Transportation Research Part E 93 (2016) 177–198

Contents lists available at ScienceDirect

Transportation Research Part E

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

Multi-period equilibrium modeling planning framework for tradable credit schemes

Mohammad Miralinaghi [a], Srinivas Peeta [b,*]

[a] School of Civil Engineering/NEXTRANS Center, Purdue University, 3000 Kent Avenue, West Lafayette, IN 47906, United States
[b] School of Civil Engineering, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form 27 May 2016
Accepted 29 May 2016
Available online 11 June 2016

Keywords:
Multi-period tradable credit scheme
Equilibrium credit price
Transfer fee
Reservation credit price

ABSTRACT

This study proposes the concept of multi-period tradable credit scheme (TCS) for a planning context. In it, travelers determine their actions in terms of consumption or sale of credits in the current period or transfer to future periods. In the first scheme, travelers can transfer credits to future periods without penalty. In the second scheme, the effects of two regulatory instruments are investigated on the market behavior. Study insights suggest that a multi-period TCS dampens credit price volatility. It allows the central authority to develop TCSs with stable credit prices in which travelers can hedge against potential monetary losses.

1. Introduction

Traffic congestion is one of the most important issues for metropolitan areas. It has led to increased productivity losses over the past few decades in the U.S. and elsewhere (Schrank et al., 2012; Nash et al., 2008). Pricing of the road network is a strategy to address the congestion problem. It can be an effective market-based instrument to manage demand by influencing traveler decisions related to travel mode, departure time and route.

There is substantial literature on congestion pricing and price-based instruments. Pigou (1920) proposed the concept of marginal cost pricing to maximize social welfare by charging the marginal external cost that travelers impose on society. It has been applied to the general traffic network with different assumptions such as link flow interactions, heterogeneity of travelers and multiple modes of transportation (Dafermos and Sparrow, 1971; Dafermos, 1973; Yang and Huang, 1998). While simple and appealing in principle, it has not been well-received in practice due to issues of equity and traveler reluctance to pay the central authority to use roads due to perceptions of indirect taxation. It also does not account for the variability in driver ability to pay, and can cause an inequitable distribution of social welfare. Lawphongpanich and Yin (2010) propose a "pareto-improving" congestion pricing scheme in which travelers perform at least as well as under the no-pricing scheme. Thereby, the link tolls are computed to reduce the total system travel time while ensuring that all travelers experience the same or lesser travel time compared to the no-pricing scenario. While the approach promotes greater equity, the issue of transference of wealth from the drivers to the central authority still exists in the proposed scheme.

To overcome the aforementioned issues, the idea of using a tradable credit scheme (TCS) has received more attention recently. It has been used in different sectors such as air pollution control, managing water resources and land use control (Leggett et al., 2012; OECD, 1997). The application of a TCS in the transportation sector to control traffic congestion can be

* Corresponding author.
E-mail addresses: smiralin@purdue.edu (M. Miralinaghi), peeta@purdue.edu (S. Peeta).

http://dx.doi.org/10.1016/j.tre.2016.05.013
1366-5545/

traced to Verhoef et al. (1997) who propose a ''tradable road-pricing smart card'' to manage road transportation externalities. Nagurney et al. (1998) investigate a system of link-based marketable pollution permits where the central planner aims to achieve certain environmental objectives. Later, it is extended to path-based and origin–destination (O–D) pollution permits (Nagurney, 2000a, 2000b). Viegas (2001) develops the notion of tradable smart card to allocate ''mobility credits'' to all taxpayers, and provides the flexibility to trade credit and use it to pay transit fare in addition to paying toll. Along this thread, Yang and Wang (2011) formulate the tradable mobility credit scheme as a variant of the standard user equilibrium (UE) model with additional constraints on the network credit feasibility condition. In this scheme, a central planner determines the total endowment of travelers and the subsequent link tolls to charge them. Thereby, in a tradable mobility credit scheme travelers need to pay credits in order to travel in the network. This can provide a central authority control mechanisms to manage the traveler demand in the network so as to achieve some system-level goals. Travelers are able to trade credits amongst themselves in the market. Since there is no transfer of wealth between the central authority and the travelers while considering the equity effects of this scheme, there could potentially be less societal objection to its implementation in practice.

Numerous efforts have sought to improve the rationality of the assumptions adopted in the Yang and Wang (2011) scheme. The associated literature can be classified into three groups based on its focus on the different stages of the TCS. The first group deals with the different assumptions of the market. Nie (2012) investigates the effect of the transaction cost in two different types of markets (negotiable and auction). He demonstrates that the transaction cost can lead to the desired equilibrium solution only in an auction market with certain assumptions rather than in a negotiated one. Shirmohammadi et al. (2013) establish linkages between TCS and congestion pricing to address different goals in the traffic network. They propose a ''safety valve'' policy in a cap-and-trade scheme to resolve the issue of price volatility under uncertainty related to a regulation. The second group of studies analyzes the effects of traveler characteristics in determining link tolls and total allocated credits. Wang et al. (2012) propose a TCS formulation by considering heterogeneous travelers with a discrete set of values of time. They investigate the relationship between the uniqueness of the aggregate UE link flow pattern and the equilibrium credit price. He et al. (2013) study the effect of the mixed behaviors of UE-following and self-optimizing oligopoly Cournot players in the optimal design of TCS with transaction costs. Bao et al. (2014) develop a more realistic TCS by considering travelers' loss aversion behaviors in their route choice. Given the market with transaction cost for buying and selling credits, they demonstrate that the system optimum link flow pattern may not be achievable when travelers' loss aversion behavior is considered. Zhu et al. (2015) investigate the UE condition under TCS where travelers are assumed to be heterogeneous with continuous distribution of value of time. It is shown that optimal allocation of credits can make travelers better off compared to the no-pricing scenario. Xu and Grant-Muller (2016) propose a simulation framework to analyze the mode-choice of travelers in the traffic network before and after implementation of TCS. This framework is applied to the case of Beijing, China where it is demonstrated that TCS is a promising policy to reduce the total vehicle-miles traveled in the traffic network. The third group of studies deals with the effects of the implementation of TCS on traffic dynamics. Nie and Yin (2013) propose a scheme to manage morning commute choices with no initial allocation of credits. First, the central authority divides the planning horizon into peak and off-peak periods. Then, the authority rewards the commuters traveling in the off-peak period and charges the commuters traveling in the peak period. While they develop a general analytical framework to determine the traveler departure choices under the proposed TCS, the credit price is constant through the planning horizon.

Categorized into the third group of studies, Ye and Yang (2013) capture the evolution of network traffic and market performance using the notion of day-to-day traffic dynamics. They consider the traveler learning process, the credit demand–supply interaction, and the proposed TCS to analyze the day-to-day evolution of the credit price. Since day-to-day models describe the evolution of travel choice decisions over time, such models can be used to capture the credit price variation until the equilibrium condition is reached. Ye and Yang develop a continuous dynamic model in a finite planning horizon and prove that the credit price reaches equilibrium over a few to several days under a sufficiently long planning horizon. In terms of the TCS, they assume that the central authority distributes credits to travelers at a certain rate at the beginning of the planning horizon itself; hence, there is no distribution of credits to travelers in the future. In deriving the credit price and traffic congestion evolution, they assume that the current credit price is not connected to the traffic network demand on future days. They employ a sequential approach to obtain the credit price by assuming that the credit price on the next day is a function of only the current credit price and the current excess credit demand in the market.

Planners/decision-makers (referred to as ''central authority'' in this study) have used TCS in different sectors to achieve steady progress toward system-level goals over a long planning horizon. For example, the European Union has implemented a TCS to reduce emissions in the aviation industry over a 15-year period, where the emission cap declines from 97% of the average of the 2005–2007 values in 2012 to 95% in 2020 (Leggett et al., 2012). In a similar way, since the road transportation sector is a major source of emissions, a TCS can be a tool for a central authority to meet some goals associated with traffic-related emission standards over a long-term planning horizon. To achieve such long-term goals, the planning horizon can be divided into multiple periods in which the central authority uses the credit supply (the total number of credits to be allocated to travelers) and the credit rate charged per link for each period as control parameters, labeled TCS parameters hereafter. Then, a TCS can be used to enable a mobility credit market in which the traveler actions also depend on the traffic network demand and supply. However, due to the long-term nature of the TCS design, the traffic network demand and supply can vary over the horizon. The TCS parameters in a multi-period TCS can be used by the central authority to control the evolution of the traffic system to ensure steady progress toward the long-term system-level goals while factoring the