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Integrating congestion pricing and transit investment planning

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A R T I C L E I N F O

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A B S T R A C T

This paper develops a mathematical model and solution procedure to identify an optimal zonal pricing scheme for automobile traffic to incentivize the expanded use of transit as a mechanism to stem congestion and the social costs that arise from that congestion. The optimization model assumes that there is a homogenous collection of users whose behavior can be described as utility maximizers and for which their utility function is driven by monetary costs. These monetary costs are assumed to be the tolls in place, the per mile cost to drive, and the value of their time. We assume that there is a system owner who sets the toll prices, collects the proceeds from the tolls, and invests those funds in transit system improvements in the form of headway reductions. This yields a bi-level optimization model which we solve using an iterative procedure that is an integration of a genetic algorithm and the Frank–Wolfe method. The method and solution procedure is applied to an illustrative example.

1. Introduction

Congestion was estimated to cost on the order of $124 billion in 2013 and is projected to rise to about $186 billion by 2030 (Forbes, 2014). The Texas Transportation Institute estimates that (TTI, 2012) in 2011 urban Americans traveled about 5.5 billion additional hours and purchased an extra 2.9 billion gallons of fuel as a result of congestion. They also estimated that travelers in congested areas needed to set out an hour earlier for a trip that should have taken only 20 min in free flow traffic conditions. While freeway incident management, freeway ramp metering, arterial street signal coordination, arterial street access management and high-occupancy vehicle lanes are estimated to save 374 million hours of travel delay and $8.5 billion of congestion cost, public transportation is estimated to save about 865 million hours of travel delay and $20.8 billion in congestion costs. It is the opportunity to more fully exploit the benefits of public transportation that motivates this research.

One mechanism to spur the use of public transportation is to increase automotive costs through congestion pricing. However, congestion pricing schemes often face political opposition. In 2008 New York City abandoned congestion pricing efforts for Manhattan (The New York Times, 2008). Similar proposals have been abandoned in Greater Manchester, UK, Hong Kong, China, for example. Some congestion pricing schemes have been implemented however; including Stockholm, London and Singapore as well as Orange County in California, and San Diego in the United States.

An important characteristic in assessing the likelihood of adoption of a congestion pricing scheme is the perceived equity in that scheme. Volpe and the U.S. DOT report (Rand Corp and Volpe National Transportation Systems Center, 2007) that travelers in the more busy direction during rush hour under congestion pricing schemes are wealthier. Further, when only

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Nomenclature

u_{rs}^{k}	travel time from r to s that use path k in the automobile network
$\hat{u}_{rs}$	travel time from origin r to destination s using transit
c_{rs}	monetary cost for the cheapest path from origin r to destination s
$\bar{q}_{rs}$	total number of trips from origin r to destination s
q_{rs}	number of trips from origin r to s by automobile
v	value of time
p_a	toll price on arc a
$\hat{p}$	a vector of the tolls prices
p_a^k	toll price on arc a in chromosome k
c_d	per mile driving cost
d_a	length of link a
δ_{ak}^{rs}	parameter that take on a value of one if arc a is on path k from r to s and is zero otherwise
f_k^{rs}	traffic flow on path k from r to s
H	transit headway
n	cost to half the existing headway
$\varnothing$	population specific parameter
t_a	free flow time on arc a
x_a	volume on arc a
C_a	capacity of arc a
α_a, β_a	link specific parameters
ω	a user defined parameter that is greater than zero and less than one

some lanes are priced, they indicate that on average, wealthier drivers make use of the priced lanes. One mechanism to offset the equity challenges associated with congestion pricing is to make use of the revenues generated to improve the transportation options of lower income groups. It is this very strategy that is behind the requirement that 18% of the funds generated from congestion pricing in the San Francisco Bay Area (DOT, 2008) be used to subsidize bus transportation. Similarly, some of the proceeds from the London congestion fee are earmarked for investment in public transit services. Those proceeds amounted to about £1.2 billion over the first 10 years in which the pricing scheme was in effect (Lydall, 2013).

Given the opportunity to stem congestion via congestion pricing, the criticality of controlling inequity in the pricing scheme developed as well as the demonstrated benefit of public transportation to control congestion, we focus on the development of a mathematical model to identify roadway prices and service improvements in an associated transit system so as to maximize the social welfare of the population.

The remainder of this paper is organized into five sections. Section 2 presents relevant literature. Section 3 formulates the bi-level optimization model. The upper level model focuses on establishing the prices and the use of those funds to improve transit services. The lower level is a traffic assignment model over the highway and transit networks. Section 4 gives the solution procedure to the formulation given in Section 3. Section 5 gives an illustrative example. Finally, Section 6 gives conclusions and opportunities for future research.

2. Literature review

There is a large theoretical and empirical literature focused on congestion pricing. For a comprehensive literature review see Liu (2011). First-best pricing, also known as marginal cost pricing, is to set toll fees equal to the negative congestion externality users impose to each other (Walters, 1961; Yang and Huang, 1998; Verhoef et al., 2008). However, the first-best pricing scheme requires that charges are assigned to every link in the network so as to achieve the system optimum solution. Practical considerations often make this approach impossible to implement. Allowing only a proportion of links to be charged, known as the second-best pricing scheme was first proposed by Marchand (1968).

The second-best pricing problem is formulated as a hierarchical network game (Shimizu et al., 1997; Bard, 1998) with a single network owner looking for prices to minimize the total travel time where a large number of competing users choose paths by optimizing over toll fees and travel cost. This is essentially a Stackelberg game (Basar and Srikant, 2002), and can be expressed as a mathematical programming model with equilibrium constraints (MPEC) (Luo et al., 1996). This basic structure has been extended in several important ways including heterogeneous users (Cole et al., 2003), and stochastic demands (Liu, 2011). Hearn and Ramana (1998) allow link tolls to be positive or negative, with negative tolls indicating a subsidy is warranted for travel on those links. Conceptually, this is similar to using toll revenues raised to subsidize other users, including those making use of transit.

Parry and Bento (1999) made the suggestion to reduce labor taxes through congestion tax revenue to offset the negative effects on the labor force caused by the congestion pricing scheme. Similarly, Small (Small, 1992) designed a package of expenditures that would use one-third of congestion pricing revenues to improve the transportation system in the congested