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# Sensor location problems in path-differentiated congestion pricing

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ABSTRACT

Path-differentiated congestion pricing is a tolling scheme that imposes tolls on paths instead of individual links. One way to implement this scheme is to deploy automated vehicle identification sensors, such as toll tag readers or license plate scanners, on roads in a network. These sensors collect vehicles' location information to identify their paths and charge them accordingly. In this paper, we investigate how to optimally locate these sensors for the purpose of implementing path-differentiated pricing. We consider three relevant problems. The first is to locate a minimum number of sensors to implement a given path-differentiated scheme. The second is to design an optimal path-differentiated pricing scheme for a given set of sensors. The last problem is to find a path differentiated scheme to induce a given target link-flow distribution while requiring a minimum number of sensors.

## 1. Introduction

Congestion pricing is a well-established instrument for congestion mitigation, in which tolls are imposed to affect travel choices of users and entice them to use road networks more efficiently. Previous attempts have been made to improve the performance and address implementation issues, e.g., public opposition and inequity, of congestion pricing by designing more efficient, equitable, or robust schemes. Among these is the idea of differentiating tolls (or prices) according to, e.g., user characteristics, vehicle types, and trip purposes. See, e.g., de Palma and Lindsey (2011) and Zangui et al. (2013) for recent reviews. This paper focuses on tolls that are differentiated by paths or *path-differentiated tolls*.

Traditionally, tolls are imposed on links and summing these link tolls along individual paths lead to one set of path tolls. Such path tolls are dependent in that a change in one link toll may affect tolls on several paths. Path-differentiated tolls relax this dependency by assigning tolls directly to individual paths, instead of links. As a result, path-differentiated tolls can be determined independently. In addition, paths are generally more numerous than links. Thus, path tolls are more flexible and can achieve better performance than link tolls. Zangui et al. (2014) illustrated the potentials of path-differentiated tolls by comparing their performance to their link-based counterpart in designing pricing schemes that impose the least financial burden on users.

To implement a path-differentiated pricing scheme, the toll collection system must be able to distinguish paths of individual vehicles. For example, a system relying on data from on-board tracking devices, such as GPS, possesses such a capability. However, such a system requires all vehicles to be equipped with tracking devices and doing so may be expensive and difficult to maintain. Alternatively, automated vehicle identification (AVI) sensors can be used to identify vehicles' paths.

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When AVI sensors detect nearby or passing vehicles, they can uniquely identify the vehicles and record the time of detection. When collected from a sufficient number of strategically located sensors, the time of detections and locations of the detecting sensors can be used to infer the path of individual vehicles. In this paper, we investigate the use of AVI sensors in identifying paths of vehicles for the purpose of implementing path-differentiated charging schemes.

In practice, a broad range of devices, including some of toll collection devices, can be categorized as AVI sensors. In fact, two of the basic tasks in any toll charging system are to identify vehicles and record their locations (or, more precisely, the locations of the detecting sensors), which are the functionalities of AVI sensors. Nowadays, most of the tolling facilities use electronic toll collection technologies such as toll-tag readers (e.g., SunPass in Florida, TxTag in Texas, and E-ZPass in 15 other states in the U.S.) or license plate scanners (e.g., Toll-By-Plate in Florida, and License Plate Toll in Colorado). These devices can detect and identify vehicles, and can thus serve as AVI sensors. See, e.g., de Palma and Lindsey (2011) for a review on sensor technologies used in toll collection.

In the literature, traffic sensors, including AVIs, have many applications in transportation systems and each application gives rise to a different sensor location problem (see, e.g., Gentili and Mirchandani (2012) for a comprehensive review). Among them, the most relevant one to this paper is to optimally locate sensors for the purpose of traffic flow inference, where the data from sensors is used to determine some of the unobserved flows. These sensor location problems can be categorized, with respect to the type of flow they attempt to obtain, as follows:

- Origin–destination (OD) demand. While most of the studies attempted to estimate OD demands by minimizing deviations from a historical trip matrix (Yang et al. (1991), Yang and Zhou (1998), Bianco et al. (2001), Ehlert et al. (2006), and Castillo et al. (2008c)), some, e.g., Liou and Hu (2009), obtained the exact value of OD demand using the least number of sensors on the network.
- Flow on all paths. Gentili and Mirchandani (2005) assumed that vehicles equipped with devices can transmit their path information to a nearby roadside sensor, and studied the location problem for this type of sensors. Others, e.g., Castillo et al. (2008c) and Minguez et al. (2010), attempted to find optimal locations of sensors for observing path flows and OD demands.
- Flow on all links. This problem has been introduced by Hu et al. (2009), who also proposed a solution algorithm that uses the link-path incidence matrix and thus requires path enumeration. Later, Ng (2012) proposed a solution method for the problem that avoids path enumeration. He (2013) introduced more variants of sensor location problem for obtaining link flows, and proposed solution algorithms for those problems.

In addition to the above, a more general form of flow observation problem has emerged, which attempts to infer different flows from a set of observed flow data, e.g., using link and path flow information collected by sensors to obtain flow on other paths. Castillo et al. (2008b), Castillo et al. (2010), and Castillo et al. (2011) discussed and proposed solution method for these types of problems.

The contributions of this paper are threefold. First, we introduce and explore the idea of using AVI sensors to implement path-differentiated tolls. Second, we develop mathematical models for three variations of the sensor location problem and investigate their properties, where two problems involve determining sensor locations and one assumes that sensor locations are given. Third, through examples, we demonstrate the advantages of using AVI sensors to implement path-differentiated tolls over traditional link-based schemes.

For the remainder, the next section introduces the notation and briefly reviews the concept of path-differentiated pricing. Section 3 defines and formulates conditions for a set of sensor locations, capable of identifying the path of every vehicle. Each of the next three sections discusses one problem in sensor locations for path-differentiated tolls. The first version aims at finding optimal sensor locations for implementing a given path-differentiated scheme, whereas the second one assumes the sensors are already located on the network and attempts to design an optimal path-differentiated scheme that is implementable using the available sensors. The third problem is to design a path-differentiated scheme that induces a given link-flow distribution and requires the least number of sensors to implement. Finally, Section 7 concludes the paper.

## 2. Background

This section introduces the notation used throughout the paper and presents an overview of path-differentiated congestion pricing. To be concise, we assume that readers are familiar with the motivation and fundamental results in congestion pricing. Otherwise, readers can consult, e.g., Yang and Huang (2005), Lindsey and Verhoef (2000), and Tsekeris and VoB (2009).

### 2.1. Notation

Let $G = (\mathbb{N}, \mathbb{A})$ represent a transportation network, where $\mathbb{N}$ and $\mathbb{A}$ are the sets of nodes and links, respectively. The set of OD pairs is denoted by $\mathbb{W}$, and $d_w$ represents the demand for OD pair $w \in \mathbb{W}$. The set of paths connecting OD pair $w \in \mathbb{W}$ is denoted by $\mathbb{P}_w$, and the union of all these path sets by $\mathbb{P}$. For each path $p$, its flow, travel time, and toll are represented by $f_p,\ t_p(f)$, and $\pi_p$, respectively. For simplicity, tolls are represented in the unit of time. (In this paper, vectors of variables are

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