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A tensor-based Bayesian probabilistic model for citywide personalized travel time estimation☆

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ABSTRACT

Urban travel time information is of great importance for many levels of traffic management and operation. This paper develops a tensor-based Bayesian probabilistic model for citywide and personalized travel time estimation, using the large-scale and sparse GPS trajectories generated by taxicabs. Combined with the knowledge learned from historical trajectories, travel times of different drivers on all road segments in some time slots are modeled with a 3-order tensor. This tensor-based modeling approach incorporates both the spatial correlation between different road segments and the person-specific variation between different drivers, as well as the coarse-grain temporal correlation between recent and historical traffic conditions and the fine-grain temporal correlation between different time slots. To account for the variability caused by the intrinsic uncertainties in urban road network, each travel time entry in the built tensor is treated as a variable following a log-normal distribution. With the help of the fully Bayesian treatment, the model achieves automatic hyper-parameter tuning and model complexity controlling, and therefore the problem of over-fitting is prevented even when the used data is large-scale and sparse. The proposed model is applied to a real case study on the citywide road network of Beijing, China, using the large-scale and sparse GPS trajectories collected from over 32,670 taxicabs for a period of two months. Empirical results of extensive experiments demonstrate that the proposed model provides an effective and robust approach for urban travel time estimation and outperforms the considered competing methods.

1. Introduction

With soaring birth and increasing migration into urban areas, urban road transportation systems experience increasing congestion. It threatens not only transportation efficiency but also living environment. To tackle this problem, knowledge about traffic dynamics and mobility, such as travel time in road network, is significantly important at many levels of traffic managements and operations. Through providing accurate travel time information, individuals can make a better route choice, fleet management companies can operate dispatching system more efficiently, traffic management departments can find problematic locations where a new or revised traffic control scheme should be introduced to increase performance, traffic policy-making agencies can analysis travel demand and assess impact of policy instrument such as congestion charges (Jenelius and Koutsopoulos, 2013). However, due to the

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inherent uncertainties caused by fluctuations in traffic demand and supply, traffic control, stochastic arrival and departure at signalized intersection, etc., travel time estimation in urban road network is a well-known challenging subject (Zheng et al., 2012).

Most recently, the advancement of information collection and communication technology is transforming a once data-starved transport field into one of the most data-rich. The increasing availability of opportunistic sensors, e.g., GPS devices installed in taxicabs, provides ample of vehicle trajectory data at a large spatial-temporal scale, and allows the use of more sophisticated models to provide traffic information for urban road network. Basically, GPS trajectories is not able to provide direct information that are usually required by analysis-based models, such as traffic flow and signal timings. Data-driven approach, which discovers the underlying latent patterns and knowledge inside data using only the data itself, seems more appropriate for this situation (Zhang et al., 2017; Zheng and Van Zuylen, 2013).

This paper proposes a tensor-based Bayesian probabilistic model for citywide and personalized (i.e., driver-specific) travel time estimation, using only the limited information from large-scale and sparse GPS trajectories derived from taxicabs. Tensor (*definition 3*) is one of the most popular methods to characterize multi-mode correlations of data. It has been widely applied with success in signal processing (Qi et al., 2017), pattern recognition (Xie et al., 2017) and personalized recommendation (Yu et al., 2017), etc. Recently, tensor-based method is also proved to be an effective method for dealing with traffic data (Goulart et al., 2017; Sun and Axhausen, 2016), e.g., traffic flow (Tan et al., 2013) and travel time (Tan et al., 2015). Personalized (Arentze, 2013; Ma et al., 2016) travel time estimation refers to provide travel time information considering not only the traffic condition but also the drivers' personal driving behaviors and preferences, e.g., Sunday driver. Intrinsically, driving preferences of drivers are implicitly encoded in the travel time data extracted from the large-scale driver-specific GPS trajectories (Wang et al., 2018; Zheng and Xie, 2011). It is proven that these user (driver)-specific preferences can be captured by a context-aware collaborative filtering approach (Cui et al., 2017), such as tensor (Li et al., 2017).

The novel model estimates travel times of each driver on all road segments (*definition 1*) in different time slots (*definition 2*), while contending with the problem of over-fitting (fitting training data excessively). It incorporates both the spatial correlation between different road segments and the person-specific variation between different drivers, as well as the coarse-grain temporal correlation between recent and historical traffic conditions and the fine-grain temporal correlation between different time slots. Besides, it accounts for the variability caused by intrinsic uncertainties in urban road network. To the best of the author's knowledge, this is the first time that a tensor-based probabilistic paradigm is employed for urban travel time estimation. The main contributions of this work are summarized as follows:

- Tensor-based citywide and personalized travel time modeling. To account for both the spatial-temporal correlation and the inter-vehicle variation of different drivers, different drivers' travel times on all road segments in different time slots are modeled with a three-order tensor. This is a pure data-driven approach without modeling the impact factors explicitly. The general idea is that road segments with similar contexts could have a similar travel time.
- Variability consideration. To explain the variability caused by the inherent uncertainty of signalized urban context, each travel time entry in the built tensor is modeled as a variable following a probabilistic distribution rather than a simple deterministic value.
- Fully Bayesian treatment adoption. To deal with the problem of over-fitting caused by the improperly tuned hyper-parameters, especially when the used data is large and sparse, a fully Bayesian treatment is introduced for the probabilistic travel time estimation.
- Evaluation. The proposed model is evaluated by a real-world application in Beijing, China, based on the large-scale and sparse GPS trajectories generated by taxicabs. Empirical results of extensive experiments demonstrate the advantage of the proposed model.

The remainder of the paper is organized as follows: Section 2 reviews the related literatures for urban travel time estimation. Problem statement and definitions are presented in Section 3. The methodology of the proposed model is elaborated in Section 4. In Section 5, the model performance is evaluated by a real-world application in Beijing, China. Some conclusions and future researches are summarized in Section 6.

2. Literature review

A number of approaches have been developed for urban travel time estimation in recent years (Chen et al., 2017; Rahmani et al., 2017; Yin et al., 2015). For the research object examined in this paper, existing literatures are discussed from the following aspects: used data, adopted model and concerned scale (or studied area).

Traditionally, location-based sensors, e.g., loop detectors, are mainly used to collect data for travel time analysis. Li and Rose predict travel time range for motorist in real time as well as up to 1 h ahead, based on the data collected by AVI sensors (Li and Rose, 2011). Hasan et al. developed an econometric framework to model the key factors contributing to travel time variations in Central London, based on the data derived from automated number plate recognition sensors (Hasan et al., 2012). However, due to the cost considerations, the share of segments equipped with these sensors is typically low. Data collected by those sensors can only cover a limited number of paths for a limited duration of time, which leaves the traffic knowledge in most of the network unknown.

Recently, analysis-based approaches have been developed to estimate travel time based on various data sources (Rahman et al., 2018; Zheng et al., 2017). Jenelius and Koutsopoulos (2013) presents a statistical model for urban road network travel time estimation using vehicle trajectories obtained from low frequency GPS probes as observations. Celikoglu (2013) investigates the