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Differentiated congestion pricing of urban transportation networks with vehicle-tracking technologies ☆

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ABSTRACT

This paper explores a new type of congestion pricing that differentiates users with respect to their travel characteristics or attributes, and charges them different amounts of toll accordingly. The scheme can reduce the financial burden of travelers or lead to more substantial reduction of congestion. Given that the scheme requires tracking vehicles, an incentive program is designed to mitigate travelers' privacy concerns and entice them to voluntarily disclose their location information.

1. Introduction

Price discrimination or differentiation is an economic concept defined by Dupuit (1894) as a situation where identical products are sold for different prices (Varian, 1992). Pigou (1932) later classified price discrimination into three categories. First-degree price discrimination is the case where everyone pays his or her maximum willingness-to-pay for the product. If the unit price of the product depends on the number of units being purchased, it is classified as second degree. Lastly, third-degree discrimination means that the price of one unit of the product can be different for different type of users.

Price discrimination is not uncommon in the transportation market. A good example for second-degree discrimination is transit fare, when, e.g., a two-way ticket is cheaper than two one-way tickets, or the price of a daily pass is independent of the number of rides taken by a passenger within one day. Moreover, some transit agencies differentiate travelers by age and collect different fares for kids, students, adults and elder people, which is an example of third-degree discrimination. Previous studies have discussed price discrimination in the context of congestion pricing. Wang et al. (2011) and Lawphongpanich and Yin (2012) investigated nonlinear pricing, which is essentially an instance of second-degree discrimination where the amount of toll depends on, not strictly proportional to, the distance traveled inside a tolling area. A case of third-degree discrimination is investigated in Holguin-Veras and Cetin (2009), which differentiated users based on their vehicle type. Others, e.g., (Small and Yan, 2001; Yang and Zhang, 2002; Yang and Huang, 2004; Yin and Yang, 2004), differentiated users based on their values of travel time. De Palma and Lindsey, 2004 compared the effect of toll differentiation based on the value of time

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and vehicle type on welfare. As pointed out by Pigou (1932), third-degree price discrimination generally requires an ability to distinguish different customer groups, i.e., there must be some observable attributes associated with each group, unless the pricing scheme possesses a self-selection mechanism. Given that the value of time is not directly observable, it is not surprising to find little practice of price differentiation with respect to the value of time.

This paper discusses another third-degree differentiated pricing scheme that differentiates travelers with respect to their travel characteristics or attributes, i.e., origins, destinations, or paths that they traverse between their origins and destinations. Although similar schemes may have been implemented in closed networks, e.g., tolled freeways, to our best knowledge, it has not been explored in an open, urban network environment for the purpose of congestion mitigation. We note that the advancements of vehicle-tracking and telecommunication technologies have technically enabled such a price differentiation.

The contributions of this paper are threefold. First, we use numerical examples to demonstrate the potentials of price differentiation with respect to origin, origin–destination (OD) pair or path. The examples show that in a first-best network condition where all the links are tollable, differentiated pricing can substantially reduce travelers' financial burden; in a second-best environment where only some links are tollable, it helps achieve a lower level of congestion. Second, we formulate optimization models to determine optimal differentiated pricing schemes for general networks. Third and more importantly, recognizing that price differentiation with respect to travel characteristics may compromise travelers' location privacy, we propose an approach of modeling privacy, and then design an incentive program to provide incentives for travelers to reveal their travel information and voluntarily participate in differentiated pricing. Such an opt-in program is designed to create a win–win situation for both travelers and society.

The remainder of this paper is organized as follows. Section 2 discusses different types of differentiated pricing and their formulations, and presents numerical examples to make a case for differentiated pricing. Section 3 discusses the location privacy issue associated with differentiated schemes, and proposes an approach of modeling privacy. Section 4 is dedicated to the development of an incentive program for differentiated pricing. Lastly, Section 5 concludes the paper and discusses another way to mitigate travelers' privacy concerns.

2. Differentiated pricing schemes

Differentiated pricing schemes we discuss in this paper include origin-specific, OD-specific and path-based. As their names suggest, travelers on the same link will be charged differently, with respect to their respective origin, OD pair or path. Intuitively, these schemes are more flexible than traditional anonymous tolling. Mathematically, they can be viewed as different levels of relaxation to anonymous schemes.

To facilitate the presentation, we label the differentiation level of anonymous pricing as zero, and subsequently the levels of differentiation for origin-specific, OD-specific and path-based pricing as one, two and three, respectively.

2.1. Notation

Let $G(N,A)$ denote a transportation network, where N is the set of nodes and A is the set of directed links. Index a is used to denote a link, which is also represented by its end nodes $i, j \in N$, i.e., $(i,j) = a$. For link a, x_a and γ_a are its aggregate flow and toll, respectively. The latter is expressed in the unit of time for the sake of simplicity. Let $W \subseteq N \times N$ be the set of OD pairs with strictly positive demand, w be the index of its elements and d_w be the demand of OD pair w. For every OD pair $w \in W$, $o(w)$ represents its origin. The set of all paths connecting OD pair w is denoted by P_w with its elements being indexed by p. A binary parameter δ represents the link-path incidence, i.e., if link a is on path p, then δ_{ap} is one; otherwise zero. For every path p, f_p and π_p denote its flow and toll, respectively. Again, the toll is represented in the unit of time. Also, $t_p(.)$ and $t_a(.)$ are the travel time for path p and link a, respectively. For second-best pricing, the set of tollable links is denoted by Ψ, and its complement set $\overline{\Psi}$ includes all the untollable links.

2.2. Formulations

As aforementioned, path-based scheme has the highest level of differentiation, because the origin or destination of a trip can be easily determined from the path utilized by the trip. Hence, a general path-based formulation is used in this paper to describe all three differentiation schemes. Notice that origin-specific and OD-specific pricing are link-based schemes, and thus the toll of each path is the sum of tolls on links comprising the path. In contrast, path-based tolls are determined for specific paths.

We first discuss a first-best network condition where all links are tollable. In such an environment, even with the lowest level of price differentiation, i.e., anonymous tolling, congestion pricing is able to induce system optimum and replicate system optimum link flows (e.g., Hearn and Ramana, 1998; Lou et al., 2010). Consequently, the benefit of price differentiation can only be reflected on a secondary objective. In this paper, we choose revenue minimization as the secondary objective because it represents a financial burden to the traveling public. Below, we formulate a program for finding a first-best path-based pricing scheme to minimize the total toll revenue:

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