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Heterogeneous sensor location model for path reconstruction

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ABSTRACT

A new traffic sensor location problem is developed and solved by strategically placing both passive and active sensors in a transportation network for path reconstruction. Passive sensors simply count vehicles, while active sensors can recognize vehicle plates but are more expensive. We developed a two-stage heterogeneous sensor location model to determine the most cost-effective strategies for sensor deployment. The first stage of the model adopts the path reconstruction model defined by Castillo et al. (2008b) to determine the optimal locations of active sensors in the network. In the second stage, an algebraic framework is developed to strategically replace active sensors so that the total installation cost can be reduced while maintaining path flow observation quality. Within the algebraic framework, a scalar product operator is introduced to calculate path flows. An extension matrix is generated and used to determine if a replacement scheme is able to reconstruct all path flows. A graph model is then constructed to determine feasible replacement schemes. The problem of finding the optimal replacement scheme is addressed by utilizing the theory of maximum clique to obtain the upper bound of the number of replaced sensors and then revising this upper bound to generate the optimal replacement scheme. A polynomial-time algorithm is proposed to solve the maximum clique problem, and the optimal replacement scheme can be obtained accordingly. Three numerical experiments show that our proposed two-stage method can reduce the total costs of transportation surveillance systems without affecting the system monitor quality. The locations of the active sensors play a more critical role than the locations of the passive sensors in the number of reconstructed paths.

1. Introduction

To effectively mitigate transportation congestion, effective transportation surveillance systems have to be in place to facilitate transportation stakeholders to develop control and guidance tools. There is a range of different traffic sensors or detectors for monitoring the transportation network. The most popular and cheapest monitoring devices, perhaps, are loop detectors, which can provide data on speed, traffic flow and occupancy. In addition, the automatic vehicle identification (AVI) technology, though more expensive, can be adopted. It is able to read vehicle plates, and thus provides travel time and flow volume information for a specific path. In general, these traffic monitoring devices are used for extracting critical information regarding Origin-Destination demand, link flows, path flows and travel time. In particular, traffic sensors are used for OD demand observation, OD demand estimation, path reconstruction, link flow inference and travel time estimation.

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Nomenclature

Notation	Description
z_a	$z_a = 1$ if link a is equipped with an AVI sensor, otherwise 0
w_a^p	$w_a^p = 1$ if link a is on path p, otherwise 0
v_a	traffic flow on link a
n_1	number of AVI sensors
n_2	number of passive sensors
n	total number of sensors ($n = n_1 + n_2$)
m	number of known paths
f_i	path flow on ith path
w_i	ith row of W_{OBSV}which is associated with ith link
W	link-path incidence matrix
W_{OBSV}	observed link-path matrix of the OBSV model
W_ε^k	matrix of the results for all combinations with k rows of W_{OBSV}.
W^*	matrix generated from W_{OBSV} by the extension operation
WJ	maximal linear independent set of W_{OBSV} whose rank is r
WI	W_{OBSV} excluding WJ
W_1	submatrix of the link-path matrix observed by passive sensors
W_2	submatrix of the link-path matrix observed by AVI sensors
E	identity matrix which is a submatrix of W_2
D	integer matrix which is a submatrix of W_2
d_a	the ath row of matrix D
0	null matrix (submatrix of W_2)
W_E	a binary matrix in W_1 corresponding to E
W_D	a binary matrix in W_1 corresponding to D
$W_{\mathbf{0}}$	a matrix in W_1 corresponding to $\mathbf{0}$
F	set of path flows
P	set of paths
V	set of link flows
V_{OBSV}	subset of V whose entries are associated rows of W_{OBSV}
$V*$	set generated from V_{OBSV} based on generation process of W^*
s	set of some links with AVI sensor
T_1	Set of all sensor locations that can be replaced solely
H	graph of replacement scheme relationships in the second stage model
d	vertex degree
$\tilde{V}$	the maximum clique of H
$\tilde{v}$	a vertex of graph H
$H_{\tilde{v}}$	subgraph of graph H which is the set of vertices adjacent to $\tilde{v}$ and Links among them
$\tilde{V}_2$	the maximum clique of $H_{\tilde{v}}$

Gentili and Mirchandani (2012) summarized the basic sensor location models and outlined future challenges. Recently, Castillo et al. (2015) performed a state-of-the-art review of mathematical programming frameworks for flow observability, estimation and prediction problems in transportation networks from different aspects including data, variables, constraints, objective functions and examples. In what follows, we explain the state-of-the-art literature review.

(i) Traffic sensors have long been used for estimating OD demand through optimally positioned traffic sensors. Yang and Zhou (1998) proposed four basic sensor location rules for OD estimation, the essence of which was to cover as much traffic flow as possible on different OD pairs. All path flow between each OD pair is required to be intercepted (Yang et al., 2006). Using these coverage rules, a mobile traffic sensor was introduced to monitor the transportation network. A vehicle routing model was proposed to model the routing behavior of the mobile sensor (Zhu et al., 2014). Furthermore, the effectiveness of the OD estimation was discussed. The OD estimation error can always be bounded for the sensor location model (Bianco et al., 2001). Hu and Liou (2014) utilized both passive and active sensors to estimate the OD demand. The existing detection and information content of the prior OD matrix was considered (Ehlert et al., 2006). The actual values of the input data parameters were considered for OD demand estimation (Yang and Fan, 2015). In addition to the OD observation or estimation-related sensor location studies, OD flow uncertainty is inevitable and was considered in estimating the OD demand matrix (Fei et al., 2007). There exists a tradeoff between the OD coverage and uncertainty reduction (Fei and Mahmassani, 2011). The recognition of uncertainty also triggered the development of new sensor location model to minimize the OD variation (Zhou and List, 2010; Simonelli et al., 2012; Fei et al., 2013). Sensor failure was also considered for the purpose of both travel time and OD trip estimation