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A network level connectivity robustness measure for connected vehicle environments

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A R T I C L E I N F O

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A B S T R A C T

This study introduces a new CONnectivity ROBustness model (CONROB) to assess vehicle-to-vehicle communication in connected vehicle (CV) environments. CONROB is based on Newton's universal law of gravitation and accounts for multiple factors affecting the connectivity in CV environments such as market penetration, wireless transmission range, spatial distribution of vehicles relative to each other, the spatial propagation of the wireless signal, and traffic density. The proposed methodology for the connectivity robustness calculation in CONROB accounts for the Link Expiration Time (LET) and the Route Expiration Time (RET) that are reflected in the stability of links between each two adjacent vehicles and the expiration time of communication routes between vehicles. Using a 117 sq-km (45-square mile) network in Washington County, located west of Portland city, Oregon, a microscopic simulation model (VISSIM) was built to verify CONROB model. A total of 45 scenarios were simulated for different traffic densities generated from five different traffic demand levels, three levels of market penetration (5%, 15%, and 25%), and three transmission range values [76 (250), 152 (500), and 305 (1000) m (ft)]. The simulation results show that the overall robustness increases as the market penetration increases, given the same transmission range, and relative traffic density. Similarly, the overall connectivity robustness increases as the relative traffic density increases for the same market penetration. More so, the connectivity robustness becomes more sensitive to the relative traffic density at higher values of transmission range and market penetration. Multiple regression analysis was conducted to show the significant effect of relative traffic density, transmission range, and market penetration on the robustness measure. The results of the study provide an evidence of the ability of the model to capture the effect of the different factors on the connectivity between vehicles, which provides a viable tool for assessing CV environments.

1. Introduction

Connected vehicle (CV) rely on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication technologies. The technological component of CV requires a robust platform that allows for not only creativity and interoperability, but also the ability to interact with the complex human behavior. This has become a cutting-edge area of research for more advanced and low cost intelligent transportation systems (ITS). Inter-vehicle communication (IVC) has the potential to link vehicles, transportation infrastructure, and personal mobile devices in a safe and inter-operable wireless network to

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approach challenging transportation areas such as safety, mobility and environment (Chandrasekharamenon and Ancharev, 2012). In a CV environment, road network with connected vehicles and/or infrastructure, each vehicle acts as a sender, receiver, and router to broadcast information to the vehicular network or transportation agency, which then uses the information to ensure safety and smooth operation of traffic (Zeadally et al., 2012). Most of the currently available traffic information systems still rely on a centralized communication model, where the collected traffic data are sent to a central processing unit before being distributed back to the drivers. This is not only inefficient, mostly because of the delay of information receiving, processing and sending, but also costly because of the high infrastructure cost (Yousefi et al., 2008). This has given rise to an increasing interest in computing and wireless communication in surface transportation systems; an emerging trend is to equip vehicles with computing and communication capabilities. Seven channels in the 5.9 GHZ band for dedicated short range communication (DSRC) have been allocated and regulated by the U.S. Federal Communications Commissions (FCC) to support the V2V applications (Ng and Travis Waller, 2010).

In contrast to the conventional centralized traffic information systems, the V2V systems support the development of a vehicle ad hoc network, also referred to as VANET. Vehicles in a VANET send and receive messages directly between each other through wireless communication and indirectly with vehicles beyond the transmission range via intermediate ones. Although estimating connectivity a priori is important to help guide specifications of appropriate communication devices, technical problems such as routing protocols, network capacity and message delivery latency are fundamental technology problems in IVC systems (Jin and Recker, 2010) yet to be tackled. An ideal IVC system is defined as the connectivity between all CV on the road network with 100% coverage of the road network and a minimal probability of failure. Two groups of factors determine such connectivity: (1) those related to the traffic stream, such as traffic flow (density) and market penetration; and (2) others related to the technology itself such as the transmission range, interference caused by infrastructure, and channel information. Generally, larger transmission range with higher traffic density and higher market penetration allow more vehicles to be connected and information to propagate further on road networks. With all these factors, a measure of effectiveness that can give an indicator for the performance of CV environments and account for as many of these factors as possible is needed.

This paper presents a mathematical model that gives an indicator to the robustness and stability of the connectivity between CV on large scale road networks. This model accounts for more than one controlling factor affecting connectivity in CV environments. The rest of the paper is organized as follows: section two presents a background about the technology and some of factors affecting its performance, section three discusses the model development and its properties, section four presents the verification of the model, section five discusses the verification results, and section six summarizes the main findings of the paper and the future research.

2. Background

The relevant literature on CV technology can be divided into two main categories. The first one focuses on simulation-based research and the second focuses on analytical studies (Ng and Travis Waller, 2010). Studies in the literature include networks in one and two dimensions (Panichpapiboon and Pattara-Atikom, 2008; Wang et al., 2011; Wu et al., 2009; Ukkusuri and Du, 2008; Guler et al., 2014; Ge and Orosz, 2014), and networks where the number of nodes can be finite or infinite (Ergen, 2010; Ng and Travis Waller, 2010). The focus of most studies is mainly on the expected propagation distance, probability of communication and the critical transmission range. In most instances, it is assumed that communication nodes (vehicles) follow a Poisson distribution on a line or a plane. This means that their locations are independent of each other, and their density is uniformly random at any location. This is not valid for a traffic stream due to interactions between vehicles. Vehicle position depends on car-following and lane-changing rules and density changes along the roadway due to driver behavior and network geometry (Jin and Recker, 2010). Considering this problem, an analytical model was developed in which positions of vehicles were known through observations, traffic simulators or traffic theories (Jin and Recker, 2010).

Basics from traffic theory have been also applied to IVC systems. Yousefi et al. (2008) studied the three macroscopic parameters that describe the state of a road (speed, density, and flow) analytically to describe the connectivity of VANETs operating in the free-flow regime. Their findings show that increasing the traffic flow and the transmission range leads to increasing connectivity. On the other hand, Ergen (2010) proposed a formula for penetration in dense scenarios. Later, Boban et al. (2011) studied the impact of vehicles as obstacles in the VANET reporting that obstructing vehicles have a significant impact in both dense and sparse vehicular networks and that effect should be included in VANET models.

As part of studying the market penetration and its effect on the connectivity in a CV environment, Goodall et al. (2013) proposed a rolling horizon traffic signal control algorithm called PMSA that enables smooth and more reliable signal control that can update itself based on traffic delay. The PMSA was tested at different market penetration levels as a sensitivity analysis. Simulation results using VISSIM on the proposed algorithm give promising results, especially when the market penetration is greater than 50%. Another study by Christofa et al. (2013) measured the effect of the different market penetrations on a methodology that they developed for real-time queue detection and signal control strategies that can mitigate the impact of oversaturated traffic conditions. Ma et al. (2012) also studied the effect of market penetration on a proposed online highway travel time prediction framework using vehicle-infrastructure Integration (VII). The authors found that 20% market penetration results in one of the best travel time prediction accuracies among the reported values in the literature in terms of