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Variable Speed Limit Design to Relieve Traffic Congestion Based on Cooperative Vehicle Infrastructure System

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Abstract

To uniform traffic flow, and to improve traffic mobility and safety, variable speed limit (VSL) is usually implemented on freeways. With predictive models, traffic states evolutions can be predicted, so VSL values can be optimized within model predictive control (MPC) frameworks to keep traffic flow at a high efficiency and suppress propagation of shockwaves, especially during congestion periods. METANET model is a widely used predictive tool, as well as its many extensions. In this paper, a new extension of METANET is proposed based on cooperative vehicle infrastructure system (CVIS), also known as vehicle-infrastructure integration (VII) system. By introducing vehicle models, vehicles' speed and position on each link are recorded, and prediction is changed to a mesoscopic scale, which describes the traffic entities at a high level of detail, but describes their behaviour and interactions at a lower level of detail (Van Woensel et al. 2007). Compared with previous studies that use macroscopic variables for prediction, the new model suits the situations in CVIS, where communication between vehicles and infrastructures will be adopted to replace variable message signs (VMS). Simulation results have shown the capacity of the proposed model in predicting state evolutions. Additionally, VSL's ability to improve traffic efficiency and prevent congestion propagation is proved.

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Keywords: Variable speed limit; Model predictive control; METANET; Cooperative vehicle infrastructure system; Traffic congestion

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1. Introduction

As freeways increasingly networked and the number of vehicles grows, traffic congestion now has an increasing negative impact on the mobility and efficiency of freeways. Although construction of new roads can to some extent alleviate the problem, a more promising and cost-efficient solution is to use the existing infrastructure more efficiently through dynamic traffic control methods, such as ramp metering (RM), variable speed limits (VSL), route guidance (RG) and so on. Among them, VSL has shown its effect in reducing accidents as well as improving mobility and efficiency of freeways. However, in most field studies, improvement about travel time and capacity is not as significant as improvement about safety (Hadiuzzaman et al. 2013). This is because VSL are mostly implemented in a reactive manner. To prevent traffic breakdown actively instead of responding to it, model predictive control (MPC) methods are proposed. In this way, traffic planners can predict the formation of active bottlenecks and evaluate traffic improvement under different control values and strategies. Therefore they are able to post optimized speed limit values to prevent breakdown and relieve traffic congestions.

In MPC approach, accurate predicting models are desirable. As a macroscopic modeling tool, METANET (Kotsialos et al. 2002) and its many extensions have been widely used in many previous works in order to make precise predictions of traffic flow state variables. Hegyi et al. (2005) proposes a new VSL model and incorporates speed limits within METANET model, revising previous methods in which the effect of speed limit is expressed by downscaling the desired speed-density diagram. The paper also includes the extension that describes the different effects of a positive or negative downstream density gradient on the speed, and extension that includes the modeling of a mainstream origin. Later, Carlson et al. (2010) extends METANET model and describes the effect of displayed VSL values using affine functions. By rendering static speed-density relationship rate-dependent, the model includes link-specific VSL rates into the link model. In addition to extensions on VSL effect, density and flow variables are also considered. Hadiuzzaman et al. (2013) includes the capacity drop concept in FD to model active bottleneck and introduces cell transmission model (CTM) (Daganzo, 1994) to represent density dynamics, replacing previous assumption that transition flow among the links is equivalent to average link flow. All these extensions are aimed for a more precise prediction. However, they are based on macroscopic data, collected by loop detectors in the real world.

Due to the advancements in information technology, the integration of vehicles and infrastructure has been receiving significant attention. One particular approach is that of cooperative vehicle infrastructure system (CVIS), also known as vehicle-infrastructure integration (VII), which is recognized to have the potentials in improving traffic safety and mobility to a greater level (Paniati, 2005). With complete network information provided by the probe vehicles, such as vehicle's real-time speed and position in the corridor, the density of links can be estimated, as well as the mean speed. Thus it is feasible to predict traffic flow states by predicting the position and speed of each vehicle, a microscopic approach, instead of predicting the evolution of density and mean speed of each link, in macroscopic ways.

This paper proposes an extension of METANET model based on cooperative vehicle infrastructure system, where speed and density evolutions are estimated using microscopic data. Thus prediction scale is transferred from links to vehicles. As a vehicle will probably move to the downstream links during a time period, its speed is affected by several consecutive links instead of one. So its speed prediction should take into account the mean speed evolution of the downstream links as well as the current link. Travel distance of each vehicle is calculated using its mean speed during a single time step. Then, by recording the group of vehicles in the link, link density and mean-speed, the macroscopic variables, during the predicted time horizon can be estimated. It is expected that through the proposed model, traffic state variables can be precisely modeled and predicted. Additionally, based on the new model, VSL values can be optimized using MPC approach.

The rest of this paper is organized as followings. The methodology section presents the VSL control strategy and the proposed traffic flow predictive model. Then in order to optimize VSL values, the MPC framework with the objective to improve total travel time and total flow is introduced. In the simulation section, the studied corridor and calibration steps are presented. Details in simulation design and the final results are also included in this part. Finally, a summary including conclusions and future research scope is given.