and autonomous vehicles. Section 3 discusses the possible effects of connected and autonomous vehicles on driving environment. Section 4 presents the acceleration framework and the logic behind selecting each model in this framework. Analytical and simulation-based investigations of string stability under different market penetration rates of connected and autonomous vehicles are offered in Section 5. It is followed by a simulation-based analysis of throughput under different market penetration rates of connected and autonomous vehicles using the proposed acceleration framework in Section 6. The paper is concluded with some summary remarks and future research needs in Section 7.

2. Background

Extensive effort has been devoted to model drivers' car-following behavior since the introduction of the General Motor (GM) stimulus-response models (Chandler et al., 1958; Gazis et al., 1959; Herman et al., 1959). However, most of these models are unable to capture driving behavior in the new connected driving environment, and models to capture these new behaviors are very limited in the literature. Early efforts to model this new driving environment focused on Automated Highway Systems (AHS) where fully autonomous vehicles were operated on a set of designated lanes (Varaiya and Shladover, 1991). Long before the "Google car", that pioneering work laid the foundation for understanding and exploring several