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Locating sensors on traffic networks: Models, challenges and research opportunities

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ABSTRACT

The problem of optimally locating sensors on a traffic network to *measure* flows has been object of growing interest in the past few years, due to its relevance in transportation systems. Different locations of sensors on the network can allow, indeed, the collection of data whose usage can be useful for traffic management and control purposes. Many different models have been proposed in the literature as well as corresponding solution approaches. The proposed existing models differ according to different criteria: (i) sensor types to be located on the network (e.g., counting sensors, image sensors, Automatic Vehicle Identification (AVI) readers), (ii) available a-priori information, and (iii) flows of interest (e.g., OD flows, route flows, link flows). The purpose of this paper is to review the existing contributions and to give a unifying picture of these models by categorizing them into two main problems: the *Sensor Location Flow-Observability Problem* and the *Sensor Location Flow-Estimation Problem*. For both the problems, we will describe the corresponding computational complexity and the existing results. After describing various models and identifying their advantages and limitations, we conclude with several promising directions for future research and discuss other classes of location problems that address different objectives than the ones reviewed in the paper.

1. Introduction

Network traffic flows may be characterized in various ways, for example, trips (in number of vehicles per hour) from each origin to each destination, and for another example, flow volumes on given routes or route segments. Depending on what we are interested in we can deploy sensors to *observe* such flows. The first issue that may be raised is "Are these flows observable?" For example, if one were interested in measuring passenger flows on a route segment, current deployable sensor technologies cannot observe that (but they may be estimated if one assumed a passenger per vehicle distribution). However, we are able to *directly observe* link flows or, in some cases route flows. Sometimes we are able to *indirectly observe* more aggregated flows such as OD trips. Generally, relationships among various flow volumes can be represented by a system of linear equations where the columns represent the unknown volume of flows and row amounts come from data from deployed sensors. The resulting sets of equations together define a system of equations associated with the deployment. The system of equations that results depends on the types of sensors and the number of sensors that are deployed. In particular, according to (a) the different type of sensors that can be located, (b) the assumptions made regarding available a-priori information, and (c) the type of flows one focuses on, different systems of equations describe the flows. In this context, the total number of measurements and their location play an important role for the determination of the flows of interest. In particular, two classes of problems arise:

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- If the system of equations obtained by locating several sensors admits a unique solution, what is the minimum number of sensors and where to locate them in order to obtain this unique solution?
- If the system of equations obtained by locating several sensors does not admit a unique solution, how to choose sensor locations to improve the quality of the flows estimates? (Informally "*quality*" is a measure of distance between the obtained estimate and the true value; it will be formally explained in Section 6).

Existing contributions in the literature addressing these problems can be grouped into these two main classes:

(i) *The Sensor Location Flow-Observability Problems*: identify the optimum location of sensors on the network that allows the unique determination of the solution of the linear system of equations associated with the located sensors.
(ii) *The Sensor Location Flow-Estimation Problems*: identify the optimum location of sensors on the network to best improve the quality of the related estimates (OD trips estimates, link flows estimates, route flows estimates, etc.) that can be obtained by the system of linear equations associated with the located sensors.

Both the problems are introduced in Section 3. A brief overview of different types of sensors is given in the next section before formally describing various sensor location problems in the subsequent sections.

2. Types of sensors

Various technologies are used in different types of sensors to detect characteristics of flows such as speed, density, volumes, occupancy, turning ratios, and vehicle identifications. In this paper we group sensor types into four categories: counting sensors, path-ID sensors, image sensors and vehicle-ID sensors. We define these four groups according to the different flow characteristics that can be derived by the information obtained from the sensors and that are used in the problems studied in Sections 5 and 6.

C*ounting sensors* predominate traffic applications; they are able to count vehicles on a lane(s) of the network. This type of sensors includes inductive loop detectors, magnetic detectors, pneumatic road tubes, piezoelectric pads, video detectors among others. Based on vehicle counts they are able to monitor lane performance such as speed, density, occupancy, and flow rates. We assume counting sensors to be located either on links or on nodes of the network. When a counting sensor is located on link a of the network we assume it measures vehicle flow volume v_a (in the considered time interval) on the link. When a counting sensor is located on a node we assume it measures the link flows of all incoming and outgoing links of the node (this occurs in scenarios where a configuration of count detectors is implemented using technologies such as video, sonar, microwave, etc., at a node so that flow volumes on all links incident to the node are measured).

Path-ID sensors are assumed to be devices that when located on a link of the network can measure the flow volumes of each route to which that link belongs. Path-ID sensors assume that active communication is provided by the class of vehicles being monitored and identifies the route being used by each vehicle in the class. For example, in some countries/states/cities, special vehicles such as commercial trucks, buses, emergency vehicles, and trucks carrying hazardous material have electronic "tags" or transponders installed on them that transmit some sort of identification, from which one can obtain its planned route through the network. Furthermore, in the planned *Connected-Vehicle* infrastructure (www.its.dot.gov/connected_vehicle/connected_vehicle.htm), equipped vehicles could communicate planned route information for route guidance applications. Although Path-ID sensors are not widely deployed, the rich information they provide make observability and estimation problems even more meaningful.

Image sensors are all of those sensors that can take images of the moving flows, such as, for example, a fixed camera mounted on a tall building or a pole measuring flows at an intersection or a link. By processing the images, it is possible to recognize moving vehicles in the scene. In this paper, such sensors are assumed to be located on the nodes of the network. When an image sensor is located on node i we assume it can provide the following information: (i) flow volumes v_a on the links incident to node i and (ii) turning ratios $t^i_{(j,k)}$ that denote the proportion of flow that goes from the incoming link (j,i) to the outgoing link (i,k) of node i.

Vehicle-ID sensors are those sensors through which a vehicle ID can be identified on the network. For example, license plate readers that use camera images, or Automatic Vehicle Identification (AVI) readers that use RFID tags or bar-codes, can be located over lanes or on roadsides to identify vehicles. License plate readers are often used to monitor travel times while AVI readers to collect tolls on equipped vehicles. Without loss of generality, our models will assume vehicle-ID sensors may be located on the links of the network and the information collected by these sensors are the vehicle ID and the time the vehicle activates the detectors.

The deployment of counting, path-ID, image and vehicle-ID sensors on a network can be translated into a set of linear equations as it is explained by means of an example in the next section and more formally stated in Section 5.

3. Where to locate sensors? An example

Consider the network in Fig. 1 where there are 6 nodes and 8 links. There are three OD pairs, namely $w_1 = (1,5)$, $w_2 = (6,5)$, and $w_3 = (2,6)$. The first OD pair w_1 is connected by routes $R_1 = \{a_3, a_4, a_5\}$ and $R_2 = \{a_3, a_6, a_7\}$, OD pair w_2 is connected by routes $R_3 = \{a_1, a_3, a_4, a_5\}$ and $R_4 = \{a_2, a_6, a_7\}$, and there is a single route $R_5 = \{a_6, a_8\}$ connecting the last OD pair.