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Optimal congestion pricing toll design under multiclass transportation network schemes: Genetic algorithm approaches

Wei (David) Fan*

Department of Civil and Environmental Engineering, The University of North Carolina at Charlotte, EPIC Building, Room 3261, 9201 University City Boulevard, Charlotte, NC 28223, United States

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ABSTRACT

The purpose of this paper is to explore bi-level genetic algorithm (GA) based approach to solving the optimal toll locations and toll levels simultaneously in a multiclass network. The upper-level subprogram intends to minimize the system total travel time and the lower-level subprogram is a traditional user equilibrium problem. It is assumed that the demand matrix is fixed and given a priori. First, two different versions of GA based solution procedures are developed and applied to Sioux Falls, SD network, assuming homogeneous users. Then, their performances are compared; the preferred GA option is identified and further applied to the network consisting of multiclass users with different value of times. The optimal toll locations and levels are thus determined. A commonly used heuristic approach in practice is also considered to determine toll levels based only on the most congested links in the network. Such heuristic toll levels are compared with the combined solution of optimal locations and toll levels. Numerical results demonstrate that the most congested links in a network may not be taken as intuitive candidates of optimal toll locations.

1. Introduction

Congestion pricing has been gaining popularity worldwide as an effective way to reduce traffic congestion and air pollution in past few decades (Yang and Zhang, 2003). In addition, it serves as a source of revenue for federal highways' funding, which could be used to expand and improve transportation infrastructure. It has been implemented in many metropolises around the world (for example, in London in 2003 which was based on a daily license charge mechanism; and Stockholm which was based on a cost per trip charge mechanism in 2006—an example more relevant to this paper). Congestion pricing and also toll roads work by diverting traffic routes, and potentially shifting purely flexible rush hour travel demand to other transportation modes or to off-peak periods. The concept of road pricing comes from the idea that road users are usually paying lower cost than the external cost they impose. To account for this difference, users on each link in a road network are charged a marginal-cost on to drive user equilibrium flow pattern to system optimum or simply to make the traffic conditions move closer to an optimal state (Yang and Zhang, 2003; Hearn and Ramana, 1998; Yang and Huang, 2005). This kind of pricing scheme is called the first best pricing.

However, the first-best pricing is not practically appealing because of high operating cost for toll collection and also it has poor public acceptance. Hence, second-best pricing scheme, in which only a subset of links is selected for tolling, has been gaining much attention (Yang and Huang, 2005). Its relative advantage over the first-best pricing scheme has been thoroughly studied and discussed by different researchers (Yang and Lam, 1996; Verhoef et al., 1996; Lindsey and Verhoef, 2001; Verhoef, 2002). A classic example of the second-best pricing problem that involves a two route network, where an un-tolled route is available, is presented by different authors elsewhere (Verhoef et al., 1996; Marchand, 1968; Liu and McDonald, 1999).

Many researchers have evaluated the efficiency of a pricing scheme by total system travel time and/or social welfare measures, and these measures can be used as objectives in an optimization framework (Yang and Zhang, 2003; Hearn and Ramana, 1998; Yang and Huang, 2005; Yang and Lam, 1996; Verhoef et al., 1996). The objectives in the framework need to be carefully defined before solving any congestion pricing problem. Once the objective is defined, important principles of transport planning such as traffic assignment (i.e., allocating traffic to paths and links) can to be used along with other heuristic techniques to find satisfactory optimal solutions to even large and complex congestion pricing problem in

* Fax: +1 704 687 0957.
E-mail address: wfan7@uncc.edu (W.(. Fan).

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which the global optimum cannot be found. The optimal solutions are usually either toll locations or toll levels (a.k.a., toll rates) for a given network. Nonetheless, little attention (except Yang and Zhang, 2003) has been given to the simultaneous determination of toll locations and toll levels. This might be attributable to the assumption that the decision of optimal toll locations is considered in the long-term planning stage, while the decision of optimal toll levels might belong to the mid-term tactical or short-term operational stage. However, there is indeed a need and also very beneficial to consider the combined toll locations and toll levels problem.

The optimal toll locations and toll levels problem can be seen as a type of the network design problem. Various methods have been presented to solve this challenging problem and a brief review of different methods can be found elsewhere (Shepherd and Sumalee, 2004). It is difficult to solve network design problem by applying conventional network optimization methods. There are simply too many possible combinations for one to select a certain number of toll links even from a small possible link subset. Therefore, an effective method, which can explore as many combinations as possible to search a good local (and possibly global) optimal solution, is highly needed. The genetic algorithm (GA) has this required capability because of its favorable procedure of natural selection. GA solution approach has been widely applied to solve second best optimal toll design problem by a few researchers (Yang and Zhang, 2003; Shepherd and Sumalee, 2004; Cree et al., 1998). However, in these studies the approach was applied to determine either toll locations or toll levels but not both simultaneously. For example, Cree et al. (1998) presented a GA based approach to solving the optimal toll problem but not the location problem. Shepherd and Sumalee (2004) applied an alternative GA solution method to determine optimal toll levels for a predefined set of chargeable links and to find optimal toll locations. The so called "CORDON" method was used to determine the toll levels in the latter case. Yang and Zhang (2003) considered selection of optimal toll levels and optimal toll locations on predetermined links, which were basically the most congested ones, for achieving maximum social welfare using a bi-level programming GA based approach with both discrete and continuous variables. In their study also, GA was used to only determine the optimal toll locations; the optimal toll levels were evaluated using another metaheuristic technique called the simulated annealing method.

As such, the first objective of this paper is to explore bi-level GA based approach to solving the second-best combined optimal toll location and toll level (OTLTL) problem. The upper-level subprogram intends to minimize the total travel time (i.e., system cost), which can certainly be changed to any objective as one may desire to consider without the need to change the general solution methodology as developed in this paper. Two different approaches of GA based solution procedure are proposed to solving the bi-level optimization problem. In this paper, it is assumed that the travel demand matrix is fixed and given a priori. Network experiments will also be conducted to compare the two versions of the GA algorithms and the best one is chosen for further analysis.

In a tolled network system, users choose their routes according to total travel time experienced and total monetary travel cost (Han and Yang, 2008). These are sometimes collectively referred to as a generalized cost of travel. In most of previous research efforts on the congestion pricing problem, homogeneous users are assumed to have existed in the transportation network. This means that the value of times (VOTs) are taken to be identical for all users in the network. However in actual case, road users differ from one another in the values they place on time. That means in reality, heterogeneous group of people use the network. Under such condition, in traffic and transportation analysis with such users in terms of different VOTs, either a discrete set of VOTs for several distinct user classes or a continuous distributed VOT across the whole users can be assumed to develop network equilibrium models (Marcotte and Zhu, 2000; Nagurney, 2000). Very limited research efforts have been done towards the combined optimal toll level and location problems under multiclass users. Though, there are indeed some authors who have addressed the problems partially in some way. For example, the congestion pricing location problem of multi-class network with social and spatial equity constraints was studied in a paper (Zhang and Zhou, 2009). However, the study was based on a known number of toll links which is usually not given in the realistic traffic network. Han and Yang (2008) also addressed the concept of multiclass and multi-criteria traffic equilibrium to evaluate the efficiency loss caused by the models. Therefore, another objective of this paper is to further investigate the preferred GA option using extensive numerical experiment and apply it to a network with multiclass users in order to determine the combined optimal toll levels and locations.

The remainder of this paper is structured as follows: Section 2 presents the model formulation of bi-level models. Section 3 elaborates the solution methodology for the OTLTL problem. Section 4 describes network experiments and discusses the comprehensive numerical results. Finally, Section 5 concludes this paper with a summary and discussion of future research directions.

2. Model formulation

2.1. Mathematical notation

Any network design problem can be represented in terms of "nodes", "links" and "routes". Consider a connected network with a directed graph $G = \{N,K\}$, which consists of a finite set of N nodes and K links (arcs). Suppose that link $k \in K$, which connect pairs of nodes. The following notations are used in order to present the model formulation.

Sets/indices:

k = *Link*

n = *Node*

w = *Origin–Destination (O–D) pair*

m = *User class*

K = *Set of links (arcs) such that* $k \in K$

N = *Set of nodes*

W = *Set of O–D pairs*

M = *Set of user classes*

Data/parameter

P_w = *Set of paths between O–D pair* $w \in W$

$f_{p,w}$ = *the flow on path* $p \in P_w$ *between O–D pair* $w \in W$ *(used for single-class formulation only)*

$f^m_{p,w}$ = *the flow on path* $p \in P_w$ *between O–D pair* $w \in W$ *r user class m(used for multiclass formulation only)*

$y^{\max}_k$ = *upper bound toll level of link* $k \in K$

$y^{\min}_k$ = *lower bound toll level of link* $k \in K$

δ^w_{kp} = *1 if link k is used in path p or* $\delta^w_{kp} = 0$ *otherwise,* $w \in W$

q_w = *a priori demand between O–D pair w*

VOT = *Average value of time for all user class (used for single-cormulation only)*

VOT^m = *Average value of time for user class m (used for multiclass formulation only)*

$t_k(v_k)$ = *travel time on link* $k \in K$ *given* v_k

Decision variables

$\overline{K}$ = *subset of links to be tolled in the optimal solution i.e.,* $\overline{K} \subseteq K$

y_k = *toll level on link* $k \in \overline{K}$

v_k = *the link flow on link* $k \in K$