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Validation of an extended discrete first-order model with variable speed limits

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ABSTRACT

This paper validates the prediction model embedded in a model predictive controller (MPC) of variable speed limits (VSLs). The MPC controller was designed based on an extended discrete first-order model with a triangular fundamental diagram. In our previous work, the extended discrete first-order model was designed to reproduce the capacity drop and the propagation of jam waves, and it was validated with reasonable accuracy without the presence of VSLs. As VSLs influence traffic dynamics, the dynamics including VSLs needs to be validated, before it can be applied as a prediction model in MPC. For conceptual illustrations, we use two synthetic examples to show how the model reproduces the key mechanisms of VSLs that are applied by existing VSL control approaches. Furthermore, the model is calibrated by use of real traffic data from Dutch freeway A12, where the field test of a speed limit control algorithm (SPECIALIST) was conducted. In the calibration, the original model is extended by using a quadrangular fundamental diagram which keeps the linear feature of the model and represents traffic states at the under-critical branch more accurately. The resulting model is validated using various traffic data sets. The accuracy of the model is compared with a second-order traffic flow model. The performance of two models is comparable: both models reproduce accurate results matching with real data. Flow errors of the calibration and validation are around 10%. The extended discrete first-order model-based MPC controller has been demonstrated to resolve freeway jam waves efficiently by synthetic cases. It has a higher computation speed comparing to the second-order model-based MPC.

1. Introduction

Over the past decades, variable speed limits (VSLs) have emerged as a popular control measure for traffic flows on freeways. The main objective of VSLs is to improve traffic operation efficiency. For this purpose, earlier studies have assumed that the freeway capacity can be raised if the speeds across vehicles in different lanes is harmonized by VSLs (Zackor, 1972). Following this line, Cremer (1979) proposed a quantitative model for the VSL-induced fundamental diagram, in which the free flow capacity was assumed to increase under certain VSL rates. It has been found that VSLs can increase utilization of the shoulder lane on a long homogeneous freeway stretch (Duret et al., 2012). For shorter freeway stretches, although VSLs can homogenize the speed of individual vehicles, no evidence has shown that VSLs can increase the free flow capacity. In fact,

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later investigations could not identify any capacity increase that could be attributed to VSLs (Smulders, 1990; Soriguera et al., 2017).

Recently, some studies have focused on resolving jam waves or preventing the onset of congestion by using analytical approaches. A well-known example of this type of approach is the SPECIALIST algorithm (Hegyi et al., 2008), which was developed based on the Kinematic Wave theory (Lighthill and Whitham, 1955; Richards, 1956). It aims to resolve freeway jam waves and achieve a higher outflow by limiting the arriving flow to the jam via VSLs. While the approach has been successfully tested in practice (Hegyi and Hoogendoorn, 2010), its disadvantage is that its feed-forward structure does not correctly handle disturbances. Many of the failures are due to significant demand increase during the VSL control (Han et al., 2015). The algorithm was later extended to a feedback structure, which is known as COSCAL v2, to better handle disturbances (Mahajan et al., 2015). Chen et al. (2014a) recently proposed several analytical VSL schemes based on the kinematic wave theory, to increase the discharge rate of both recurrent and non-recurrent bottlenecks. In those approaches, a triangular fundamental diagram with stable states on the congestion branch was assumed. However in reality, traffic states on the congestion branch are unstable, which might undermine the implementation potential of those approaches.

Another avenue of the VSL control is the model-based optimization method. Traffic model predictive control (MPC) predicts the evolution of traffic dynamics and calculates the optimal control scheme for the time period in which the relevant traffic dynamics occur. This feature enables the controller to take advantage of potentially larger future gains at a current (smaller) cost, so as to avoid myopic control actions. Hegyi et al. (2005b) and Carlson et al. (2010) presented MPC approaches that are based on a non-linear second-order traffic flow model METANET (Kotsialos et al., 2002). In Hegyi et al. (2005b), VSLs were applied to suppress freeway moving jams. The application of VSLs upstream of a moving jam temporarily decreases the mainstream arriving flow to resolve the moving jam. The assumed VSL effect was to replace the left part of the flow-density curve by a straight line with the slope corresponding to the displayed VSL values. In Carlson et al. (2010), the main objective was to control the free-flow traffic upstream of a bottleneck to prevent the bottleneck activation. It was assumed that sufficiently low VSLs lead to lower capacity in the fundamental diagram than in no-VSL cases. Thus, the application of VSLs upstream of a bottleneck permanently reduces the mainstream arriving flow, which helps to avoid the bottleneck activation. The incorporated VSL model was based on the empirical findings from Papageorgiou et al. (2008).

In recent years, linear or quadratic MPC approaches of VSLs that are based on extended discrete first-order models have become a popular choice because they can achieve a low computation time, which is beneficial for real-time applications (Muralidharan and Horowitz, 2015; Roncoli et al., 2015b; Hadiuzzaman and Qiu, 2013). Due to the fact that the prediction models of those controllers are not able to reproduce the propagation of jam waves accurately, the type of traffic jam that those controllers addressed is limited to standing queue. Recently, Han et al. (2017) presented a linear quadratic MPC which is based on a new extended discrete first-order model to resolve freeway jam waves. The new extended discrete first-order model is solved by the minimum sending flow and receiving flow method, in which the boundary flow between two cells are determined by the minimum between the sending flow (demand) and the receiving flow (supply) (Lebacque, 1996). For the VSL model incorporated in the new extended first-order model, it was assumed that lower values of VSLs reduce the sending flow of a cell and the receiving flow of a cell keeps unchanged. With this assumption VSLs can be used to regulate flows from the mainstream of freeways. In that paper, the presented controller was compared with a METANET-based MPC in terms of computation speed and resolving freeway jam waves. Simulation results show that the new extended discrete first-order model-based MPC is able to resolve freeway jam waves efficiently, and it has less computation cost than the METANET-based MPC.

Although many MPC approaches of VSLs have been demonstrated to be effective in resolving traffic jams or reducing total travel delay through simulations, few have validated the prediction model in reproducing the behavior of VSLs. The MPC approach presented in Han et al. (2017) was based on a new extended discrete first-order model with a triangular fundamental diagram, which was validated with reasonable accuracy without the presence of VSLs. As VSLs influence traffic dynamics, the prediction model of the MPC forecasts the evolution of traffic states under VSLs based on the effects of VSLs, and the control performance relies on the accuracy of the forecasting. Thus, the predicting traffic dynamics under VSLs need to be validated since the accuracy of the prediction model is essential to the control performance. This paper moves towards this direction.

For conceptual illustrations, we use two synthetic examples to show how the model reproduces the key mechanisms of VSLs that are applied by existing VSL control approaches in the literature. In addition, model calibration and validation are performed by using real traffic data from Dutch freeway A12, where the field test of a speed limit control algorithm called SPECIALIST was conducted. In the calibration and validation part, the prediction model is extended by using a quadrangular fundamental diagram which keeps the linear feature of the model and represents traffic states at the under-critical branch more accurately. An extended METANET model with VSLs, which is commonly used for MPC of VSLs, is also calibrated and validated with the same data for comparison (Hegyi et al., 2005a). The results for both models are evaluated qualitatively and quantitatively.

The remaining of the paper is organized as follows. Section 2 presents the extended first-order model and the incorporated VSL model. In Section 3, two synthetic cases are presented to show how the model behaves in reproducing the key mechanisms of VSLs that are used by existing VSL approaches in the literature. In Section 4, model calibration and validation are performed to demonstrate that the prediction model can accurately forecast the effects of VSLs to jam waves. Section 5 presents the conclusions.