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A stochastic program approach for path reconstruction oriented sensor location model

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ABSTRACT

Path flow identification is of particular interest for a number of traffic applications, such as OD demand estimation, link flow inference, and toll freeway revenue management. Optimal positioning of active sensors can help to identify path flows. Due to the stochastic nature of transportation systems, we propose a scenario based two stage stochastic programming framework which considers the uncertainty of the link-path matrix. The first stage model aims to minimize the total traffic sensor installation cost and the expected penalty for uncovered and undifferentiated paths. The second stage model attempts to minimize uncovered and undifferentiated paths for a given sensor location pattern and a specific scenario. In addition, a mean risk measure is also incorporated into the two stage stochastic programming framework, and consequently a mean risk two stage stochastic programming model is proposed. Both models have the same structure, where the first stage and second stage decision variables are binary. The second stage decision variable can be relaxed to a continuous variable without changing the nature of the model. To solve the two stochastic programming models, a branch and bound based integer L-shaped algorithm is presented. Finite steps convergence is guaranteed for the algorithm. To handle the problem with a large number of scenarios, a sampling technique is introduced, and the confidence bound is analyzed with respect to the scenario size. Extensive numerical experiments are conducted to verify the effectiveness of the proposed models and algorithm. The most important numerical results are as follows: (i) the stochastic programming framework is capable of capturing the reality more efficiently and accurately, (ii) the path differentiation factor is more critical than the path coverage factor in determining the sensor placement pattern, and (iii) in the partial parameter setting case, the mean risk based stochastic programming model results in a significantly different sensor placement pattern compared to the normal stochastic programming model. The study contributes to practical sensor placement design.

1. Introduction

Traffic sensors have been used in the past several decades to effectively monitor transportation systems. Different types of traffic sensors are employed for various purposes. Traffic sensors are installed for OD estimation, link flow observation and estimation, path flow reconstruction, travel time estimation, and so on (Yang and Zhou, 1998; Castillo et al., 2008a,b; Hu et al., 2009; Li and Ouyang, 2011; Ng, 2012; He, 2013; Ng, 2013; Zhu et al., 2014; Hu and Liou, 2014; Cerrone et al., 2015; Wang et al., 2012; Wang and Mirchandani, 2013). In general, there are two types of traffic sensors, namely, passive

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and active sensors. A passive sensor can detect a vehicle when it passes. The obtained information from passive sensors includes the traffic flow volume, vehicle speed and occupancy. An active sensor is able to read vehicle plates. Accordingly, path and travel time information can be inferred. In practice, active sensors are much more expensive than passive sensors. Due to budget limits, transportation agencies attempt to find optimal sensor locations for specific purposes.

Among all data based traffic applications, research on path flow reconstruction is of particular interest. A major reason for this is that once the path flow is known, links and OD flows can be derived immediately. The OD estimation error (Yang and Fan, 2015) can be high if the route choice behavior is highly uncertain and the path information is unknown. Moreover, path flow identification can mitigate the prior information dependence on the OD flow, and consequently reduce the prior information survey cost (Castillo et al., 2008b). From the toll and pricing aspect, path flow identification helps to set accurate charges. In addition, the knowledge of the path flow can lead to fair revenue sharing in toll freeway networks.

Most studies consider transportation networks as static and stable. However, this rarely corresponds to the reality. A number of factors show their impact on a transportation system state. From the supply side, the transportation network capacity may be changed due to accidents, weather conditions, road maintenance, and so on. From the demand side, temporal spatial variations in traffic demand change the distribution of traffic flows in the network. After the demand is established in the transportation network, the route choice behavior is highly uncertain due to the changes in supply and demand. Therefore, the system link-path matrix can be seen as highly uncertain, but it has to be considered in traffic sensor deployment. Further discussion on the motivation of our study is provided in Appendix A.

2. Literature review

The paper essentially involves two viewpoints and perspectives, namely, the network sensor location problem (NSLP) and stochastic programming approach, used to optimize the locations of traffic sensors.

2.1. Sensor location literature review

There are two survey papers that provide the state-of-the-art review of the network sensor location problem (Gentili and Mirchandani, 2012; Castillo et al., 2015). In these papers, traffic flow observation and estimation models are reviewed. In general, solution methods consist of mathematical programming approaches and algebra methods. In what follows, we review studies related to our work. Providing an accurate and comprehensive review of network sensor location problem literature is not a goal of this paper.

Deterministic models decide sensor locations in a stable transportation network context. The first sub-class of deterministic models focuses on OD flow observation and estimation. A number of mathematical programming models are proposed to fully capture OD flows so that they can be estimated (Yang and Zhou, 1998; Bianco et al., 2001; Ehlert et al., 2006; Yang et al., 2006; Castillo et al., 2008a). Hu and Liou (2014) determine a sensor location scheme based only on the topological structure. Yang and Fan (2015) point out that the reliability of the prior OD demand influences the accuracy of OD estimation.

Another sub-class of deterministic models aims to decide locations with the goal to infer full or partial link flows. The algebraic methods of link-path matrix (Hu et al., 2009), node-link matrix (Ng, 2012; 2013) and spanning tree (He, 2013) are proposed to solve the link flow inference problem. A new metric is presented to quantify the quality of a solution in the context of partial observation (Viti et al., 2014). Link flow correlations are also utilized to infer link flows (Liu et al., 2015).

The third sub-class of deterministic sensor location problem models aims to determine active sensor locations to reconstruct paths. A bi-objective model is proposed to minimize the number of active sensors using a strong and unrealistic assumption on path identification (Gentili and Mirchandani, 2005). Realistic path identification assumptions are later adopted using known path information (Castillo et al., 2008b; 2010; Mínguez et al., 2010). The order of active sensors on a path is also considered (Cerrone et al., 2015).

All the above path reconstruction models use active sensors only. Recently, heterogeneous sensor location models were proposed to reduce the cost of sensor systems by reducing installation costs. Exact (Fu et al., 2016) and heuristic (Castillo et al., 2012) methods are employed to determine the location of heterogeneous traffic sensors.

In addition to deterministic sensor location models, there are models addressing different types of uncertainty in transportation networks. Mathematical programming models for the minimization of the uncertainty of the estimated OD demand while taking into account as much OD demand as possible are proposed (Fei et al., 2007; 2013; Fei and Mahmassani, 2011). Zhou and List (2010) propose a sensor location model considering several error sources of OD demand estimation including uncertainty in historical demand information and sensor measurement errors. A beam search algorithm is adopted to find near-optimal solutions. A synthetic dispersion measure is proposed to optimize the locations of traffic sensors (Simonelli et al., 2012). The minimization of route flow estimation uncertainty is also considered in the traffic sensor location context (Wang et al., 2012; Wang and Mirchandani, 2013). Besides, Xing et al. (2013) minimize travel time uncertainty based on the information theory. A stochastic programming model is proposed to deal with uncertain sensor failures when installing sensors in freeway corridors (Li and Ouyang, 2011; Zhu et al., 2016).