



Models and a relaxation algorithm for continuous network design problem with a tradable credit scheme and equity constraints



Guangmin Wang^{a,b}, Ziyou Gao^{a,*}, Meng Xu^c, Huijun Sun^c

^a Institute of System Science, Beijing Jiaotong University, Beijing 100044, PR China

^b School of Economics and Management, China University of Geosciences, Wuhan 430074, PR China

^c MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing 100044, PR China

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ABSTRACT

The sustainable problems of transportation have become noticeable in the majority of cities worldwide. Many researchers are devoted themselves into traffic congestion. Generally, traffic congestion could be alleviated via increasing road capacity (supply) or reducing traffic (demand). In this paper, we model CNDP which has a tradable credit scheme and equity constraints in order to research on the way of releasing congestion by combining increasing supply and reducing demand. Firstly, the bilevel programming problem is proposed to model the CNDP with a tradable credit scheme. The upper level (the government) chooses optimal capacity enhancement for some existing links to minimize the total system costs under a budget constraint. The lower level chooses the optimal route based on considering the generalized travel cost in which both travel time and credit charging for using the link are involved. And then, considering the inequity problem in terms of equilibrium O-D travel cost and link travel time, the model is proposed by incorporating equity constraints into CNDP with a tradable credit scheme. After presenting a relaxation algorithm, the experiments on Sioux Falls network are illustrated. Finally, conclusion and some future research directions are presented.

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1. Introduction

Problems of sustainability in transportation are already quite noticeable in almost all large cities worldwide. The increasing level of traffic congestion has induced to economic inefficiency, social disruption, excessive energy consumption. Not only that, the environmental deterioration can also be largely due to the traffic congestion. In both developed and developing countries, one of the chief driving factors of the growth in greenhouse gases (GHG) emission is the growth in transport activities. Transport represented 23% of global energy related carbon emissions in 2004 [21]. In the United States, transportation sources accounted for 29% of total GHG emissions in 2006 [48]. In the Organisation for Economic Cooperation and Development (OECD) countries, transportation was the fastest growing source of GHG's between 1990 and 2002; in the non-OECD countries, it was the second fastest [37,45]. Indeed, vehicle emissions are substantially higher in congested conditions than under conditions of freely flowing traffic [46]. 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 [58].

In general, two ways can be used to alleviate traffic congestion: increasing road capacity (supply) or reducing traffic (demand) [58]. The former way is a crucial decision of the network enhancement for allocating a limited financial budget to the capacity expansion of existing links and/or to the addition of new candidate links. In transportation network modelling and optimization literature, such a decision is referred to as the network design problem (NDP), which determines the optimal decision variables (e.g. existing capacity expansions and/or new link additions) so as to minimize (or maximize) a specific network performance index (e.g. total travel time or generalized cost) while accounting for the travelers' route choice behavior in a deterministic user equilibrium (DUE) or a stochastic user equilibrium (SUE) manner [40]. Naturally, NDP can be modeled into a bilevel programming problem [55]. In the mathematical programming literature, the bilevel programming problem is also frequently referred to as a mathematical program with equilibrium constraints (MPEC). Luo et al. [30], Shimizu et al. [41] and Outrata et al. [38], respectively characterized the optimality conditions and derived the corresponding solution methods for MPEC where the non-smooth approach [7] has been taken into

* Corresponding author.

E-mail addresses: wgm97@163.com (G. Wang), zygao@bjtu.edu.cn (Z. Gao), mengxu@bjtu.edu.cn (M. Xu), hjsun1@bjtu.edu.cn (H. Sun).

account. The NDP can be formulated as a mathematical programming with equilibrium constraints (MPECs) [15,16], especially the UE is asymmetric. Similarly, as a special case of an MPEC, mathematical programming with complementarity constraints (MPCCs) has been extensively studied [39], and the general CNDP is developed as MPCC by formulating the general UE (both symmetric and asymmetric) as a link-node [2]. Generally, the NDP can be categorized into three classes: continuous network design problem (CNDP) (determining the optimal capacity expansions of the existing links), discrete network design problem (DNDP) (finding the optimal link additions from a set of candidate links), and mixed network design problem (MNNDP) (mixture of the CNDP and DNDP) [29]. It is also treated as NDP that the traffic control and management, such as traffic signal setting [1], estimation of origin–destination (O–D) matrices from traffic counts [57], ramp metering in freeway–arterial corridor [59], and optimization of road tolls [53], are used to minimize (or maximize) a specific network performance index. More details about NDP can refer to Refs. [54,55].

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 [18,20]. Therefore, the focus is now turning to demand management which has been considered 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 [58].

Historically, road pricing as a demand management instrument has been paid far more attention than quantity control, both theoretically and practically. Congestion pricing, regarded as an efficient pricing strategy, is perceived as being unfair or just another flat tax because it requires the users to pay more for the public good even if it can increase the welfare gain or net benefit for society. Indeed, equity debates play prominent roles in road pricing and explain why its application on urban roads is still limited to few cities worldwide [58,36]. Thus, many kinds of Pareto-improving pricing schemes are researched to develop a more equitable and acceptable pricing scheme [42,23,28,35,19]. 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 be verified, thus perhaps hard to believe [58]. The compensation (to those who are priced off the roads due to road pricing) is insufficient and procedures play an essential role [14]. Comprehensive reviews on congestion pricing have been published by Yang and Huang [56], Lawphongpanich et al. [22], Lindsey [26,27], and recently Tsekeris and Voss [47].

Given the general political resistance to congestion charges, some researchers and planners have turned to quantity instruments to reduce demand. 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. 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 [10,31]. So long-term number plate rationing may lose its effectiveness over time as car ownership increases. Dales [9] proposed the creation of transferable rights for the purpose of attaining water quality targets in a cost-effective manner, and discussion of similar schemes now abounds in the realms of water permits at Fox River in Wisconsin; U.S. phase-out of leaded gasoline; Sulfur dioxide trading under the U.S. Clean Air Act

Amendments; Regional Clean Air Incentives Market (RECLAIM) in Southern California; Renewable energy credits (RECs) in the United States; Individual Transferrable Quotas (ITQs) in New Zealand; Carbon credits in the European Union-Emissions Trading Scheme (EU-ETS); Carbon offsets in the Kyoto Protocol’s Clean Development Mechanism (CDM) [43] and therein. And, this 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. Verhoef et al. [49] reviewed the many practical applications of tradable permits schemes from user-oriented and supply-side-oriented. Yang and Wang [58] also reviewed the tradable credit scheme in transportation and examine an alternative simple but forceful tradable credit distribution and charging scheme.

In this paper, we model CNDP with tradable credit scheme equity constraints to research on the way of releasing congestion by combining increasing supply and reducing demand. Firstly, the bilevel programming problem is proposed to model the CNDP with tradable credit scheme. The upper level (the government) chooses optimal capacity enhancement for some existing links to minimize the total system costs under a budget constraint. The lower level chooses the optimal route by considering the generalized travel cost including the travel time and value of credit charging for using the link. In this model, the network design problem is considered to increase the supply, while the credit is charged for decreasing the demand. By replacing the lower level problem with its KT conditions, the bilevel programming (BLP) model can be equivalently transformed into single-level nonlinear programming problem (NLP1). Then, a relaxation algorithm can be presented to solve the transformed NLP. Motivated by the inequity problem in term of equilibrium O–D travel cost proposed by Meng and Yang [32], the model NLP2 is proposed by considering equity constraints about equilibrium O–D travel cost and link travel time. Here, the inequity problem in terms of link travel time is that some links are improved (travel time on these links become shorter) while some links get worse (travel time on these links become longer) by implementing a CNDP project. And, the relaxation algorithm can also be used to solve the model NLP2.

The paper is organized as follows. In Section 2, we formulate the bilevel programming problem to model CNDP with tradable credit scheme. And then, equity constraints about equilibrium O–D travel cost and link travel time are incorporated in the CNDP with tradable credit scheme. Section 3 presents a relaxation algorithm for solving the above models. In Section 4, the experiments are illustrated by using Sioux Falls network. Section 5 concludes this paper and some future works are presented.

2. Problem formulation

2.1. Notations

In this section, the notations are listed as follows:

$G=(N,A)$	transportation network
N	set of nodes in the network
A	set of links in the network
a	index for links in the networks, $a \in A$
W	set of O–D pairs
w	index for O–D pairs
R_w	set of all simple paths connecting O–D pair $w \in W$
q_w	amount of credit distributed to each traveler over the O–D pair $w \in W$
y_a	incremental capacity on expanded link $a \in A$,
$\underline{y}_a, \bar{y}_a$	$\mathbf{y} = (y_a), a \in A$ denotes the incremental capacity vector lower and upper bounds for capacity enhancement of link $a \in A$, respectively

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