Transportation Research Part C 88 (2018) 208–226

Contents lists available at ScienceDirect

Transportation Research Part C

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

A time-varying parameters vector auto-regression model to disentangle the time varying effects between drivers' responses and tolling on high occupancy toll facilities

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ARTICLE INFO

Keywords:
High Occupancy Toll (HOT)
Time-varying parameter vector autoregressive model
Tolling
Time series
Impulse response function

ABSTRACT

High Occupancy Toll (HOT) lane systems are considered one of most effective countermeasures to mitigate freeway congestion. Existing studies have largely focused on developing optimal tolling strategies to maximize the benefits of congestion pricing. Limited effort has been made to model the dynamic feedback mechanism of drivers' responses to tolling. A thorough understanding of how the interactive relationship between demands (in both HOT lane and general purpose lanes) and toll rates evolves over time is necessary. The underlying mechanism can be used directly for guiding future HOT facilities investment decisions. This study builds upon the traditional vector autoregressive model and enables its parameters to be time-varying. Such a relaxation, namely, time-varying parameter vector autoregressive model (TVP-VAR), is used to answer the following two questions: (1) Is there a time varying effect between general purpose lane volume, HOT lane volume and dynamic toll rate? (2) If there is, how to quantify such time-varying interdependencies? Based on the empirical data from loop detectors and toll logs on Washington State Route 167 (SR167), we identified the existence of time-varying effects between drivers' responses and toll rates, and quantified the evolving interactions amongst HOT demand, general purpose demand and tolling via time-varying impulse responses. In addition, we found that drivers' perceptions on HOT lanes across distinct geographical locations are significantly different.

1. Introduction

To effectively address the underutilization of High Occupancy Vehicle (HOV) lanes due to restrained vehicle eligibility, the concept of High Occupancy Toll (HOT) lanes was introduced to allow those vehicles that do not meet the occupancy requirements to buy in to use the lanes. In recent years, HOT lane has become an increasingly popular traffic management strategy for congestion mitigation (Gardner et al., 2013). To help alleviate the general purpose (GP) lanes' load while ensuring its own reliability, the toll on HOT lanes is usually time-varying in response to changing traffic conditions. Two types of tolling strategies are commonly used on

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https://doi.org/10.1016/j.trc.2018.01.025
Received 29 May 2017; Received in revised form 14 January 2018; Accepted 28 January 2018

HOT lane facilities: schedule-based (by time-of-day, day-of-week), and dynamic (based on real-time traffic conditions) (Chung and Recker, 2011). The tolling scheme would influence people's willingness of using the HOT lanes. Thus a number of studies investigated the operational mechanism of tolling in an effort to provide guidance for policy-making and congestion relief (Fan, 2016; Zhang et al., 2008).

In the past decades, a wealth of studies have emerged striving to design optimal tolling mechanisms on the basis of HOT lane usage. Most of the proposed models are built upon dynamic tolling algorithms, aiming to minimize delay and/or maximize revenue (Shen and Zhang, 2009; Yin and Lou, 2009; Lou et al., 2011). However, these studies either have theoretically stringent assumptions or resort to simulation, which might refrain from real-world applicability. Liu et al. (2011) analyzed the traffic patterns on HOT lanes and GP lanes. They found that separation type has significant impact on friction intensity between the two, and a time-varying relationship might exist amongst toll rate, HOT lane traffic and GP lane traffic. The majority of previous studies, however, either only considered the unilateral effect without acknowledging the interactive influence of the three (toll rate, HOT lane traffic and GP lane traffic), or neglected the temporal variation on the extent of such interdependency. From the roadway users' perspective, their lane choice decisions are highly influenced by the operating conditions of both HOT lanes and GP lanes, as well as the toll rate, all of which are time-varying in nature. Therefore, a comprehensive understanding of how such interactive relationship evolves over time is necessary, which is also crucial in guiding future HOT lane investment decisions.

In theory, when GP lanes experience congestion, drivers may opt to enter the HOT lanes for travel time savings. This leads to an increase of demand in the HOT lanes and a decrease of demand in the GP lanes. As more and more Single Occupancy Vehicles (SOVs) pay to use the HOT lanes to avoid congestion, the level of service in the HOT lanes may deteriorate, causing a higher toll rate to discourage more drivers from entering. When congestion in the HOT lane is further reduced due to restrained demand, the toll rate will likely go down, and drivers may continue to use the GP lane since not much travel time savings can be achieved. In the context of managed lanes, both GP and HOT lanes' demands fluctuate in response to the toll rate. Interactively, the changes of traffic volumes in GP and HOT lanes also influence the toll. GP lane volume, HOT lane volume and toll rate thus interplay with each other, and emulate a feedback mechanism to improve the overall transportation system efficiency. Modeling the above dynamic feedback mechanism is challenging since motorists' responses to the toll are time-varying, and are influenced by a series of factors such as traffic condition and drivers' heterogeneous behaviors. Conversely, the dynamic toll functions as a signal to control the number of SOVs entering the HOT lane, and gives rise to the changes of HOT and GP lane volumes. Two questions remain unclear: (1) Is there a time-varying effect between GP lane volume, HOT lane volume and dynamic toll rate? (2) If the answer to the first question is yes, can we quantify such time-varying interdependencies? Understanding the time-varying mechanism between drivers' responses (and volume in the aggregated level) and toll rates provides useful insights to optimal tolling strategies design, theory on congestion pricing modeling, and managed lanes related investment and facility construction.

A robust tool to address the aforementioned issues is Vector Autoregression (VAR) model. Although being widely applied in macroeconomic econometrics, control theory and policy analysis, VAR has never been used in transportation, let alone managed lane operational modeling. In recent years, researchers extended the conventional VAR models by configuring the model coefficients and variance-covariance matrices of disturbance terms to change over time, which becomes Time-Varying Parameter VAR (TVP-VAR) model (Primiceri, 2005). Such a relaxation of traditional VAR models has the potential to model the interactions between demand (GP and HOT lanes) and tolling for HOT lane facilities, given their time-varying and dynamic nature. Such interactions (among GP lane volume, HOT lane volume, and toll rates) are intertemporal and contemporaneous.

In this study, we focus on exploring the time-varying interactive relationships among toll rate, HOT lane and GP lane traffic volume along the State Route 167 (SR 167) HOT lane facility in Seattle, Washington. A systemic framework is presented to unveil such interactive effects that have previously escaped notice. The contributions of this study are threefold: (1) the existence of time-varying effects between drivers' responses and toll rates is confirmed based on empirical data; (2) the evolving interactions amongst HOT demand, GP demand and tolling are quantitatively and respectively measured via time-varying impulse responses, which can be derived from the TVP-VAR model; and (3) behavioral heterogeneities of drivers' perceptions on HOT lanes across distinct geographical locations are captured.

The rest of the paper is organized as follows: Section 2 reviews literature on exploring the relationships among toll rate, traffic volume on HOT lanes and GP lanes. In Section 3, we present the TVP-VAR model in detail and its adaptability for unveiling the interactive effects of the aforementioned quantities. Using data from SR 167 HOT lane system in Seattle, Washington, we further put the model into perspective with thorough discussion. Implications and results are discussed at the end.

2. Literature review

2.1. HOT lane operation

In recent decades, with the increasing annual Vehicle Miles Traveled (VMT) and limited roadway capacity expansion, attention has been directed to effectively managing the existing infrastructure with traffic control strategies (Chen et al., 2015). Managed lane, especially congestion pricing, has been gaining popularity as an effective treatment for alleviating freeway congestion (Lindsey and Verhoef, 2001; Lindsey, 2006). Existing studies have focused on designing optimal tolling schemes for congestion pricing (Gardner et al., 2010; Meng et al., 2005; Lawphongpanich and Yin, 2012; Lou et al., 2011; Yin et al., 2004; Wu et al., 2011; Hamdouch et al., 2007; Laval et al., 2015; Zangui et al., 2013; Zhang et al., 2014b, 2014a; Chen et al., 2015). For example, Lawphongpanich and Yin (2012) proposed nonlinear pricing models to optimize the tolling algorithm with piecewise linear functions and found that equilibrium distribution functions formulated as convex optimization can be solved with traditional algorithms. Van den Berg (2012)