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# Congestion pricing under operational, supply-side uncertainty

Stephen D. Boyles [a,*], Kara M. Kockelman [b], S. Travis Waller [b]

[a] Department of Civil and Architectural Engineering, University of Wyoming, Department 3295, 1000 E University Ave., Laramie, WY 82071, USA
[b] Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 1 University Station C1761, Austin, TX 78712, USA

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ABSTRACT

This paper is concerned with finding first-best tolls in static transportation networks with day-to-day variation in network capacity, as accounted for by changes in the volume-delay function. The key question in addressing this problem is that of *information*, namely, which agents have access to what information when making decisions. In this work, travelers are assumed to be either fully informed about network conditions before embarking on travel, or having no information except the probability distributions; likewise, the network manager (toll-setter) is either able to vary tolls in response to realized network conditions, or must apply the same tolls every day. Further, travelers' preference for reliable travel is accounted for, representing risk aversion in the face of uncertainty. For each of the scenarios implied by combinations of these assumptions, we present methods to determine system-optimal link prices. A demonstration is provided, using the Sioux Falls test network, suggesting that attempts to incorporate uncertainty into nonresponsive tolls involve significantly higher prices.



## 1. Introduction

In recent years, pricing of highway driving (tolling) has attracted much political and institutional attention for a variety of reasons, including its potential as an alternate revenue stream, the introduction of technologies allowing efficient toll collection and dynamic pricing, and consideration of public–private partnerships. To support the process of determining appropriate prices, a large amount of research has been conducted to provide guidance on how users respond to prices, and how they should be set to achieve particular objectives. From the standpoint of maximizing social welfare, the fundamental notion, originated by Pigou (1920), is that economic efficiency occurs when the cost faced by each traveler equals the marginal social cost of his or her trip.

Traditionally, this marginal cost is determined by assuming a separable and differentiable volume-delay function (VDF) mapping travel demand to travel delay on each roadway segment, a homogeneous population of user-optimizing travelers with the same value of time, and commonly-known network structure and travel demand. Within this framework, the marginal cost of tripmaking is readily calculated, along with the associated Pigouvian tolls.

One significant assumption in this process is the determinism of the transportation network. Uncertainty pervades both transportation planning and operations, and researchers are realizing the importance of explicitly incorporating this into transportation models. Uncertainty exists both in the short run, at the "operational" level (due to incidents, weather conditions, fluctuations in travel demand, etc.), and in the long run, "planning" level, due to imperfect prediction of future land use, economic conditions, and other model parameters, both on the supply and demand sides of transportation. In this paper,

* Corresponding author. Tel.: +1 307 766 1771; fax: +1 307 766 2221.
*E-mail addresses:* sboyles@uwyo.edu (S.D. Boyles), kkockelm@mail.utexas.edu (K.M. Kockelman), stw@mail.utexas.edu (S. Travis Waller).

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the focus is on operational, supply-side uncertainty including, for instance, the impact of incidents, while excluding forecasting errors, or variations in travel demand.

This type of uncertainty directly leads to unreliability in travel times, which has a clear impact on user behavior. At the very least, the assumption that travelers seek to minimize travel time is ill-defined, since travel time is a random variable. The simplest extension is to assume that travelers seek to minimize *expected* travel time, but this is problematic because of an implicit assumption of risk neutrality. That is, under this assumption, travelers are indifferent between a trip which takes 30 min (with absolute certainty), and one which can either take 10 min or 50 min, with equal probability. For almost any conceivable trip purpose, the former is much preferred, since the consequences of late arrival are typically much worse than the benefits of early arrival. In fact, due to this asymmetry, it is reasonable to expect a traveler would even prefer a slightly longer trip, say, 35 min, if this travel time could be guaranteed.

However, this concept has not yet been integrated into pricing models intended for use in large-scale networks. Further, given recent technological advances, network operators and planners wonder whether prices should be dynamically varied in response to traffic incidents or other disruptions, and, if so, how this variation should occur. For instance, one might argue that tolls on a facility should increase if an incident occurs, to discourage additional vehicles from entering and exacerbating the resulting congestion. However, one might also argue that users paying a higher toll should expect a higher level of service. Would not travelers resent paying a higher toll, while most likely still experiencing greater-than-average delay? Or is there some way to account for uncertainty on a daily basis without varying tolls?

As with most problems concerning uncertainty, the question of information is key: who knows what, when they make their decisions? For instance, the issue of resentment for higher tolls during an incident is diminished if operators can communicate to motorists the presence and severity of the incident. This research presents four possible scenarios relating to the information available to motorists when choosing a travel route, and to the ability of the network manager to adjust the toll in response to network conditions.

The key contribution of this work is the development of pricing methods to apply in the presence of operational supply uncertainty and risk-averse travelers, for several information provision scenarios. The remainder of this paper is organized as follows: Section 2 discusses prior literature related to pricing, travel time uncertainty, and user attitudes to risk. Section 3 describes the modeling approach, introducing appropriate notation and defining the four information scenarios. Section 4 presents solution methods for each of these scenarios. The models described thus far make a number of simplifications, and Section 5 discuss how they can be adapted to account for correlated link states, user heterogeneity, and elastic demand. Section 6 demonstrates the basic model using the well-known Sioux Falls test network, and suggests that constant tolls should not be used to address nonrecurring congestion. Finally, Section 7 concludes the paper, and summarizes the key findings.

## 2. Literature review

This section summarizes prior related work, focusing on three areas: pricing under uncertain network conditions; the impact of reliability on route choice; and how pricing and reliability interact. In this light, the contribution of this paper should be more apparent, and is briefly discussed at the end of the section.

The question of how to appropriately price freeway facilities in uncertain environments is still very open. Yang (1999a) considered the problem of determining optimal prices when users behave according to the stochastic user equilibrium principle, where uncertainty lies in user perception, rather than system conditions. It is known that there need not exist a set of tolls that can drive a stochastic user equilibrium traffic flow pattern to a system optimal one (Akamatsu and Kuwahara, 1988; Smith et al., 1994). Yang (1999b) also considered how road pricing can be combined with advanced traveler information systems which inform users of system conditions. A number of numerical experiments were performed in a small test network, from which the author concluded that the two technologies "complement each other and that their joint implementation can reduce travel time more efficiently". Separately, de Palma and Lindsey (1998) considered information provision under three different scenarios: free access, nonresponsive congestion pricing, and dynamic pricing based on congestion levels. These authors explicitly considered capacity uncertainty in all of their models, but in a simplified setting without network effects and multiple origins and destinations. Under these assumptions, when pricing is dynamic and responsive to congestion, these authors showed that better information always improves welfare. A key result of Mohring and Harwitz (1962) is that marginal-cost pricing generates enough revenue to provide socially-optimal facility capacity; Lindsey (2009) showed that this result generalizes to the case of uncertain capacity if drivers are perfectly informed and tolls are responsive, or under imperfect information if tolls are set according to the same information drivers have, and if the price elasticity of demand does not vary with system conditions.

It is clear that reliability plays a significant role in route choice decisions; however, there is no consensus on how "reliability" should be defined. Usually, this is done in relation to the distribution of possible path costs. For instance, Small et al. (2005) and Liu et al. (2007) used the difference between the 80th- and 50th-percentile travel times, while Pinjari and Bhat (2006) used the maximum additional time that could be needed, compared to a typical case. Gao (2005), on the other hand, assumed a piecewise-linear utility function to model risk aversion. de Palma and Picard (2005) considered four utility function specifications to represent risk aversion: penalizing the standard deviation of travel time, penalizing travel time variance, constant relative risk aversion, and constant absolute risk aversion. Bates et al. (2001) and Noland and Polak (2002) provided overviews of theoretical and empirical research in travelers' valuations of travel time reliability. Typically, travel-