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Resolving freeway jam waves by discrete first-order model-based predictive control of variable speed limits

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ABSTRACT

In this paper we develop a fast model predictive control (MPC) approach for variable speed limit coordination to resolve freeway jam waves. Existing MPC approaches that are based on the second-order traffic flow models suffer from high computation load due to the nonlinear and non-convex optimization formulation. In recent years, simplified MPC approaches which are based on discrete first-order traffic flow models have attracted more and more attention because they are beneficial for real-time applications. In literature, the type of traffic jam resolved by these approaches is limited to the standing queue in which the jam head is fixed at the bottleneck. Another type of traffic jam known as the jam wave, has been neglected by the discrete first-order model-based MPC approaches. To fill this gap, we develop a fast MPC approach based on a more accurate discrete first-order model. The model keeps the linear property of the classical discrete first-order model, meanwhile takes traffic flow features of jam waves propagation into consideration. A classical nonlinear MPC and a recently proposed linear MPC are compared with the proposed MPC in terms of computation speed and jam wave resolution by a benchmark problem. Simulation results show that the proposed MPC resolves the jam wave with a real-time feasible computation speed.

1. Introduction

Due to increasing demand, traffic jams happen frequently at current freeway networks. Traffic jams generate many negative effects such as reducing freeway capacity, inducing travel delays and potentially unsafe traffic conditions. Infrastructure expansion is an effective way to combat traffic jams. However, adding additional lanes and new freeways are not always viable due to economical or environmental concerns. Instead, traffic control measures are playing more and more important roles in improving traffic operation efficiency.

To implement effective traffic control measures to resolve traffic jams, the features of traffic jams have to be investigated. In general, two types of traffic jams on freeways can be identified. As has been presented in (Hegyi et al., 2008), traffic jams with the head fixed at the bottleneck are known as standing queues, and jams that have an upstream moving head and tail are known as jam waves (also known as wide moving jams in some studies, e.g., (Kerner and Rehborn, 1996)). A standing

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queue can be formed at a busy on-ramp, a lane drop bottleneck, or any kind of infrastructural bottleneck. According to empirical studies in literature (Cassidy and Bertini, 1999; Chung et al., 2007; Srivastava and Geroliminis, 2013), the outflow of a standing queue is typically 10–15 percent lower than the free flow capacity, which is known as the capacity drop. Jam waves usually originate from breakdowns, and in most cases from standing queues. Possible triggers for the formation of a jam wave could be a vehicle suddenly braking or a lane-changing vehicle in a high-demand traffic flow situation. Therefore, since so many (partially unobservable) factors influence the formation process, the formation of a jam wave is considered stochastic and difficult to be reproduced. However, from different empirical studies, some common patterns of its propagation can be distilled. For example, the propagation speed of jam waves is relatively constant, typically between 15 and 20 km/h (Kerner and Rehborn, 1996). The queue discharge rate of a jam wave is typically around 30 percent lower than the free flow capacity (Schönhof and Helbing, 2007). It can propagate for a long time period and distance, and resolves only with the traffic demand decreasing (Kerner and Rehborn, 1996). Jam waves are considered more difficult to reproduce than standing queues, because the bottleneck of jam waves moves dynamically rather than fixed at specific locations.

The common feature of standing queues and jam waves is that both of them are associated with a capacity drop. Thus, the aim of many freeway traffic control methods are often to prevent the activation of bottlenecks, so as to avoid the occurrence of the capacity drop and maximize the outflow of the bottleneck. Variable speed limit (VSL) and ramp metering are commonly used control measures on freeway networks to regulate the flow and delay the onset of congestion. Ramp metering regulates the inflow from the on-ramp to the mainstream of the freeway to delay or prevent the activation of the bottleneck. The performance of ramp metering control is limited by available storage space at on-ramps (Carlson et al., 2011). Normally VSLs do not suffer from the storage capacity restriction since the mainstream of freeways are wider and longer than on-ramps. VSLs may be used to reduce the mainstream flow, so as to resolve traffic jams or delay or prevent the activation of bottlenecks. There are two mechanisms of VSLs in reducing mainstream flows that are explained as follows. First, when lower VSLs are applied on a freeway stretch at under-critical densities, there is a transition to a new traffic state, which serves the same flow at lower speed and high density. During this transition, the density increase leads to a temporary reduction of the mainstream flow (Carlson et al., 2010). Second, sub-critical VSLs lead to a fundamental diagram that has lower capacity with lower VSLs.

There are various theories and algorithms to determine the appropriate values of the VSLs. SPECIALIST is an analytical approach for VSL control to resolve jam waves based on the shock wave theory (Hegyi et al., 2008). While the approach was successfully tested in practice (Hegyi and Hoogendoorn, 2010), its disadvantage is that due to its feed-forward structure, disturbances during activation of the VSLs are not handled. Later on, the algorithm has been extended to a feedback structure, which is known as COSCAL v2 (Mahajan et al., 2015), to overcome the deficiency of the SPECIALIST algorithm. Analytical approaches are usually efficient in computation and easy to be implemented. However, they are not easy to be adapted to new situations (e.g., changes in infrastructure). Traffic model predictive control (MPC) is another control approach which has attracted the attention of many researchers. It predicts the evolution of traffic dynamics and calculates the optimal control scheme for the time period in which the relevant traffic dynamics occurs. This feature enables the controller to take advantage of potentially larger future gains at a current (smaller) cost, so as to avoid a myopic control actions. The coordination of VSL by MPC to suppress jam waves has been investigated by Hegyi et al. (2005b), where the design is based on a non-linear second-order model METANET (Kotsialos et al., 2002). Another advantage of MPC is that various of control measures can be easily integrated into one control system. Consequently, VSL control is often integrated with other control measures such as ramp metering by MPC (Hegyi et al., 2005a; Carlson et al., 2010; Roncoli et al., 2015b).

Optimal control formulations based on the discrete macroscopic second-order model, METANET, have become a popular choice since the model has been calibrated and validated with a reasonable accuracy. However, the non-linear and non-convex optimization formulation of METANET-based MPC might result in high computation load, especially if the optimization is solved by the standard SQP algorithm (Hegyi et al., 2005b). Researchers have managed to solve this problem by developing more efficient computational algorithms, such as the feasible-direction algorithm (Kotsialos et al., 1999a), the parameterization algorithm (Zegeye et al., 2012; van de Weg et al., 2015). A noticeable problem for METANET-based MPC of VSL is that the solution of the optimization may depend on the selection of the initial guess trajectory, in the sense that if the initial guess is not appropriately chosen, the solution of the optimization might get stuck at a local minimum. In recent years, linear or quadratic optimizations for traffic control have attracted more and more attention. The origin of this type of approach dates back to (Gazis and Potts, 1963), who suggested a store-and-forward modeling approach to traffic control problems. Following this line, Papageorgiou (1995) proposed a linear optimization approach for integrated traffic control based on a store-and-forward model. Later on, Lo (1999) and Ziliaskopoulos (2000) embedded the cell-transmission model into a linear optimization problem for dynamic traffic assignment purpose. Since the capacity drop was not considered, the only gain of the controller was coming from increasing the off-ramp flows. Recent research has incorporated the capacity drop into linear MPC for VSL and ramp metering control (Muralidharan and Horowitz, 2015; Roncoli et al., 2015b). The controllers have been demonstrated to be efficient in terms of computation speed and reducing total travel delay by the designed case studies. However, the type of traffic jam considered in their case studies is only the standing queue.

As far as we are concerned, there is no specific research in literature which aimed to resolve freeway jam waves through a linear MPC formulation. To fill this gap, in this paper we develop a linear-quadratic MPC based on an extended discrete first-order traffic flow model. The extended model keeps the linear property of the classical discrete first-order model, meanwhile takes traffic flow features of jam waves propagation into consideration. The performance of the proposed controller is com-