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Minimizing CO_2e emissions by setting a road toll

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ABSTRACT

The main purpose of this paper is to develop a bi-level pricing model to minimize the CO_2e emissions and the total travel time in a small road network. In the lower level of the model, it is assumed that users of the road network find a dynamic user equilibrium which minimizes the total costs of those in the system. For the higher level of the model, different road toll strategies are applied in order to minimize the CO_2e emissions. The model has been applied to an illustrative example. It shows the effects on traffic flows, revenues, total time and CO_2e emissions for different numbers of servers collecting tolls and different pricing strategies over a morning peak traffic period. The results show that the CO_2e emissions produced can be significantly affected by the number of servers and the type of toll strategy employed. The model is also used to find the best toll strategy when there is a constraint on the revenue that is required to be raised from the toll and how this affects the emissions produced. Further runs compare strategies to minimize the CO_2e emissions with those that minimize total travel time in the road system. In the illustrative example, the results for minimizing CO_2e emissions are shown to be similar to the results obtained from minimizing the total travel time.

Introduction

With the growth of road traffic, the problem of traffic congestion attracts increasing concern from the public, academic researchers and government authorities. A road toll is one policy that could reduce traffic congestion and improve the quality of the air conditions. Road tolls have become a well-researched topic in transportation planning. Road toll pricing is about charging money for access onto a road/specific area at certain times or for certain road users. The road toll will influence the usage of the road system for different departure times and choices of alternative routes. So different road toll strategies will change the traffic patterns and choosing a suitable and practical tolling strategy is important to reduce the fuel emissions in the whole road network.

Existing methods are available for modelling road toll pricing, but most of them focus on optimizing the total travel time or its relevant costs. There is little research on how to apply these models for a different objective such as minimizing emissions. Therefore, the research described in this paper aims to fill this gap.

The rest of the paper is organized as follows: the next section provides a literature review of previous work about road toll pricing. Section 'Bi-level pricing model' describes the road toll pricing problem and how to apply it to minimize CO_2e emissions and total travel time. Section 'Road toll pricing strategies' presents an illustrative case study and in the following section the computational results obtained through the proposed methods are discussed. The last section presents conclusions and directions for further research.

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Literature review related to road toll pricing

Road tolls are implemented in different cities around the world, such as Stockholm, London, Singapore and many other places. The road toll can be not only for a single road but also for an area. In some places the road toll is set as a constant while in other places it may be set as a variable charge which is different at different times of the day. There are two main types of method that are used to model the effect of road tolls: the first is to use marginal cost pricing theory and the other is to use a bi-level pricing model.

Pigou (1952) was the first to suggest that vehicles using congested roads should bear a tax equal to the difference between marginal social and marginal private cost. This suggestion has often been repeated and explored. Walters (1961) applies the theory of marginal cost pricing to estimate an efficient system of taxation for a network of highways. He suggests that efficient taxes (marginal private cost) should be equal to marginal social cost and proposes a mixture of gasoline taxes, mileage taxes, and congestion tolls.

Dafermos (1973) applies marginal cost pricing theory to decide the toll patterns for multiclass-user transportation networks and formulates the link-toll and path-toll collection problems.

Smith (1979) presents a small example to illustrate marginal cost theory, where vehicles using congested roads should bear a tax equal to the difference between marginal social and marginal private cost. The paper proves that if the cost and demand functions satisfy certain weak smoothness conditions then the marginal cost taxation of a transportation network is optimal, where the objective of the model is to maximize the benefit (revenue).

Johansson (1997) discusses some important external costs associated with road transport in urban areas. The paper uses the marginal cost model to calculate the road toll and also discusses the speed-flow relationship, showing that the maximum flow is obtained at a certain speed level, which is equal to (or higher than) the actual speed at the peak hour. The relationship between fuel consumption and speed is described and the paper goes on to illustrate the optimal tax by considering the marginal private cost (own pollution) and marginal social cost (pollution for others, fuel consumption for others and time losses for others).

Wie and Tobin (1998) states that there are generally two classes of congestion pricing model in the literature: one is based on a static analysis and the other is based on a dynamic analysis. The first class of congestion pricing models assumes the general traffic network to be at a steady-state condition at all times and thus travel demands and costs are not time varying. The second class of congestion pricing models is dynamic in that travel demands and costs vary over time and thus congestion tolls need to be time varying. These two types of dynamic congestion pricing model are based on the theory of marginal cost pricing. The first model is appropriate for situations where commuters have the ability to learn the best route choices through day-to-day explorations on a network with arc capacities and travel demands that are stable from day to day. The second model is appropriate for situations where commuters optimize their routing decisions each day on a network with arc capacities and travel demands that fluctuate significantly from day to day.

Wardrop (1953) discusses some theories about road traffic research. Wardrop's principle of user equilibrium is introduced which assumes that traffic will tend to settle down into an equilibrium situation in which no driver can reduce his journey time by choosing a new route and then the driver has no incentive to improve their route. This principle is the theoretical basis for the bi-level pricing model. It describes a condition where the road network settles down into equilibrium at a particular time. Using the principle of equilibrium, an assumption is made that all drivers have the same perfect knowledge of routes in the network, and that they all seek to minimize the cost of travel subject to every other driver doing the same.

Yan and Lam (1996) presents some developments in model formulation and solution procedures for the congestion road pricing problem under queuing network equilibrium conditions. It describes a bi-level model of a leader–follower type, where the system manager is the leader and the network users are the followers. The lower-level problem is a queuing network equilibrium model that describes users' route choice behaviours under conditions of both queuing and congestion for a given link toll pattern. The model assumes a fixed travel demand pattern and in the light of any toll decision, the road users make their route choice decisions in a user-optimal manner.

The upper-level problem determines the toll pattern to optimize system performance, while taking into account the users' reactions in response to alternative road tolls. There are several alterative choices for the objectives, such as to minimize the total network cost, to maximize total revenue, or to maximize the ratio of the total revenue to total cost. Sensitivity analysis is used to provide the derivatives of link flows and queuing delays with respect to link tolls and hence indicates the "direction" in which the queuing network equilibrium pattern will move if the toll pattern is changed. The model helps to determine optimal road tolls such that total travel time is minimized or total toll revenue is maximized and the paper also provides a small example to show how the algorithm works. The bi-level pricing model is being applied to coordination of tunnel toll patterns in the Hong Kong road network.

Labbé et al. (1998) describes the road toll problem as a bi-level problem. The paper proves that it is an NP-hard problem. It is a relatively early paper which makes some assumptions to simplify reality. Firstly, it assumes no dispersion of traffic along the routes of the network. Secondly, it assumes that the value-of-time parameter is uniform throughout the user population, and that, given the choice between two paths of equal cost, the users always select the one with the highest toll. These assumptions imply Dynamic User Equilibrium (DUE) is not achieved, where no user can unilaterally reduce their origin to destination travel time (or cost). The major contribution of the paper is to describe the bi-level framework for optimal motorway pricing.