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Accounting for dynamic speed limit control in a stochastic traffic environment: A reinforcement learning approach

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ABSTRACT

This paper proposes a novel dynamic speed limit control model accounting for uncertain traffic demand and supply in a stochastic traffic network. First, a link based dynamic network loading model is developed to simulate the traffic flow propagation allowing the change of speed limits. Shockwave propagation is well defined and captured by checking the difference between the queue forming end and the dissipation end. Second, the dynamic speed limit problem is formulated as a Markov Decision Process (MDP) problem and solved by a real time control mechanism. The speed limit controller is modeled as an intelligent agent interacting with the stochastic network environment stochastic network environment to assign time dependent link based speed limits. Based on different metrics, e.g. total network throughput, delay time, vehicular emissions are optimized in the modeling framework, the optimal speed limit scheme is obtained by applying the R-Markov Average Reward Technique (R-MART) based reinforcement learning algorithm. A case study of the Sioux Falls network is constructed to test the performance of the model. Results show that the total travel time and emissions (in terms of CO) are reduced by around 18% and 20% compared with the base case of non-speed limit control.

1. Introduction

Speed limits are implemented in the traffic infrastructure system primarily based on the safety consideration. There are many studies which examine the safety benefits of imposing speed limits. To name a few, Kloeden et al. (2001) and Ossiander and Cummings (2002) showed that increasing the speed limit could lead to higher fatal crash rate and more deaths. Lee et al. (2006) proposed a real time crash prediction log-linear model to evaluate the relationship between crash potential (the likelihood of crash) and speed limit. It is demonstrated that 5–17% reduction of crash potential can be achieved by imposing real time variable speed limit control. Nowadays the environmental benefits of speed limits are also noticeable due to the growing traffic pollutions and the awareness of the impact of greenhouse gases, especially in urban areas. (Keller et al., 2008) showed that a 4% reduction of NO_x emissions was obtained when speed limit on Swiss motorways decreased from 120 kph to 80 kph. Madireddy et al. (2011) found that CO_2 and NO_x emissions could be reduced by 25% if speed limits decrease from 50 kph to 30 kph in the study area of Belgium.

1.1. Literature review and motivations

In recent years, the mobility benefits of speed limit control began to attract researchers' interest. Deterioration of traffic condition in urban areas has long been a burden to urban economic development and people's quality of life. From the

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demand side, many traffic control management strategies have been proposed to relieve congestion problems. As one of many traffic control strategies, speed limit control is an important strategy to alleviate congestion and emission in traffic networks.

Typically, depending on temporal dimension, the speed limit control problem can be classified to two categories: static and dynamic speed limit control. In the static case, the speed limit control problem is usually considered as part of the network design problem. Yang et al. (2012) revisited the static user equilibrium (UE) problem with speed limits, and investigated the impact of speed limits on total travel time and vehicular emission at a network level. The numerical studies show reduction in both travel time and vehicular emission with an appropriate speed limit design. Based on the notion of user equilibrium, Wang (2013) developed a bi-level programming model to design optimal speed limits considering both network efficiency and equity. No decisive conclusion can be reached on whether the total travel time reduces under the UE principle with speed limits. On the other hand, dynamic speed limit control is implemented in practice especially in highway work zones, known as variable speed limit (VSL) control (NRC, 1998). Empirical studies have shown the effectiveness of VSL in smoothing traffic flow and reducing traffic breakdowns (van den Hoogen, 1994; Raemae, 2002). Kang et al. (2004) developed an on-line algorithm for dynamic VSL control in highway work zone operations. Hegyi et al. (2005) integrated VSL control and ramp metering and solved the coordination control problem by applying the model predictive control (MPC) approach. The model can also be extended to consider main-stream metering. Significant travel time reduction (15%) compared with non-control case is obtained in the numerical case study. Followed the line, Carlson et al. (2010) formulated the integrated VSL control and ramp metering problem as a constrained discrete-time optimal control problem. A universal open-loop optimal control tool (Papageorgiou and Kotsialos, 2002; Kotsialos et al., 2002) by computing suitable feasible directions is applied to solve the problem.

It is worth to note that one limitation of the above studies of speed limits (both static and dynamic) is that the stochastic property of network either from the demand side or supply side is not considered. Another limitation is that most of the above studies utilize macroscopic model to simulate traffic flow propagation. Hence they are not able to capture the more realistic and important characteristics of traffic, e.g. shockwave propagation, spill-back effect of heavy congestions. One motivation of this paper is to fill these research gaps in the literature.

Another motivation of this study is to address the dynamic speed limit control problem under the connected vehicle (CV) environment. CV environment is a recently developed concept owing to the development of wireless communication technology, especially the Dedicated Short Range Communications (DSRC) technology. DSRC has great potential in the area of intelligent transportation system (ITS), as it enables the wireless exchange of information between vehicles, as well as between vehicles and roadside infrastructure. The CV technology is primarily developed to improve the safety of traffic (crash collision avoidance) at intersections. The secondary concern is to alleviate congestion and reduce vehicular emission. Acknowledging the potential, the intelligent transportation system program of the U.S. Department of Transportation (DOT) emphasizes CV research in the ITS Strategic Plan (2010–2014). CV environment facilitates communication platform where vehicles can talk to adjacent vehicles (i.e., Vehicle-to-Vehicle, V2V), to the infrastructure components (i.e., Vehicle-to-Infrastructure, V2I), and also infrastructure to infrastructure communication (i.e., I2I). CV has also received attention in Europe, where it is known as Car to Car (C2C) and Car to X (C2X) technology. Though CV has not been implemented in the real world transportation system yet, many auto companies are expending significant efforts to produce vehicles with communication features. In addition, many test beds are ongoing in US, Europe, and Japan. Recent advances in CV environment offer useful technologies in detection and acquisition of high fidelity data that can be used for more efficient traffic control strategies. In particular, under the CV environment, the speed limit controller has access to the traversing information of the surrounding vehicle, e.g. origin, destination, path taken, speed, distance traveled, etc. Based on the information, the controller produces the time-varied speed limit scheme and sends the speed limit back to the vehicle. The vehicle adjusts its free flow speed accordingly. The interacting process between the controller and the vehicle is going on continuously, hence the realization of dynamic speed limit control.

1.2. Contributions of the paper

Triggered by the above motivations, this paper sets out to propose a novel dynamic speed limit control model based on reinforcement learning approach. In the model, it is required that the traffic flow information of the link is known to the speed limit controller. This setting is technologically possible under the CV environment. Under the CV environment, vehicles are able to communicate with infrastructure, thus the controller is able to inform speed limit to the vehicles. In current practice, it is also plausible to implement the dynamic speed limit by imposing variable speed limit signs and deploying roadside sensors along the links of interest.

The contributions of the paper are mainly twofold. (1) We have developed a link-based dynamic network loading (LDNL) model with the consideration of speed limits under the stochastic network environment. The demand input is generated randomly according to a certain probability distribution. Similarly, the saturation capacities of the specified links are also randomly generated to account for the uncertain supply (e.g., highway crash, lane closure, work zone, etc.). In the proposed LDNL model, every link in the given network is divided into three parts, namely, the beginning part, the main part, and the ending part. The beginning part and the ending part are of fixed size depending on the preset resolution, while the main part allows flexible size depending on the residual length of the link. Flow propagation to and from the main part is strictly analyzed applying the kinematic wave theory. The shockwave propagation is well defined and captured by checking the