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Review

Review of optimal sensor location models for travel time estimation

M. Gentili[a,c,*], Pitu B. Mirchandani[b]

[a] *Industrial Engineering Department, J.B. Speed School of Engineering, University of Louisville, United States*
[b] *School of Computing, Informatics and Decision Systems Engineering, Arizona State University, United States*
[c] *Department of Mathematics, University of Salerno, Fisciano, Italy*

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ABSTRACT

The problem of optimally locating fixed sensors on a traffic network infrastructure has been object of growing interest in the past few years. Sensor location decisions models differ from each other according to the type of sensors that are to be located and the objective that one would like to optimize. This paper surveys the existing contributions in the literature related to the problem of locating fixed sensors on the network to estimate travel times. The review consists of two parts: the first part reviews the methodological approaches for the optimal location of counting sensors on a freeway for travel time estimation; the second part focuses on the results related to the optimal location of Automatic Vehicle Identification (AVI) readers on the links of a network to get travel time information.

1. Introduction

Transportation networks are the blood veins of the urban form. They provide conduits and channels for people to physically connect, for workers to keep the engines of the economy functioning, for delivery and purchase of food, fuel, and services for a sustained quality of life, for distribution of resources, and in general multiplying the extent and livability of a populated region. All this depends on the performance of the transportation system. Therefore, efficiently operating and maintaining it becomes crucial for mobility and urban sustainability.

One of the key considerations in the performance of a transportation network is the congestion level measured in terms of delays and travel times. Real-time estimation of travel times is a useful tool for traffic management and for providing information to travelers. Travel time estimation can be computed by collecting data on vehicles (flows, speeds, queues, densities, etc.) on the network. This data can be collected either manually (by questionnaires, surveys, census, or even standing at street corners and counting vehicles), or by installing sensors (hardware and software) that collect such or similar data. Traditionally, collection of observations for travel time estimation has been carried out by transportation agencies through an extensive use of counting sensors (i.e., loop inductance detectors) uniformly located on freeways and highways usually at distances of 0.5–1.0 miles. The origin of such a practice is based on past analysis that has shown uniform spacing among detectors is useful for Automatic Incident Detection algorithms (ADI). The role of ADI algorithms, however, is now less important for traffic management (Parkany and Xie, 2005; Williams and Guin, 2007), due, on the one hand, to the poor performances of these algorithms in terms of detection rates, false alarm rates and mean time to detect, and, on the other hand, to the widespread use of mobile phones that have become increasingly important in the detection of incidents.

* Corresponding author at: Industrial Engineering Department, J.B. Speed School of Engineering, University of Louisville, United States.
E-mail addresses: monica.gentili@louisville.edu (M. Gentili), pitu@asu.edu (P.B. Mirchandani).

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The massive use of cellular phones with GPS is now the most common source of real time data to estimate travel times. However, unlike fixed sensor data which is anonymous and is freely usable by transportation agencies, vehicle/individual GPS trajectory data comes with privacy concerns. On the other hand, public vehicles with GPS like buses can be used as probe vehicles[1] that also give travel times on their routes. However, for situations where this kind of information is not readily available, the location of sensors is still an important and relevant approach to gather real time data for estimating and predicting travel times.

Studies on locating sensors have grown rapidly due to development of new methods and technologies. Following this vein, few papers, some by us and other co-authors, have studied various models that optimally locate sensors to:

(a) Estimate vehicle flows on links and routes (Lam and Lo, 1990; Castillo et al., 2011, 2013; Gentili and Mirchandani, 2012; Ng, 2012, 2013; He, 2013; Bianco et al., 2014; Shao et al., 2016)
(b) Estimate OD trips (Hu and Liou, 2014; Wang and Mirchandani, 2013; Hadavi and Shafahi, 2016)
(c) Observe the exact flows on routes (Cerrone et al., 2015; Fu et al., 2016)
(d) Collect data on traffic network for some general measures (Ban et al., 2011; Gentili and Mirchandani, 2014; Sherali et al., 2006)

In this paper, we survey the main contributions in the literature related to the problem of optimally locating fixed sensors on a transportation network to estimate travel times. The types of sensors we will consider are the following:

(a) *Passive fixed sensors.* These sensors do not require any active information being provided from a passing vehicle. Most common passive detectors (we use the term sensors and detectors interchangeably), and most widely used, are the single or double induction loop detectors mounted in the pavement at fixed locations. When a vehicle passes over it, the metal mass of the vehicles causes a change in the magnetic flux in the loop producing an impulse in the current through the loop; these impulses thereby count cars. Often in traffic signal operations such loops are used as counters that indicate the vehicle flow rate approaching the signalized intersection. *Single loop detectors* can be used as counting sensors and speed sensors, although as speed sensors there are errors introduced because of an underlying assumption that equal standard sized vehicles pass over the sensors. *Double loop detectors* have two loops embedded a few feet apart in the pavement. Double loops measure speeds more accurately since a vehicle size need not be assumed. There are other technologies used for sensing vehicles producing (i) acoustic detectors, (ii) magnetic detectors, (iii) microwave detectors, (iv) ultrasonic sensors, (v) infrared sensors, and (vi) video or image sensors; all these detect vehicles passing over a fixed point where the sensor is pointed. Some image sensors can measure vehicle queues and track vehicles in its field of view using image-processing techniques. An appropriately placed radar detector can also detect and track vehicles in the sensor's field of view. Roadside sensors are also available that can measure emissions from vehicles using real-time chemical analyses.
In this paper, we will use the term (fixed) *counting sensors* to refer to this class of detectors.
(b) *Active Fixed Detectors.* Active detectors require vehicles to actively provide its identification, needed for specific purposes such as toll collection. License plate readers, Bluetooth sniffers, and RFID or bar coded tags on vehicles are other examples.
In this paper, we will use the term *Automatic Vehicle Identification* (AVI) sensors or readers to refer to this class of detectors.

This review focuses on fixed sensors, that is, sensor location is fixed with respect to the network infrastructure. There are also mobile sensors (piloted helicopter or drones) which can be used to provide information on traffic conditions. These contributions are not reviewed in this paper.

There are several contributions which use empirical data or simulation models to evaluate some functional performance of a predefined set of potential sensor locations for specific networks. To cite a few examples: (i) the effect of detectors spacing on travel time estimation quality was studied by Fujito et al. (2006) based on real data from the field in freeways corridors in Cincinnati and Atlanta; (ii) the quality of different travel time estimation methods was studied by Li et al. (2006) by using empirical data from motorways in Melbourne (Australia) and by Liu et al. (2006) by using data from simulation models of I-70 corridor in Maryland; (iii) a microscopic traffic simulation model of a freeway segment located in Prince William County and Fairfax County in Norther Virginia was used by Kim et al. (2011) to evaluate the location of sensors for a genetic algorithm to optimally locate them; and (iv) Thomas (1999) developed a simulation model to simulate a three-mile section of Southern Avenue arterial located in Tempe and Mesa (AZ) and to compare the performance of four different sensor placement patterns. These type of contributions are not reviewed in this paper. The paper instead focuses on contributions which propose analytical models to optimally locate sensors for travel time estimation which are not limited to a specific network under study or a specific set of data.

In this context, the existing contributions can be classified into two main classes: analytical models to optimally locate counting sensors on a freeway, and analytical models to optimally locate AVI readers on a network. These two classes are reviewed in Section 2 and Section 3, respectively.

2. Locating counting sensors to estimate travel times on a freeway

As already mentioned, freeways have been usually equipped with counting sensors (mainly inductive loop detectors) to support

[1] Vehicles that can be tracked via GPS locations can be used as probes to monitor the traffic; such vehicles could be specifically used by traffic agencies or could be vehicles such as buses and trucks that provide similar data.