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Variable speed limit control for severe non-recurrent freeway bottlenecks

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ABSTRACT

Variable speed limit (VSL) schemes are developed based on the Kinematic Wave theory to increase discharge rates at severe freeway bottlenecks induced by non-recurrent road events such as incidents or work zones while smoothing speed transition. The main control principle is to restrict upstream demand (in free-flow) progressively to achieve three important objectives: (i) to provide gradual speed transition at the tail of an event-induced queue, (ii) to clear the queue around the bottleneck, and (iii) to discharge traffic at the stable maximum flow that can be sustained at the bottleneck without breakdown. These control objectives are accomplished without imposing overly restrictive speed limits. We further provide remedies for (a) underutilized bottleneck capacity due to underestimated stable maximum flow and (b) a re-emergent queue at the bottleneck due to an overestimated stable maximum flow. We analytically formulate the reductions in total delay in terms of control parameters to provide an insight into the system performance and sensitivity. The results from the parameter analysis suggest that significant delay savings can be realized with the proposed VSL control strategies.

1. Introduction

Variable speed limit (VSL) control seeks to improve safety by smoothing out traffic state transitions temporally and/or spatially and freeway efficiency by deferring the onset of congestion or increasing the bottleneck (BN) discharge rate. Earlier efforts to improve freeway efficiency via VSL focused on harmonizing the speed across vehicles in different lanes to create a more homogenous, stable one-pipe flow with few lane-changes (LC) (Smulders, 1990; Zackor, 1991). This can presumably lead to higher capacity and critical density, thereby deferring or preventing onset of congestion (Papageorgiou et al., 2008). Several studies have shown that VSL control indeed induces more balanced speed and utilization of lanes (Duret et al., 2012; Knoop et al., 2010; Smulders, 1990; Weikl et al., 2013; Zackor, 1991).

SPECIALIST (SPEed ControllIng ALgorIthm using Shock wave Theory) seeks to proactively resolve a moving jam and maximize the discharge rate by limiting the speed and density of the inflow to the moving jam via VSL (Hegyi et al., 2008, 2009). The algorithm was tested in the field with reasonable success. Another notable scheme is the mainstream traffic flow control (MTFC) developed in the framework of discrete-time optimal control (Carlson et al., 2010a). The main objective is to control the free-flow traffic upstream of a BN (before a queue arises) via VSL or ramp metering to prevent BN activation. The algorithm was tested on a Dutch network via simulation (Carlson et al., 2010b). Later, local feedback control was incorporated into MTFC to further improve the potential for field implementation (Carlson et al., 2011).

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Chen et al. (2014) developed different VSL schemes based on the Kinematic Wave (KW) theory (Lighthill and Whitham, 1955; Richards, 1956) to increase freeway BN discharge rates and manage the queue upstream (for smoother speed transition) under two scenarios: steady queue and oscillatory queue that can inevitably arise at fixed BNs. The key principle is to impose VSL control some distance upstream of a BN to starve the inflow to the BN and dissipate the queue. Once the queue near the BN vanishes, another less restrictive VSL is imposed upstream to (i) resolve the heavy queue generated by the first VSL and (ii) regulate the inflow to sustain the stable maximum BN discharge rate and prevent BN re-activation.

The strategies cited above were designed primarily to address recurrent BNs or moving jams, in which a reduction in discharge rate typically ranges from 5% to 15% (e.g., Bertini and Leal, 2005; Cassidy and Bertini, 1999). These strategies, however, are not very suitable for non-recurrent severe BNs induced by major road events such as incidents or work zones. These types of severe BNs usually involve (partial) lane blockage and are characterized by moderate to severe congestion due to significant reductions in system throughput (in greater proportion than lanes blocked (Knoop et al., 2008, 2009a,b)) and sharp transitions upstream from free-flow traffic to the queues, which may cause secondary incidents. A significant reduction in system throughput is attributable to: (1) a decrease in capacity due to road blockage, (2) rubbernecking around the road event, (3) change in driver characteristics (Knoop et al., 2009b), and (4) disruptive LCs away from the road event. In regard to (4), speed and flow may vary significantly among lanes with lower speed and flow closer to the road event. LCs away from the road event are likely to create voids in other lanes and reduce the discharge rate similar to the capacity drop phenomenon of recurrent BNs (Laval and Daganzo, 2006).

In this study, we develop VSL strategies to proactively improve the discharge rate of non-recurrent severe BNs and manage the upstream queue for smoother speed transition. An increase in discharge rate is achieved by clearing the queue around the BN and then maintaining a stable maximum flow with harmonized speed to minimize disruptive LCs. We assume that other aforementioned effects on discharge rate reductions ((1)–(3) in the previous paragraph) are reflected in the FD of the BN (e.g., rubbernecking may decrease the free-flow speed), but our VSL strategies do not significantly change these effects. The strategies developed in this paper are based on the KW theory and use the logic similar to Chen et al. (2014). However, the new strategies address more effectively several critical issues for non-recurrent severe BNs: (a) a very restrictive speed limit (lower than the speed in queue as in Chen et al. (2014)) should be avoided for better driver acceptance and compliance because congestion for this type of BN is likely more severe; (b) the upstream queue management should be more elaborate to provide smoother queue transition; and (c) it may not be straightforward to precisely estimate the stable maximum discharge rate, which can lead to underutilization of BN or re-emergent queue at the BN.

This study develops a theoretical framework for VSL control to improve the performance of severe BNs (or any BNs where low VSL is not desired, and gradual speed transition is preferred). This is an important contribution given that existing strategies were primarily designed to mitigate recurrent BNs. The VSL control strategies developed in this study are relatively simple, yet capable of addressing two critical issues for severe BNs: (i) reducing total delays significantly and (ii) providing smoother speed transition for better safety. The theoretical approach provides insights into traffic dynamics with VSL control and the impact of control parameters on the system performance (e.g., delay savings). Moreover, it provides a foundational framework to address more complex freeway networks and incorporate various implementation issues (e.g., detection and control technologies).

The remaining manuscript is organized as follows. Section 2 describes the basic VSL control strategy including the analysis of parameters on the system performance and sensitivity. Section 3 develops VSL strategies to address uncertainty in the stable maximum flow estimation. Concluding remarks are provided in Section 4.

2. Basic VSL control for severe bottlenecks

2.1. Baseline case

We study severe freeway BNs due to major road events that may partially block the roadways and reduce the throughputs, as shown by Fig. 1(a). We assume that the traffic evolution can be well approximated by the KW model with triangular fundamental diagrams (FD). The main logic of our VSL control, however, does not depend on the shape of FD, although some details of traffic evolution, such as shock wave speed, would change. The upper FD in Fig. 1(b) describes traffic states upstream of a BN with free-flow speed u, wave speed w and jam density k_j; and the lower FD describes traffic states at the BN location with lower free-flow speed u^{evt} and jam density k_j^{evt}. Note that we assume $u^{evt} < u$ due to rubbernecking and other effects induced by the road event.

We assume that traffic demand is constant in state A, and traffic breaks down to state H when the BN becomes active. After the road event is cleared, traffic recovers the full, normal capacity of q_{max} in state M. State e represents the stable maximum flow state that can be sustained at the BN without breakdown for an extended period; i.e., the BN capacity, $q_{BN} = q_e$. (The notation, q_{-}, represents flow in the traffic state denoted in subscript.) Note that $q_H < q_{BN}$ due to LC disruptions; and $q_{BN} - q_H$ represents the potential gain of system throughput. States G and E correspond respectively to the free-flow and congested states with the same flow as q_{BN} (i.e., $q_{BN} = q_E = q_G = q_e$) upstream of the BN.

The spatiotemporal traffic evolution without any control is illustrated in Fig. 1(c). After the road event, a heavy queue (in state H) propagates upstream, forming a shock wave, s_{AH}. (Hereafter, s_{-} refers to a shock wave delineating two different traffic states denoted in subscript and represents the shock wave speed when used in equations.) When the road event is cleared at