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Assessing the effect of route information on network observability applied to sensor location problems

Marco Rinaldi [a], Francesco Corman [b], Francesco Viti [c] *

[a] Leuven Mobility Research Centre, KU Leuven, Celestijnenlaan 300A, 3001, Heverlee, Belgium
[b] Maritime and Transport Technology Department, Delft University of Technology, Mekelweg 2, 2628 CD Delft, the Netherlands
[c] Research Unit of Engineering Sciences, University of Luxembourg, 6 rue Coudenhove-Kalergi, L-8081, Luxembourg

Abstract

Link flow observability in traffic networks strongly relies on where sensors are installed. Full observability solutions are found by adopting various techniques exploiting existing relationships between links, which are determined either by using link-node relations, or by link-route relations. While the first relations are elegant as they do not require explicit route enumeration and therefore remain tractable for large-sized networks, they do not contain all the information at the route and OD levels. However, in case full route enumeration is not possible, route selection criteria are of paramount importance. In this paper we explore the impact of using k-shortest path algorithms for determining the route sets needed to solve the observability problems using link-route relations. In particular, we show how a limited amount of routes per OD pair is needed in order to incorporate all relevant information. Further, we demonstrate that selection route criteria that consider only linearly independent routes allows to find full observability solutions that need a lower number of sensors. Finally, we show that observability metrics, such as those presented in Viti et al. (2014), describe a direct relation between number of routes considered and degree of information. Through these metrics, we can show that link-route relations selected using only linearly independent links contains systematically more information. Moreover, there is empirical evidence that the marginal increment of information per additional route added decreases. This defines an asymptotic maximum value of information, which is found for a relatively limited amount of routes.

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Keywords: Network Sensor Location Problem; Observability; Null-Space metric; k-shortest paths; Linearly-independent routes

* Corresponding author. Tel.: 3524666445352; Fax: +3524666445200.
E-mail address: francesco.viti@uni.lu

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1. Introduction

Network Sensor Location Problems (NSLP) aim to find an optimal set of sensors in order to maximize some information on a network. These problems have been dealt with in the past in two ways. A large deal of literature sees the problem as inverse of the origin-destination (OD) estimation (see e.g., Gentili and Mirchandani, 2012 for an overview), while a more recent research direction explores the observability of any state variable (link, route or OD) on the basis of the measured flows, and by explicitly exploiting topological information (see e.g., Viti et al., 2014 for an overview). This paper focuses on the latter class, which is normally referred to as *observability problem*.

In observability problems, the goal is to find the minimum set of observed link (or route, OD) flows that can provide information on the remaining non-observed links. In particular, in *full* observability solutions, all unobserved flows are indirectly observable, as they are function of the observed flows. Closely related to this, a more general goal is to find the tight upper bound of the minimum number of observed flows such that the system becomes fully observable, while, at the same time, the observed flows are linearly independent, i.e. no redundant information is included.

Crucial information needed to solve observability problems are the topological relations expressed in the so-called incidence matrix, which relates link, node, route and possibly OD variables to each other. These relations may be expressed as route-based (Castillo et al., 2008) or node-based (Ng, 2013; He, 2013). The latter approach has the advantage of not requiring route enumeration, which is a very handy property in case of large-sized networks. Node-based solutions, however, lack some important relationships originating at the route level, i.e. those between sequences of links along a specific path. Because of this, route-based approaches may find full observability solutions with a smaller number of sensors. On the other hand, finding how and which routes to enumerate is currently a challenge (Castillo et al., 2014).

In this paper we study this last problem, by proposing and assessing a methodology based on using k-shortest path algorithms for determining the route sets considered in the incidence matrix, when solving the observability problems. In particular, we show how a limited amount of routes per OD pair is needed in order to incorporate all relevant information, and that including routes that are independent with each other yields higher information content. Observability metrics, as those presented in Viti et al. (2014), are able to quantitatively describe a direct relation between number of routes considered and degree of information. Through these metrics, we can show that link-route relations selected using only linearly independent links contains systematically more information. Moreover, there is empirical evidence that the marginal increment of information per additional route added decreases. This defines an asymptotic maximum value of information in a network, which is found for relatively limited amount of routes. We provide such empirical evidence, with the help of different mid- and large size networks, and we compare the aforementioned findings with the node-based solution counterparts.

This paper is structured as follows. The next section introduces the observability problem and a selection of the relevant literature. Section 3 presents a metric previously introduced by the authors to solve partial observability problems and to classify full observability solutions. Section 4 focuses on the impact of k-shortest paths in the definition of the link-route relations and consequently in the efficiency of full observability solutions. The impact of shortest paths is then analyzed using toy networks in Section 5. Section 6 discusses the implication of our findings and provides some direction to explore in terms of k-shortest path heuristics. Finally, Section 7 provides conclusions and recommendations.

List of symbols

$\boldsymbol{h}$	route flows vector
$\boldsymbol{v}$	link flows vector
$\boldsymbol{f}$	OD flows vector
R	route set
L	link set
δ	link-route incidence matrix
ρ	OD-route incidence matrix