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Effectiveness of variable speed limits considering commuters' long-term response

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A B S T R A C T

This paper examines the effectiveness of variable speed limits (VSLs) on improving traffic flow efficiency and reducing vehicular emissions in a stylized setting of morning commute where a fixed number of individuals commute from home to work through the freeway with a single recurrent bottleneck. The mechanism of interest is for a VSL system to prevent the bottleneck from being activated and thus avoid detrimental capacity drop that arises at the activated bottleneck. We firstly consider a VSL system installed along the freeway towards the bottleneck, which adjusts commuters' cruising speeds in a continuous fashion and essentially regulates the upstream flow into the bottleneck. By investigating the resulting departure-time equilibrium of commuters, we find the VSL system can eliminate the efficiency loss caused by capacity drop, and further bound its improvements on various performance measures. We then turn to a more practical VSL system, which adjusts commuters' cruising speeds in a discrete fashion. The conditions for such a system to improve various performance measures are established and its efficiencies are bounded. Based on empirical data, we conclude that the discrete VSL system can avoid or delay capacity drop associated with an active bottleneck and thus reduce queuing delay. It can help reduce the schedule delay cost and total emissions cost. However, it is unlikely for the system to reduce total travel time, individual travel cost and social cost in this particular setting. These results shed light on the effectiveness of VSL systems on realistic freeway networks.

1. Introduction

Imposing speed limits is a widely used and effective tool for speed regulation to reduce traffic accidents and prevent road casualties. As static speed limits designed for ideal or prevailing conditions may not be effective during adverse weather or heavy congestion, variable speed limits (VSLs) have been proposed to commend safe driving speeds during less than ideal conditions (see, e.g., Elefteriadou et al., 2012, for a recent review of implementations of VSLs in the U.S. and Europe). Considerable efforts have been made to evaluate the effects of VSLs on reducing crash potentials and enhancing safety (e.g., Boyle and Mannering, 2004; Lee et al., 2006; Abdel-Aty et al., 2006).

On the other hand, VSL control has emerged as a widespread scheme to improve traffic flow efficiency on freeways. A contemporary VSL system consists of a series of traffic sensors, VSL signs, variable message signs and a central processing

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unit, which integrates all system sensors and signs to determine time-varying speed limits and display them in a timely fashion (Lin et al., 2004). VSL systems can be designed to harmonize speeds across lanes to delay the onset of traffic breakdown and attain higher capacity and critical density, or reduce the probability of breakdown (e.g., Zackor, 1979; Smulders, 1990; Papageorgiou et al., 2008; Geistefeldt, 2011). More proactively, by forcing traffic to slow down in a controlled manner, VSL systems can be utilized as mainline metering devices to prevent traffic flow breakdown and avoid capacity drop at active bottlenecks (e.g., Hegyi et al., 2005a,b; Carlson et al., 2010). Although theoretically appealing, these VSL systems may not have significant impacts on traffic conditions if drivers do not comply with displayed speed limits for various reasons (e.g., Nissan and Koutsopoulosb, 2011).

This study conducts a theoretical analysis of the effectiveness of VSL systems on reducing travel cost and vehicular emissions. The mechanism of interest is for VSL systems to regulate traffic inflow to prevent bottlenecks from being activated and thus avoid detrimental capacity drops that arise at activated bottlenecks (e.g., Carlson et al., 2010). In contrast to the abundant literature on VSLs that mainly focuses on their localized impacts on traffic flow and microscopic behaviors of drivers, this study examines VSL systems from an equilibrium perspective and considers individual travelers' long-term response to VSL systems. Attempts have been made to investigate how speed limits reallocate traffic flow across a network in an equilibrium manner (e.g., Yang et al., 2012, 2013b; Wang, 2013). However, when variable or time-varying speed limits are concerned, the reallocation effect on traffic would no longer be limited to the spatial dimension, e.g., the choice of routes, but also the temporal dimension, e.g., departure-time choices. For instance, if a relatively low speed limit is imposed at a given time, some drivers may choose to depart at another time to avoid it. Such changes in departure times of travelers will yield different time-dependent traffic demands and inevitably affect the effectiveness of VSL systems.

As we seek to mitigate congestion closely associated with rush hour commute trips, we conduct our analysis in this paper based on Vickrey's bottleneck model (Vickrey, 1969). In this model, a fixed number of individuals commute from home to work through a potential bottleneck. If the bottleneck is activated, a first-in-first-out (FIFO) queue will develop and, consequently, commuters incur a queuing delay, in addition to a free-flow cruising travel time to the bottleneck. Commuters also incur a schedule cost if they arrive at work earlier or later than desired arrival times. Assuming that each individual chooses his or her departure time to minimize a commute cost that combines (constant) cruising time, queuing delay and schedule cost, Vickrey's analysis shows how individuals' choice of departure time shapes traffic congestion and provides policy implications on how to mitigate morning commute traffic congestion. Given its analytical tractability, Vickrey's bottleneck model has been used to study various transportation policies, such as congestion pricing, flexible work schedule, parking management and tradable mobility credits (e.g., Yang et al., 2013a; Liu et al., 2014a,b). For recent comprehensive reviews, see, e.g., Arnott et al. (1998) and de Palma and Fosgerau (2011). When a VSL system is introduced to Vickrey's morning commute setting, it adjusts the free-flow cruising time to the bottleneck to influence commuters' departure-time choices. A well-designed VSL system can control the traffic inflow rate to the downstream bottleneck to prevent its activation. This paper is to investigate the design of such a VSL system and bound its efficiency on reducing commuters' travel cost, vehicular emissions and total social cost of morning commute.

The remainder of this paper is organized as follows. Section 2 reviews Vickrey's bottleneck model and then extends it to capture the impact of capacity drop without VSL. In Section 3, an ideal VSL system is designed to prevent the onset of congestion and avoid capacity drop, and its effectiveness and efficiency are then discussed. Section 4 introduces a more practical VSL system operating in a discrete fashion, and Section 5 evaluates such a VSL system against a variety of performance measures, including total travel time, total schedule cost, total travel cost, total emission cost and total social cost. Finally, Section 6 concludes the paper.

2. Morning commute problem without VSL

2.1. Basic setting

Consider a continuum of mass N commuters traveling from home to work every morning, as shown in Fig. 1. All commuters are assumed to have identical preferences concerning the timing and cost of their trips. Departing at time t, a commuter will experience the following travel cost, which includes both the travel time cost and the schedule delay cost:

$$c(t) = \alpha \cdot T(t) + \beta \cdot \max\{0, t^* - t - T(t)\} + \gamma \cdot \max\{0, t + T(t) - t^*\}, \tag{1}$$

where $T(t)$ is the travel time at departure time t; t^* is the desired arrival time at the destination, i.e., workplace; α is the value of unit travel time, and β and γ are the schedule penalties for a unit time of early and late arrival respectively. The travel time,

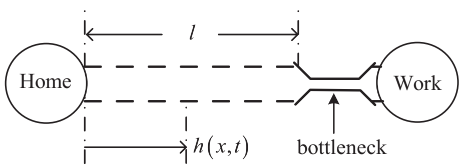

Fig. 1. Morning commute with a single bottleneck.