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Using connected vehicles in a variable speed limit system

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Abstract

Variable speed limit systems are used to improve the traffic conditions on specific road stretches. This is done by adjusting the speed limits according to current traffic situations. A variable speed limit system usually consist of stationary detectors to estimate the traffic state and variable message signs at predefined locations for the application of new speed limits. Advances in vehicle technology have made it possible to use connected vehicles to improve existing variable speed limit systems. Connected vehicles can continuously transmit information about speed and location. This can be used to get more detailed information about the traffic state. By including information from connected vehicles in a variable speed limit system there is a potential to identify bottlenecks also in between stationary detectors. Further, it is possible to use direct control of the connected vehicles to adjust vehicle speeds towards the new traffic situation. In this study, we propose such a variable speed limit system based on connected vehicles. The aim is to allow for application of variable speed limits in connection with non-recurrent bottlenecks. The proposed system is evaluated with respect to traffic efficiency using microscopic traffic simulation. An incident is simulated as an example of a non-recurrent bottleneck. The traffic performance when the proposed VSL system is applied is compared to the performance without the system. The results indicate that the VSL system manage to improve traffic efficiency in a majority of the simulated cases.

Keywords: connected vehicles; variable speed limit; traffic management; microscopic traffic simulation; traffic efficiency

1. Introduction

Variable Speed Limit (VSL) systems make use of an estimate of the current traffic state, described by traffic density, speed and flow, to adjust the speed limit towards the traffic situation on a specific road stretch. The goal is to improve the traffic situation with respect to safety and/or efficiency. However, the estimate of the traffic state is usually based on data from stationary detectors and the VSL is displayed on variable message signs at predefined locations. The development in vehicle technology has opened up for a new type of VSL systems based on connected vehicles. Connected vehicles are able to continuously transmit and receive information about their current speed, position on the road, speed limit, etc. Therefore, an enhanced VSL system can take advantage of connected vehicles both for traffic state estimation and for the application of VSLs.

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In this paper, we propose a VSL system including connected vehicles with the potential to increase traffic efficiency at non-recurrent bottlenecks. The aim is to allow application of VSLs at non-recurrent bottlenecks with limited use of stationary detectors and variable message signs (VMSs). In the proposed VSL system, connected vehicles are used as sensors and to communicate variable speed limits to individual vehicles. This allow for traffic state estimation at arbitrary locations, unlike today's VSL systems which uses traffic state estimates based on data from stationary detectors at fixed locations. Thereby, the need for expensive infrastructure can be reduced. The current speed limit is communicated directly to the connected vehicles instead of using VMSs. This allows direct control of the speed of connected vehicles towards the new speed limit, similar to an adaptive cruise control. Hence, the proposed VSL system consists of three parts: (1) estimation of the traffic state using information from connected vehicles, (2) calculation of an appropriate variable speed limit by identification of non-recurrent bottlenecks based on changes in the traffic state, (3) application of the variable speed limit through direct control of the speed of the connected vehicles. In this study, we use microscopic traffic simulation for evaluation of the effects on traffic efficiency of the proposed VSL system. An incident scenario is simulated as an example of a non-recurrent bottleneck. Traffic performance with the proposed VSL system is compared to the performance without the system.

The reminder of the paper is organized as follows. In Section 2, a background to the methods used in the different parts of the VSL system is given. The proposed VSL system is presented in Section 3. In Section 4, the evaluation method and the simulated incident scenario are described. Simulation results are presented in Section 5. Finally, conclusions are given in Section 6.

2. Background

The proposed VSL system consists of an estimate of the traffic state based on data from connected vehicles; identification of non-recurrent bottlenecks as changes in the traffic state; and application of a VSL control strategy based on the estimated capacity levels by direct control of connected vehicles.

The most common way to estimate the traffic state is to make use of data from stationary detectors, such as for example loop and radar detectors (Kurkjian et al., 1980; Coifman, 2003; Singh and Li, 2012). This is limiting the traffic state estimation to specific points in space, and the conditions in between detectors remains unknown. Data assimilation and fusion techniques based on filters and traffic modelling are common methods to get the complete picture of the traffic state in between the detectors, see for example Munoz et al. (2003), Mihaylova et al. (2007), Wang and Papageorgiou (2005) and Duret et al. (2016). As more sources of traffic data are becoming available, e.g. data from connected vehicles and mobile phones, these have been used as input to update the modelled traffic state. Examples are presented by Herrera and Bayen (2007), Work et al. (2010) and Seo et al. (2015b). Other methods that are making use of data from connected vehicles for traffic stated estimation without an underlying traffic model are presented by Herrera et al. (2010), van Lint and Hoogendoorn (2010), Ma et al. (2011), Seo et al. (2015a), Montero et al. (2016) and Grumert and Tapani (2017b).

The process of identifying changes in the traffic state is often referred to as incident detection. In order for the incident detection to be useful in a VSL system it has to be automatically triggered by an underlying algorithm. In automatic incident detection algorithms the approach is either statistical using artificial intelligence and machine learning (Payne et al., 1976; Samant and Adeli, 2001; Wang et al., 2013; Kinoshita et al., 2015) or based on traffic modelling (Wang et al., 2009; Dabiri and Kulcsár, 2015; Grumert and Tapani, 2017a). Traffic modelling based algorithms use a traffic model to estimate the traffic state and changes in the model parameters are monitored to identify an incident. The model parameters can be estimated based on on-line calibration, such as described by Wang and Papageorgiou (2005), Antoniou et al. (2007) and Tampère et al. (2007).

Finally, a VSL is applied at the identified non-recurrent bottlenecks based on the observed changes in the traffic state. VSL systems can be categorized into two main types, *incident detection* systems and *homogenization* systems. Incident detection systems, sometimes also referred to as warning systems, have as main objective to resolve congestion caused by an incident and limit the risk of further breakdown. Homogenization systems have as aim to reduce differences in speed to reduce potential instabilities and to keep the capacity as high as possible. The main difference between the systems is that homogenization systems are often applied before reaching congested traffic states, while incident detection systems are triggered when a breakdown, i.e. very low speed situations, in the traffic states is detected. As a result, the speed limit is often reduced gradually, while more abrupt speed limit changes often are applied in incident detection systems. Up until now, most real implementations of variable speed limit systems are of incident detection systems, although combinations of incident detection and homogenization systems does also exist. Empirical studies of the effects of incident detection systems (van den Hoogen and Smulders, 1994; Smulders and Helleman, 1998; Highway Agency, 2007; Nissan and Koutsopoulos, 2011) have shown a reduction in the number of incidents and a decreased variance in mean speed between lanes. No increase, or even a decrease, is seen in the throughput, i.e. traffic efficiency is not increased by the systems. Since the aim of the proposed VSL system is to increase traffic efficiency at non-recurrent bottlenecks it is suitable to use a homogenization algorithm, such as the one described in Carlson et al. (2011).

The growing amount of technology related to connected vehicles have resulted in recent studies where connected vehicles are used as a part of VSL systems. Kattan et al. (2015) extend a VSL algorithm by Hegyi et al. (2005) which is based on model predictive control. The aim is to minimize travel time by including measurements of speed from connected vehicles. Khondaker and Kattan (2015) take into account estimates of each connected vehicle's total travel time, time to collision and emission levels and optimize the corresponding aggregated values in the model predictive control strategy. The goal of the optimization is to find the VSL to be displayed on VMSs. Wang et al. (2016) introduce a car-following control algorithm taking into account the