Transportation Research Part C 69 (2016) 418–435

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Optimal locations and travel time display for variable message signs

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ARTICLE INFO

Article history:
Received 2 September 2015
Received in revised form 20 June 2016
Accepted 22 June 2016
Available online 5 July 2016

Keywords:
Variable message signs
Utilization rates
Network equilibrium
Locations and travel time display

ABSTRACT

This paper first develops a network equilibrium model with the travel time information displayed via variable message signs (VMS). Specifically, the equilibrium considers the impact of the displayed travel time information on travelers' route choices under the recurrent congestion, with the endogenous utilization rates of displayed information by travelers. The existence of the equilibrium is proved and an iterative solution procedure is provided. Then, we conduct the sensitivity analyses of the network equilibrium and further propose a paradox, i.e., providing travel time information via VMS to travelers may degrade the network performance under some poor designs. Therefore, we investigate the problem of designing the VMS locations and travel time display within a given budget, and formulate it as a mixed integer nonlinear program, solved by an active-set algorithm. Lastly, numerical examples are presented to offer insights on the equilibrium results and optimal designs of VMS.

1. Introduction

Variable message sign (VMS) is an electronic message board that is located close to a road and disseminates the information of incidents, weather, congestion, travel time or others to drivers. Deploying VMS can reduce travel time delays caused by incidents or recurrent congestion. For instance, informing drivers about incidents and congestion can guide them to divert to alternative routes in advance. Moreover, displaying travel time or traffic conditions on VMS also allows drivers to predict their arrival time and further make appropriate arrangements to reduce the negative effects of the potential late arrivals, thus alleviating drivers' anxiety associated with traveling. Because of their effectiveness, VMS have developed to be an important component in an intelligent transportation system.

Different from the in-vehicle route guidance system (e.g., Du et al., 2015; Ma et al., 2015), the contents displayed on VMS cannot be personalized. With VMS's fast popularity, many guidelines for its use have been developed. For instance, the 2009 Manual on Uniform Traffic Control Devices provided guidance regarding VMS usage (FHWA, 2009). In the absence of adverse traffic incidents or events, it is suggested by the US Federal Highway Administration that credible travel time or traffic condition should be displayed on VMS (FHWA, 2004). Florida Department of Transportation now treats displaying travel times as a default on VMS (Yin et al., 2011; Chen et al., 2012). Although the guidelines for the operations of VMS have been largely explored, the number of studies about its optimal location and configuration of travel time displays (such as determining which destinations and routes to display) is limited in the literature. Among the existed studies, many focus on the incident

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http://dx.doi.org/10.1016/j.trc.2016.06.016
0968-090X/

scenario. Abbas and McCoy (1999) studied the optimal VMS location problem for incident management, which quantifies the benefit of VMS deployment by the reduction of delay, and utilizes a deterministic queuing model to estimate delays. Fu et al. (2007) further extended the optimization model through incorporating incident rates on individual links and logit-choice model to capture drivers' diversion behavior in response to the incident information provided by VMS. Peeta et al. (2000) and Peeta and Gedela (2001) investigated the impact of different contents of VMS on drivers' willingness to divert under incidents, and then proposed a real-time VMS control heuristic to seek diversion during incidents. Another group of studies (e.g., Chiu et al., 2001; Huynh et al., 2003; Chiu and Huynh, 2007) combined the dynamic traffic simulation and meta-heuristics to solve the optimal VMS location problem under random traffic incident situations.

Besides reducing delays in the incident scenario, some researchers noticed that VMS also has the potential of improving the network-wide performance under recurrent congestion (Kraan et al., 1999). If travel times are displayed on VMS under normal conditions, surveys suggested that drivers' route choice behaviors are positively impacted in a long term (Ban et al., 2009). To evaluate the impact of providing travel time information via VMS, Lam and Chan (1996) proposed a stochastic traffic assignment model for a road network with VMS in both steady and time-varying states. Specifically, the proposed model assumes the perceived error of a link's travel time is zero if it is displayed on VMS, and numerical examples show the impact of VMS is more significant in congestion conditions. Assuming commuters will gradually learn and adjust their route choice behavior based on the displayed travel times and then decide their route choices pre-trip instead of en-route, Ban et al. (2009) proposed a stochastic network-stochastic user static equilibrium model to describe the stationary network flow pattern under a particular VMS configuration plan, based on which the VMS locations and travel time display problem is formulated as a bi-level mathematical program, and solved by a simulated annealing algorithm. Note that none of the above studies consider the possibility that some drivers may refuse to follow the instructions of VMS because it increases their perceived travel time. In summary, the researches regarding the optimal locations of VMS mostly focus on VMS's function of diverting drivers to alternative routes in the incident scenarios, and overlook examining the effect of VMS displaying travel time information under recurrent congestion in normal traffic condition. Still lacking is a mathematically tractable modeling framework that optimizes the locations and travel time display for VMS with a comprehensive consideration of the impact of VMS displays on drivers' route choice behavior under normal traffic conditions.

Inspired by Lam and Chan (1996) and Ban et al. (2009), this paper firstly aims to develop a stochastic network equilibrium model with the travel time information displayed via VMS under recurrent congestion. The proposed network equilibrium model considers that the displayed travel time information on VMS affects drivers' perception errors of the link travel times. Moreover, we take into account that drivers have the flexibility of choosing whether to adopt the information displayed on VMS. The adoption rate of the displayed information on VMS is not fixed as a constant number, but modeled as an endogenous variable, calculated based on the perceived benefit the VMS can bring to drivers. Similar modeling approach can also be found in the studies on the network equilibrium models with advanced traveler information system (ATIS), which is a "user-based" facility and provides the traffic condition information of the whole network to the equipped drivers (e.g., Yang, 1998; Yang and Meng, 2001; Yin and Yang, 2003). ATIS provides drivers with the information of the whole network, but VMS can only disseminate the traffic condition of some specific links. Therefore, unlike the network equilibrium model with ATIS which can estimate drivers' perception errors in a path level and hence adopt the logit-based stochastic user equilibrium model, the models with VMS need to address link-specific perception errors.

Based on the proposed network equilibrium models with VMS, we further conduct the sensitivity analysis through taking derivative of the total network delays at equilibrium with respect to the link-specific perception errors. The results of the sensitivity analysis can provide insights on adjusting VMS's locations and travel time display to enhance the network mobility. Moreover, from the obtained derivative equations, we introduce a paradox where improving the accuracy of drivers' perceived travel times in existing links degrades the performance of a road network. This paradox justifies the necessity of optimizing the deployment and travel time display of VMS as well. Lastly, we formulate the problem of optimizing the locations and travel time display of VMS within a given budget as a mixed integer nonlinear program. In the light of the results of sensitivity analysis, we adopt the active set algorithm, proposed by Zhang et al. (2009), to solve it. Table 1 summarizes the reviewed studies about the optimal locations of VMS.

For the remainder of this paper, Section 2 defines the network equilibrium model with VMS displaying travel time information, proves its existence, and provides the solution method. Section 3 discusses the sensitivity of the total equilibrium network delays to the drivers' link-specific perception errors of travel times, and further utilizes a two-link

Table 1
Literature summary.

Publication	Recurrent or non-recurrent congestion	The adoption rate of the displayed information on VMS
Abbas and McCoy (1999), Chiu et al. (2001), Huynh et al. (2003), and Chiu and Huynh (2007)	Non-recurrent congestion	Not considered
Peeta et al. (2000), Peeta and Gedela (2001), Fu et al. (2007)	Non-recurrent congestion	Considered
Kraan et al. (1999), Ban et al. (2009), and Lam and Chan (1996)	Recurrent congestion	Not considered
This paper	Recurrent congestion	Considered