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Variable speed limit: A microscopic analysis in a connected vehicle environment

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ABSTRACT

This paper presents a Variable Speed Limit (VSL) control algorithm for simultaneously maximizing the mobility, safety and environmental benefit in a Connected Vehicle environment. Development of Connected Vehicle (CV)/Autonomous Vehicle (AV) technology has the potential to provide essential data at the microscopic level to provide a better understanding of real-time driver behavior. This paper investigated a VSL control algorithm using a microscopic approach by focusing on individual driver's behavior (e.g., acceleration and deceleration) through the use of Model Predictive Control (MPC) approach. A multi-objective optimization function was formulated with the aim of finding a balanced trade-off among mobility, safety and sustainability. A microscopic traffic flow prediction model was used to calculate Total Travel Time (TTT); a surrogate safety measure Time To Collision (TTC) was used to measure instantaneous safety; and, a microscopic fuel consumption model (VT-Micro) was used to measure the environmental impact. Real-time driver's compliance to the posted speed limit was used to adjust the optimal speed limit values. A sensitivity analysis was conducted to compare the performance of the developed approach for different weights in the objective function and for two different percentages of CV. The results showed that with 100% penetration rate, the developed VSL approach outperformed the uncontrolled scenario consistently, resulting in up to 20% of total travel time reductions, 6–11% of safety improvements and 5–16% reduction in fuel consumptions. Our findings revealed that the scenario which optimized for safety alone, resulted in more optimum improvements as compared to the multi-criteria optimization. Thus, one can argue that in case of 100% penetration rates of CVs, optimizing for safety alone is enough to achieve simultaneous and optimum improvements in all measures. However, mixed results were obtained in case of lower % penetration rate which showed higher collision risk when optimizing for only mobility or fuel consumption. This indicates that with such % penetration rate, multi-criteria optimization is crucial to realize optimum and balanced benefits for the examined measures.

1. Introduction

Variable Speed Limit (VSL) systems are Intelligent Transportation System (ITS) solutions that enable dynamic changes of posted speed limits in response to prevailing traffic, incidents and/or weather conditions. VSL systems utilize traffic speed,

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volume detection, and road weather information systems to determine the appropriate speeds at which drivers should be traveling, given the current traffic and road conditions. Changes in posted speed limits are indicated by displays on overhead or roadside variable message signs. VSL systems have great potential to be used as an incident management tool and have significant impact on traffic operations, congestion management, safety and environmental sustainability on major roadways. The main benefits of VSL implementation can be summarized as follows:

1. *Improvements in safety:* Which is achieved by the reduction of speed differences among vehicles traveling in the same lane and/or adjacent lanes. This reduction in speed variance synchronizes drivers' behavior and discourages lane changing behavior, thereby decreases the probability of collisions (Abdel-Aty et al., 2006).
2. *Resolving traffic breakdown:* When traffic is close to capacity, any disruption in the traffic stream can lead to traffic breakdown. VSL can restore freeway capacity by slowing down traffic that would otherwise enter bottleneck locations, thereby delaying or in some cases preventing occurrence of traffic flow breakdowns (Hegyi, 2004).
3. *Improved throughput and environmental benefits:* Since congestion is also associated with increased fuel consumption and emissions, the capability of VSL in improving traffic flow also results in environmental benefits (Zegeye et al., 2010).

The VSL control strategies developed so far can be divided into two broad categories: reactive rule-based approaches and proactive approaches. Reactive rule-based VSL strategies have limited potential, due to their reliance on simplistic localized control logic; whereas network-wide coordinated proactive VSL control strategies have the inherent capability of acting proactively, while anticipating the complex behavior of dynamic systems. The majority of the developed proactive VSL strategies, however, have been based on the 2nd order macroscopic traffic flow model and utilized aggregate data (such as average speed, flow and density) from point detection technology. Deployment of such technologies corresponds to high installation, maintenance and communication costs, as well as high failure rates (Herrera et al., 2010). Moreover, this relatively coarse aggregation of data obscures many features of interest, such as any possible changes in the traffic state within the aggregation interval (Wu and Liu, 2014). In addition, these macroscopic models used for VSL design do not reflect the behavior of individual drivers in a traffic stream. When traffic is in congested state, any disturbance in the flow can create shockwaves that may result in traffic breakdown. Such shockwaves result from microscopic driver behavior, such as sudden deceleration, merging or lane changing, leading to uneven headways. The use of a macroscopic traffic model cannot completely reflect the occurrence of such disturbances (Khondaker and Kattan, 2015).

The current strategy of VSL design can be improved in a Connected Vehicle environment where the wireless communication system acts as the next generation of new sensors. More specifically, Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication initiatives (moving close to deployment) will provide a basis to detect individual vehicle trajectories. These data at a microscopic or individual vehicle level can be used as more accurate input to design advanced traffic control devices aiming to reduce congestion and enhance safety on roadways. The main advantage of using microscopic data is that the behavior of drivers can be described in detail. For instance, the analysis of individual trajectory data is important to identify the location and magnitude of shock wave formation that can be created at the individual vehicle level, such as a vehicle changing lanes or coming to a sudden stop. This step is crucial to activate advanced traffic control devices in a timely fashion. Consequently, studies that focus on individual driver's behavior (e.g., acceleration/deceleration, lane changing, over passing, etc.) rather than aggregate behavior are needed to develop the next generation of advanced and robust traffic control devices.

This paper has taken a further step toward developing a VSL control strategy by using traffic data at the microscopic/individual vehicle level to achieve concurrent sustainability objectives. This is the first study, to our knowledge, to incorporate driver behavior (acceleration/deceleration and compliance to posted speed limit) in designing a proactive VSL system that is formulated as a multi-objective optimization function to simultaneously optimize mobility, safety and environmental sustainability. In this research, improvement of network efficiency has been measured in terms of minimizing Total Travel Time (TTT) of all the vehicles in the network. A surrogate safety measure, Time To Collision (TTC), has been used to capture the instantaneous safety between each individual pair of vehicles. For assessing the environmental benefit, VT-Micro model developed by Rakha et al. (2004) has been used which has the capability of performing the evaluations of environmental aspects of traffic management, operations and ITS strategies at microscopic level. Rather than using a fixed driver's compliance rate, the algorithm incorporated real-time driver's compliance to adjust the optimal speed limit values. The developed approach has been tested using the VISSIM microsimulation tool via an integrated VISSIM-COM (Component Object Model)-MATLAB interface.

This rest of the paper is organized as follows: In Section 2, a detailed literature review on VSL control strategy is presented. Section 3 provides an overview of the adopted methodology, including the traffic flow, safety model, VT-Micro model, objective function, and optimization method that have been used in this study. Section 4 describes a case study that has been done using the proposed approach, followed by simulation results in Section 5. Section 6 presents the conclusions and scope for future research.

2. Literature review

Early VSL studies were mainly formulated as simple reactive rule-based logic. In those approaches, real-time VSL decisions were changed based on preselected thresholds of traffic flow, occupancy or mean speed. The main objectives of these