Transportation Research Part B 45 (2011) 580–594

Contents lists available at ScienceDirect

Transportation Research Part B

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

Managing network mobility with tradable credits

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ARTICLE INFO

Article history:
Received 27 July 2010
Received in revised form 4 October 2010
Accepted 4 October 2010

Keywords:
Mobility management
Traffic equilibrium
Tradable credits
Networks
Congestion pricing

ABSTRACT

A system of tradable travel credits is explored in a general network with homogeneous travelers. A social planner is assumed to initially distribute a certain number of travel credits to all eligible travelers, and then there are link-specific charges to travelers using that link. Free trading of credits among travelers is assumed. For a given credit distribution and credit charging scheme, the existence of a unique equilibrium link flow pattern is demonstrated with either fixed or elastic demand. It can be obtained by solving a standard traffic equilibrium model subject to a total credit consumption constraint. The credit price at equilibrium in the trading market is also conditionally unique. The appropriate distribution of credits among travelers and correct selection of link-specific rates is shown to lead to the most desirable network flow patterns in a revenue-neutral manner. Social optimum, Pareto-improving and revenue-neutral, and side-constrained traffic flow patterns are investigated.

1. Introduction

Problems of sustainability in transportation are already quite noticeable in almost all large cities worldwide, and it is clear that the current unrestricted use of private cars is at the center of this problem. Due to congestion, more travel time is wasted on the roads, drivers are more likely to get stressed and frustrated, which in turn causes accidents. Forecasts of traffic condition are less reliable, so punctual arrival becomes difficult and travelers suffer losses from early departure or late arrival. Traffic congestion also contributes substantially to environmental problems. In the United States, transportation sources accounted for 29% of total greenhouse gas (GHG) emissions in 2006, and have been the fastest-growing source of GHGs, accounting for 47% of the net increase in total US emissions since 1990 (US Environmental Protection Agency, 2006). Indeed, vehicle emissions are substantially higher in congested conditions than under conditions of freely flowing traffic (Transek, 2002). It is reasonable to believe that the world will soon have to confront high levels of air pollution and congestion problems caused principally by the unrestricted use of private cars, and have to deploy practical instruments to achieve transportation sustainability efficiently, effectively and in a politically feasible manner.

There are in general two ways to alleviate traffic congestion: increasing road capacity (supply) or reducing traffic (demand). As the cliché 'you cannot pave your way out of traffic congestion' says, providing more road space has been proven to be self-defeating in congested areas because the increased capacity will soon be absorbed by induced travel demand (Goodwin, 1996; Hansen and Huang, 1997). Therefore, the focus is now turning to demand management as a tool to address congestion problems. Treating road space as a common commodity, travel demand can be controlled either by price instruments or quantity instruments.

Historically, road pricing as a demand management instrument has received far more attention than quantity control in both theory and practice. Since the influential work by Pigou (1920) who suggested that vehicles using congested roads

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doi:10.1016/j.trb.2010.10.002

should bear a tax equal to the difference between marginal social and marginal private costs involved, a large body of research has been developed on congestion pricing. In the context of a congested network, various mathematical models and algorithms have been proposed to determine the optimal link tolls for system performance optimization under given physical and economic pricing constraints. Comprehensive reviews have been published by Yang and Huang (2005), Lawphongpanich et al. (2006), Lindsey (2006, 2010), and recently Tsekeris and Voss (2009).

Economists advocate congestion pricing as an efficient pricing strategy that requires the users to pay more for a public good, thus increasing the welfare gain or net benefit for society. However, one of the major concerns with road pricing is that it is perceived as unfair or just another flat tax. Indeed, equity debates play prominent roles in road pricing and explain why its application on urban roads is still limited to a small number of cities worldwide.

To develop more equitable and acceptable pricing schemes, Lawphongpanich and Yin (2010) and Song et al. (2009) studied a class of Pareto-improving pricing schemes without revenue rebate as they apply to networks. They formulated the problem of finding Pareto-improving tolls as a mathematical program with complementary constraints, and proposed a solution algorithm via manifold sub-optimization. However, such Pareto-improving toll schemes exist only conditionally.[1] In parallel, Liu et al. (2009) and then Nie and Liu (2010) adopted a continuous value of time (VOT) distribution and examined the existence of Pareto-improving and revenue-neutral road pricing and transit fare schemes in a simple bi-modal network consisting of a single road and a parallel transit line. Guo and Yang (2010) investigated Pareto-improving congestion pricing *cum* revenue refunding schemes in general networks and established a sufficient condition for the existence of origin–destination-specific but class-anonymous Pareto-improving refunding schemes. However, even with revenue redistribution and the appealing Pareto-improvement, the government plays a role as an objectionable toll collector, and its claim of revenue-neutrality is not always easy to verify and thus perhaps hard to believe. Compensation (to those who are priced off the roads due to road pricing) is insufficient and procedures play an essential role (Frey et al., 1996).

Given the general political resistance to congestion charges, some researchers and planners have turned to quantity instruments to curtail the unrestricted use of private vehicles. In quantity control, the government determines the travel demand to be served, and then assigns fixed mobility rights equally to all individual travelers or inhabitants so that fairness is explicitly demonstrated. The simplest quantity control method—plate-number-based road space rationing, has been in place in many Latin American cities like Mexico City and Sao Paulo, and has recently been tried in a few large cities in China including Beijing and Guangzhou. Modeling and efficiency analysis of plate-number-based rationing schemes in general networks have been carried out recently by Wang et al. (in press) and Han et al. (2010). Under such a rationing policy, every private car's access to the road is restricted on the same fraction of days according to its plate number, with enforcement carried out through an automated traffic surveillance network. Observable congestion reduction and air quality improvement have been reported under short-term rationing, but it is also known that the pure plate-number-based rationing strategy tends to promote undesirable second-car ownership in order to circumvent the restriction. Indeed, there is evidence that driving restrictions in Mexico City (*Hoy No Circula*) led to an increase in the total number of vehicles in circulation as well as a change toward old, cheap and polluting vehicles (Davis, 2008; Mahendra, 2008). So long-term number plate rationing may lose its effectiveness over time as car ownership increases.

Daganzo (1995) has suggested a hybrid strategy between pricing and rationing for a single bottleneck, and proved the possibility of achieving Pareto-optimum without toll redistribution. He further specified a certain time-dependent congestion reduction scheme involving tolls and rationing which can benefit every driver when each driver is assumed to pass the bottleneck at a given time (Daganzo, 2000). Nakamura and Kockelman (2002) applied Daganzo's idea to the San Francisco-Oakland bay bridge and showed the practical difficulty or impossibility of Pareto-improvement through pricing and rationing.

A more sophisticated quantity control method—termed the tradable driving permit (right or credit) or the emission cap-and-trade scheme—has been proposed in the transportation literature. A variant of this method was originated earlier by Dales (1968) for the purpose of attaining water quality targets in a cost-effective manner, and discussion of similar schemes now abounds in the realm of environmental policy (including, for example, in the Kyoto Protocol and the European Union Emission Trading Scheme (Perrels, 2010)). In a tradable credit scheme, a policy target is defined in terms of quantity and the associated consistent equilibrium price of credits is determined by the market through free trading.

Chin and Smith (1997) and Seik (1998) studied the vehicle ownership quota system implemented in Singapore in 1995. The government designed that system to control and limit the growth in supply of private vehicles. Under the system, the number of new vehicle registrations allowed each year is determined by the Land Transport Authority (LTA) while the market determines the price of owning a vehicle.[2] Raux (2004) looked at two existing permit systems, the Ecopoint program in Austria designed to limit pollution and noise from truck traffic, and the Zero Emision Vehicle (ZEV) program in California which aims to reduce vehicle emissions. Raux and Mariot (2005) described a potential application of a domestic market for car fuel consumption permits and outlined an evaluation of the socioeconomic consequences of market operation and the surpluses that

[1] The existence of the Pareto-improving tolls without revenue redistribution discussed by Lawphongpanich and Yin (2010) requires that the untolled equilibrium flow pattern be dominated by an alternative feasible flow pattern, under which some users are better off and no user is worse off than at the untolled equilibrium. Such a dominating flow distribution and the Pareto-improving tolls exist only for certain special networks that exhibit the generalized Braess paradox defined and characterized by Hagstrom and Abrams (2001).

[2] Following the strategy of Singapore, the city of Shanghai has implemented policies to restrain both car use and ownership. Since 1998, the number of new car registrations per year has been limited and the rights are sold in a public auction.