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Effect of information availability on stability of traffic flow: Percolation theory approach

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ABSTRACT

Connectivity and automation are expected to enhance safety and efficiency in transportation systems. Connectivity will provide information to drivers/autonomous vehicles to enhance decision-making reliability at the operational and tactical levels. Consequently, drivers are more likely to execute safe and efficient maneuvers and autonomous vehicles will have a more accurate perception of the traffic condition and an "error-free" execution of the driving maneuvers. At the operational level, ensuring string stability is a key consideration since unstable traffic flow results in shockwave propagation and possibly crashes. While several studies have examined the effects of information availability on string stability in a connected environment, most of the approaches are focused on automated driving (e.g., Cooperative Adaptive Cruise Control systems) and do not consider a mixed environment with regular, connected, and autonomous vehicles. To ensure connectivity in such a mixed environment, the correlation between communication range and connected vehicles density should be considered. To capture the effects of this correlation, this study uses the Continuum Percolation theory to determine the effects of the vehicular density and communication range on the connectivity level in telecommunications network and consequently, on the string stability of traffic flow. Based on the Continuum Percolation theory, there is a critical density of connected vehicles above which the entire system is connected. This critical density also depends on the communication range. This study presents an analytical derivation of this critical density. Moreover, this study evaluates the string stability under different communication ranges and market penetration rates of connected and autonomous vehicles. Results revealed that as communication range increases, the system becomes more stable and at high communication ranges, the system performs similar to the system with full connectivity. Moreover, results indicated the existence of an optimal communication range to maximize stability and ensure information delivery.

1. Introduction

Connected and autonomous vehicles continue to promise improvements in the efficiency and safety of individual vehicle maneuvers throughout the surface transportation systems. In a connected Vehicle-to-Vehicle (V2V) and Vehicle-to-

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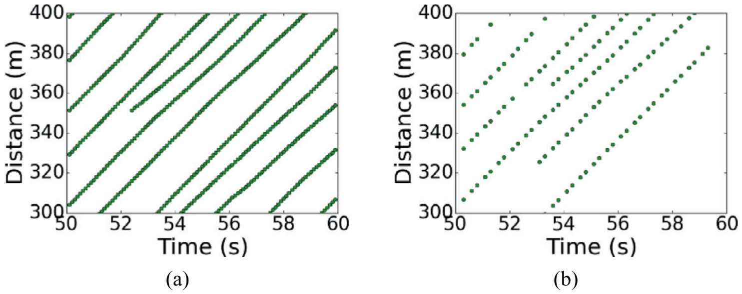

Fig. 1. Vehicle trajectory data based on NGSIM US-101 dataset (a) complete trajectories, (b) received data (simulated using ns-3) (Talebpour et al., 2016).

Infrastructure (V2I) communications network, a vehicle receives information from other vehicles in its vicinity and traffic management center (TMC). This information can help drivers and autonomous vehicles execute safer and more reliable and efficient maneuvers. Efficient maneuvers, on the other hand, result in different traffic patterns, which can influence communications and information availability. Unfortunately, the collective effects of this additional information on traffic flow dynamics are not sufficiently known. Preparing the surface transportation systems to maximize the benefits of these technologies requires an understanding of these possible collective effects on traffic flow dynamics. Therefore, considering such information is essential to investigate the effects of connected environment on transportation systems (Mahmassani, 2016).

At the operational driving decision-making level and car-following behavior, traffic flow stability is a key factor. A string stable system resolves shockwaves and prevents them from propagating upstream and creating severe congestion. Unfortunately, the effects of information propagation and signal interference on the stability of traffic flow have not been investigated extensively in the literature. Though a few studies have investigated the effect of telecommunications on stability, most of these assume full connectivity (Talebpour et al., 2016). However, full connectivity in a V2V communications network does not always exist due to several factors, including physical barriers and signal interference (Talebpour, 2015; Talebpour et al., 2016). Talebpour et al. (2016) illustrated the effects of signal interference on data quality by comparing the actual vehicle trajectories and the location data received by a roadside unit through V2I communications (See Fig. 1). The actual vehicle trajectories are based on the NGSIM US-101 dataset (Federal Highway Administration, 2006) and data transmission is simulated using ns-3 (ns-3.25). One roadside unit is simulated in the middle of the 2100 ft segment on US-101, which was used to collect the NGSIM data. The message routing protocol is the Adopted Message Routing Protocol (AODV).

In addition to imperfect communication, vehicular density and communication range are important factors in communication networks. In a real-world environment, 1-hop communication (i.e., direct communication between vehicles) is not always possible and does not guarantee propagation of all relevant messages. In fact, multi-hop communication is essential to ensure that all the vehicles in immediate need of the information will receive it. To ensure this multi-hop communication, enough vehicles should be within the communication range of each vehicle. Therefore, communication range should be carefully selected in relation with the vehicular density. Without V2V communications and additional information, drivers are uncertain about their leaders' behavior and their car-following behavior is expected to be very similar to that of regular vehicles. Therefore, considering the communication range along with the vehicular density is essential to determine the effect of connectivity and automation on stability of traffic flow.

The propagation of information within vehicular networks is very similar to the behavior of a fluid spreading through a porous medium, a disease spreading among people, or information propagation in social networks. The latter physical and behavior phenomena/observations have been studied extensively in the literature and several models have been introduced to capture the underlying mechanisms. Percolation theory (Broadbent and Hammersley, 1957) is among the most reliable and accurate approaches to model these phenomena. The original Percolation theory describes the behavior of connected clusters in a random graph with infinite number of nodes and edges (Meester and Roy, 1996) and describes a critical phenomenon in which a connected path with an infinite size will almost surely appear for the first time in the original graph. Recognizing the similarity between information propagation in wireless communication networks and these phenomena, a few studies showed that the propagation of information in these networks can be captured by the Percolation theory (Ammari and Das, 2008).

Similar to the original percolation model, the information propagation problem in vehicular networks is focused on the behavior of connected cluster in the connectivity graph. Building upon the findings of Ammari and Das (2008), this paper presents an analytical derivation of the critical density above which the system is connected when percolation occurs in vehicular networks, and uses the Percolation theory to determine the effects of the vehicular density and communication range on the stability of traffic flow. The analytical investigation of stability uses Percolation theory to determine the connectivity level among vehicles, and adopts Ward's approach (Ward, 2009) to investigate string stability in a mixed platoon of connected, automated, and regular vehicles. Accordingly, the contributions of this paper consist of the following: (1) analytical derivation of the critical vehicular density beyond which communication may be secured between all vehicles in a given platoon; (2) the use of percolation theory to investigate the platoon string stability as a function of the communication range and the traffic conditions (i.e. density levels); and (3) endogenous consideration of the market penetration rates

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