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Capturing Value of Reliability through Road Pricing in Congested Traffic under Uncertainty

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Abstract

Empirical studies showed that travel time reliability, usually measured by travel time variance, is strongly correlated with travel time itself. Travel time is highly volatile when the demand approaches or exceeds the capacity. Travel time variability is associated with the level of congestion, and could represent additional costs for travelers who prefer punctual arrivals. Although many studies propose to use road pricing as a tool to capture the value of travel time (VOT) savings and to induce better road usage patterns, the role of the value of reliability (VOR) in designing road pricing schemes has rarely been studied. By using road pricing as a tool to spread out the peak demand, traffic management agencies could improve the utility of travelers who prefer punctual arrivals under traffic congestion and stochastic network conditions. Therefore, we could capture the value of travel time reliability using road pricing, which is rarely discussed in the literature. To quantify the value of travel time reliability (or reliability improvement), we need to integrate trip scheduling, endogenous traffic congestion, travel time uncertainty, and pricing strategies in one modeling framework. This paper developed such a model to capture the impact of pricing on various costs components that affect travel choices, and the role of travel time reliability in shaping departure patterns, queuing process, and the choice of optimal pricing. The model also shows the benefits of improving travel time reliability in various ways. Findings from this paper could help to expand the scope of road pricing, and to develop more comprehensive travel demand management schemes.

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Keywords: Travel time uncertainty, road pricing, value of reliability

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1. Introduction

Travel time and travel time reliability are two major factors influencing travel decisions. The importance of travel time is intuitive and is well summarized in the Wardrop Principle (Wardrop, 1952), which constitutes the foundation for many transportation studies. The latter is also well studied in the literature (e.g. Small 1982, Noland and Small 1995, Bates et al. 2001, and Fosgerau and Karlström 2010) and its importance for travel decisions is well supported by many empirical studies. In particular, Carrion and Levinson (2012) provided a comprehensive review of empirical evidences. Although many studies propose to use road pricing as a tool to capture the value of travel time (VOT) savings and to induce better road usage patterns (e.g. Button and Verhoef, 1998; Yang and Huang, 2005), the role of the value of reliability (VOR) in designing road pricing schemes has rarely been studied.

Travel time variance has been used in many studies to quantify travel time reliability (or predictability). Empirical studies showed that travel time variance is strongly correlated with travel time itself. For example, Chen et al (2003) reported a correlation coefficient of 0.85 using data collected from I-5 in Los Angeles, California. Therefore, while road pricing may have helped to reduce congestion by inducing better route choice and departure time choice patterns, it may also at the same time generate additional social benefits by reducing travel time variability, or unreliability. The latter has not attracted sufficient attention in road pricing studies. By ignoring VOR in road pricing studies, we may forego great potential in improving the transportation system efficiency.

There are typically two approaches of modeling reliability consideration in departure time choice: the mean-variance approach and the scheduling approach. Researchers following the mean-variance approach assume that travel time variability (or unreliability) carries a disutility per se, and the utility function in this research strand usually constitutes a linear combination of travel time and its standard deviation. Other measures of travel time unreliability, including travel time variance (Jackson and Jucker 1982) and inter-quantile ranges (e.g. Small et al. 2005), have also been introduced. In contrast, the scheduling approach assumes travelers prefer punctual arrivals, and any earliness or lateness would constitute a cost. This assumption is consistent with the theory that travel demand is a derived demand. Although these two approaches start from very different behavioral assumptions, Bates et al (2001) and Fosgerau and Karlström (2010) demonstrated that for a wide range of travel time distributions, the disutility derived from these two approaches are approximately the same.

Although these two approaches provide a reasonable way to describe the preference for punctual arrival, they do not necessary provide a framework to capture the value of reliability. In static equilibrium analysis, the only source of delay comes from the insufficient bottleneck capacity which causes queuing, without regard to travel time uncertainty or variability. In reality, travel time is highly volatile when the demand approaches or exceeds the capacity. Therefore, travel time variability is associated with the level of congestion. By using road pricing as a tool to spread out the peak demand, traffic management agencies would improve the utility of travelers who prefer punctual arrivals under traffic congestion and stochastic network conditions. We can capture the value of travel time reliability by road pricing, which is rarely discussed in the literature. To quantify the value of travel time reliability (or reliability improvement), we need to integrate trip scheduling, endogenous traffic congestion, travel time uncertainty, and pricing strategies into one modeling framework. A lot of efforts have been dedicated to each isolated topic, or combinations of some of them. Nevertheless, considerably less effort has been sought in unifying all of them into one integrated framework. This study intends to fill in this gap.

2. Problem Formulation

This paper is built upon the work of Siu and Lo (2009) in modeling equilibrium trip scheduling in congested traffic under uncertainty. For completeness of exposition, we will briefly repeat some assumptions and formulations here.

Let's consider the ideal arrival time for everyone is 0, and the time a person X joining the bottleneck is

$$t_{in} = 0 - b(X) = -b(X) \tag{1}$$

b(X) is travel time budget associated with individual X.

When X enters the bottleneck, the queue length at the moment is Q(X). The time when this individual leaves the bottleneck is