Transport Policy 68 (2018) 142–157

Contents lists available at ScienceDirect

Transport Policy

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

An axiomatic characterization of fairness in transport networks: Application to road pricing and spatial equity

Xun Li[a,*], David Rey[b], Vinayak V. Dixit[b]

[a] *Research Centre for Integrated Transportation Innovation (rCITI), School of Civil and Environmental Engineering, UNSW Australia, Civil Engineering Building (H20), Room LG9, UNSW Sydney, NSW 2052, Australia*

[b] *Research Centre for Integrated Transportation Innovation (rCITI), School of Civil and Environmental Engineering, UNSW Australia, Civil Engineering Building (H20), UNSW Sydney, NSW 2052, Australia*

ARTICLE INFO

Keywords:
Fairness
Acceptability
Road pricing
Revenue assignment
Transport network
Spatial equity

ABSTRACT

This paper considers the important issue of fairness in transportation. Designing fair policies in transportation is critical since transport networks are generally recognized as public goods. Moreover, the effects of road pricing may be significantly different for travellers from different geographical regions. Hence, any revenue collected from road pricing or infrastructure funding policies ought to be appropriately redistributed among the population of different geographical regions. In this work, we focus on spatial equity in the road pricing revenue assignment problem. We examine well-known fairness schemes commonly discussed in the literature: opportunity fairness, proportional fairness (individual value and marginal value), and market fairness. We conduct an axiomatic characterization of these schemes to demonstrate their properties and highlight their policy implications. We then present a practical implementation of the proposed fair pricing revenue assignment mechanisms on Winnipeg's downtown network. The results reveal that market fairness is the most axiomatically restrictive scheme and that this scheme is related to individual value and proportional value proportional fairness under specific conditions. We also demonstrate a paradoxical situation where a market or marginal value proportional fair assignment requires a certain group to pay taxes, because they receive more benefits than other groups. In turn, opportunity fairness is shown to be the least restrictive revenue assignment scheme and to require minimal computational resources.

1. Introduction

Road pricing policies have been extensively considered by policymakers as a tool to manage traffic congestion over the past few years. However, Eliasson (2016) found that road pricing is regressive and unfair since low-income groups pay a higher share of income compared to high-income groups. Moreover, a survey involving 32 cities in the UK found that only 35% of road users supported road pricing policies (Jaensirisak et al., 2005). The lack of public acceptance is a major hurdle for the use of such tools (Viegas, 2001; Schade and Baum, 2007). To improve the acceptability of road pricing, approaches are required to compensate regressive effects and increase social welfare. A commonly agreed measure is to refund pricing revenue in a fair manner, or directly return a portion of the revenue to travellers (Levinson, 2010; Small, 1992; Schuitema and Steg, 2008). In fact, Jaensirisak et al. (2005) observed that the acceptability rate of road pricing policies increases from 35% to 55% when the refund of revenue is explicitly specified and is found to be fair.

Revenue from road pricing offers a great opportunity to yield benefits for travellers. Previous studies have proposed and explored a number of pricing revenue usage strategies, such as investing general public goods (Schuitema and Steg, 2008; Grisolía et al., 2015); improving alternative traffic modes (Litman, 2015; Basso and Jara-Díaz, 2012; Ubbels and Verhoef, 2005; Caggiani et al., 2017b); reducing vehicle-related costs (Schlag and Schade, 2000; Goodwin, 1989), and maintaining network infrastructure (Schuitema and Steg, 2008; Small, 1992). Most of these strategies aim to maximise travellers' benefit from pricing revenue and gain the broadest possible group of pricing supporters. Existing studies have revealed that these revenue usage strategies have different effects on travellers from different geographical regions, and therefore, each region has its preferred strategy of revenue usage (Santos and Rojey, 2004; Eliasson and Mattsson, 2006). In a case study of Stockholm, Eliasson and Mattsson (2006) found that road pricing produced negative net effects to the inner city and positive net effects to surrounding areas. Further, they found that travellers from the inner city preferred to use the revenue for public transport while

* Corresponding author.
E-mail addresses: xun.li@unsw.edu.au (X. Li), d.rey@unsw.edu.au (D. Rey), v.dixit@unsw.edu.au (V.V. Dixit).

https://doi.org/10.1016/j.tranpol.2018.05.003
Received 3 July 2017; Received in revised form 3 May 2018; Accepted 3 May 2018
0967-070X/

travellers from surrounding areas preferred to refund the revenue to car-related costs. Eliasson and Mattsson (2006) highlighted that the inconsistency in preferred revenue usage strategies raises the demand for spatial equity in road pricing revenue assignment.

The road pricing revenue assignment problem consists of assigning the total revenue obtained from tolls to predefined geographical groups, where a group may be defined based on travellers' origin or destination. Using geographical groups as recipients of pricing revenue assignment has two advantages: on the one hand, it allows each region to select its preferred strategy; on the other hand, the coalition of travellers generates the political and economic power that ensures the successful implementation of revenue usage strategies (King et al., 2007).

Fairness plays a central role in pricing revenue assignment. Studies have revealed a strong relationship between fairness and policy acceptability (Jakobsson et al., 2000; Sun et al., 2016; di ciommo et al., 2013; Eriksson et al., 2008). Moreover, the importance of fairness in cost/benefit assignment problems has also been recognized and proved under a number of circumstances: an unfair assignment is not implementable because of the resistance of a part of recipients (Georgiadis et al., 2006; Bertsimas et al., 2011). Thus, to improve acceptability, revenue assignment should be fair with regards to recipients' utility.

A pricing revenue assignment is said to be fair if it is treating all groups equally. Two dimensions of fairness have commonly been discussed in the literature: horizontal and vertical fairness (Caggiani et al., 2017a; Litman, 2002). Horizontal fairness is the equal treatment of groups that are considered equal in ability and need. Vertical fairness concerns the treatment of groups differing in ability and need (Caggiani et al., 2017a; Rey et al., 2015). The principle of vertical fairness is that the disadvantaged groups should accrue more benefit (Litman, 2002). Levinson (2010) provides a comprehensive review of different fairness schemes in road pricing policies. The simplest fairness strategy involves assigning the pricing revenue across jurisdictions based on the size of the population (Eliasson and Mattsson, 2006). This is also referred to as *opportunity fairness*, since everyone gets the same opportunity to access the pricing revenue. This is notably applicable to welfare optimization in humanitarian applications (Nair et al., 2017; Rey et al., 2018). However, since there is significant heterogeneity in the population with respect to the impacts of a policy, alternative schemes, such as allocating based on toll payments (Litman, 1996) and fuel usage (Newbery, 1990) have also been explored. *Proportional fairness* distributes the revenue based on people's contribution to the impact of the policy. Shapley (1953) proposed a method to assign resources (pricing revenue) to groups based on their marginal impact, which is known as the Shapley Value. The Shapley Value has been widely used in cost/benefit sharing games, such as for determining aircraft landing fees (Littlechild and Owen, 1973) and for allocating highway infrastructure costs (Dong et al., 2012; Kuipers et al., 2013; Zhang et al., 2015). This method is referred to as *market fairness*, since it accounts for the marginal contributions in a system where the impacts are endogenous. Transportation systems are a perfect example of systems with endogenous impacts because the travel times experienced by travellers are a function of the travel choices made by the travellers' themselves.

There are a large number of fairness measures that have been used for assignment problems (Young, 1985a; Banker, 1981; Bertsimas et al., 2011). However, in the context of road pricing policies, there is a limited literature studying fair mechanisms for revenue assignment. Existing efforts have either neglected the revenue assignment problem (i.e. all travellers are considered as one group) or used simplistic rules for revenue assignment such as the size of population and travel demand (Small, 1992; Levinson, 2010; Eliasson and Mattsson, 2006). In addition, the properties of fair pricing revenue assignment mechanisms have not been evaluated. This gap fundamentally motivates our efforts to systematically study fair policies in pricing revenue assignment.

In this paper, we formulate four fair pricing revenue assignment mechanisms corresponding to opportunity fairness, individual value proportional fairness, marginal value proportional fairness, and market fairness. We then conduct an axiomatic theoretical comparison as well as a numerical evaluation of these four fair pricing revenue assignment mechanisms. With regards to the dimension of fairness, we focus on horizontal fairness and all travellers are considered of a single social group. The reasons for considering horizontal fairness are twofold. First, the four fair revenue assignment mechanisms are derived from horizontal fairness. They commonly require that pricing assignment should not favour any group over the others (Young, 1985a; Banker, 1981). Second, geographical region is usually not involved in the classification of social and economic groups. Previous works on spatial equity also suggest to treat all regions and origin-destination pairs equally (Meng and Yang, 2002; Chen and Yang, 2004). The main outcome of this study is to investigate the properties of different fairness schemes in the context of road pricing. This aims to help policy makers recognise the fundamental assumptions being made and the potential impacts when implementing a particular pricing scheme.

The rest of the paper is organised as follows. Section 2 describes the theoretical constructs for fairness schemes in road pricing revenue assignment; Section 3 discusses the axioms and the properties associated to each of the axioms; Section 4 maps the axioms to the proposed fair pricing revenue assignment mechanisms; Section 5 conducts a numerical analysis using Winnipeg' downtown transport network, and Section 6 summarises our findings.

2. Pricing revenue assignment problem

2.1. Problem formulation

To present the pricing revenue assignment problem, we first provide a mathematical representation of a tolled transportation network. Let G be a transport network, which consists of a set of nodes N and a set of directed links A. Travellers using network G are classified into m groups, and the set of groups is M, where $|M| = m$. We assume that every traveller belongs to and only belongs to one group. That is, the interaction of any two groups is empty, and the union of all groups yields the total population. Each group is defined as a recipient of the pricing revenue assignment; hence the set of groups is also the set of recipients. The number of travellers in a group is called the *group size* and is denoted by $d_i, \ \forall \ i \in M$. The group size corresponds to the travel demand of this group and the total demand on the network can be represented by a vector $\boldsymbol{d} = (d_1, d_2, ..., d_m)$. We also assume that all travellers are homogeneous except in that they belong to different geographical regions. This implies that all travellers are assumed to have the same income, value of time, and other personal characteristics.

Let $t_a(x_a)$ be the volume delay function on link $a \in A$, and $\tau_a(x_a)$ be the link toll function. The generalized link cost function $\tilde{t}_a(x_a)$ (Sheffi, 1985) can be expressed as:

$$\tilde{t}_a(x_a) = \mu t_a(x_a) + \tau_a(x_a)\,, \ \forall \ a \in A \tag{1}$$

where μ represents the value of time, which translates travel times to monetary travel costs. The generalized cost represents the disutility experienced by an individual traveller traversing link $a \in A$. We assume that all travellers make route choice decisions to minimize their generalized trip costs, and thus, the traffic assignment in the network is conducted based on the User Equilibrium (UE) principle. Specifically, without road pricing, traffic is governed by link travel times $t_a(x_a)$, whereas with road pricing, traffic is governed by generalized link costs $\tilde{t}_a(x_a)$.

The pricing revenue assignment problem is defined over a set of recipients and a characteristic function which maps the recipients to fair assignment resources generated from pricing. In this paper, the total generalized effect from pricing to travellers and the total revenue collected from pricing are considered as the fair assignment resources. The motivation behind these assignment resources are twofold: from the viewpoint of travellers, the generalized effects and total revenue