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Non-parametric estimation of route travel time distributions from low-frequency floating car data

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A B S T R A C T

The paper develops a non-parametric method for route travel time distribution estimation using low-frequency floating car data (FCD). While most previous work has focused on link travel time estimation, the method uses FCD observations for estimating the travel time distribution on a route. Potential biases associated with the use of sparse FCD are identified. The method involves a number of steps to reduce the impact of these biases. For evaluation purposes, a case study is used to estimate route travel times from taxi FCD in Stockholm, Sweden. Estimates are compared to observed travel times for routes equipped with Automatic Number Plate Recognition (ANPR) cameras with promising results. As vehicles collecting FCD (in this case, taxis) may not be a representative sample of the overall vehicle fleet and driver population, the ANPR data along several routes are also used to assess and correct for this bias. The method is computationally efficient, scalable, and supports real time applications with large data sets through a proposed distributed implementation.

1. Introduction

Monitoring traffic conditions in light of increasing congestion in urban areas is critical for traffic management and effective transport policy. Provision of travel time information is also important as a means of dealing with congestion. There are a number of well-established technologies for travel time data collection, including loop detectors and automatic vehicle identification (AVI) sensors (Antoniou et al., 2011). AVI systems (Automatic Number Plate Recognition (ANPR) cameras, Bluetooth devices, etc.) provide direct measurements of route travel times. However, the spatial coverage is typically small, and may not be representative of the network as a whole.

Floating car data (FCD) collected from GPS devices installed in vehicle fleets or smart phones are becoming increasingly available. FCD can complement stationary sensors by providing information from the entire network. Methods for highway and arterial traffic state estimation based on speed measurements from FCD and loop detectors have been developed (Treiber et al., 2011; Cipriani et al., 2012; Yuan et al., 2014). Other studies use the concept of a virtual probe vehicle inferred from detectors and signal status data along a corridor helps improve the allocation of observed travel time of FCD to different sections of the road (Liu and Ma, 2009). Travel time estimation from FCD is often challenging because of low polling frequency (less than once or twice per minute due to bandwidth limitations and data transmission costs), which means that vehicles may traverse multiple links between consecutive probes (Jenelius and Koutsopoulos, 2015).

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The research on FCD-based travel time estimation has largely focused on network *links* (Sanaullah et al., 2013; Hofleitner et al., 2012; Zheng and van Zuylen, 2012; Hellinga et al., 2008). In general, these methods allocate the travel time between two consecutive probes to the traversed links. Average route travel times can be estimated from the average link travel times. However, a drawback of the link-based approach is that statistics of the route travel time distribution (apart from the mean value) are not straightforward to derive from the travel time distributions of the constituent links. For many applications, for example, monitoring of path travel time reliability, estimation of the variance and percentiles is as important as the calculation of the mean. While several models have been proposed (Hofleitner et al., 2012; Westgate et al., 2013; Ramezani and Geroliminis, 2012; Jenelius and Koutsopoulos, 2013), they typically rely on strong assumptions about the functional form of the link travel time distributions and the correlation structure. For real-time applications, there is also a trade-off between the complexity of the model and the computational efficiency of route travel time calculations.

A somewhat different approach is taken in Westgate (2013), with *trip* travel time distributions estimated from origin–destination FCD travel time observations. The proposed parametric method avoids the problems of aggregating link travel times into route travel times, but does not utilize the information from intermediate FCD reports.

The objective of the paper is to propose a computationally efficient, non-parametric method for estimating the distribution of route travel times using low-frequency FCD, incorporating all available information. No assumptions are made regarding the form of the distribution. Given the complexity of urban traffic, it is likely that the form of the travel time distribution varies by route and time of day. Thus, the flexibility of the proposed method is highly valuable whenever the variability of travel times is of interest.

The method incorporates all available observations (fully or partially overlapping with the route of interest). The reason that partially overlapping observations are utilized is the limited availability of fully overlapping ones. In the case study presented in Section 4.2, even with FCD from 1500 taxis over the period of one year, the number of direct observations is rather low. Therefore, it is important to develop a method that incorporates both fully and partially overlapping observations.

The methodology addresses several challenges due to the nature of FCD (which to a different degree also exist when estimating link travel time distribution). Examples include partial overlap, oversampling of sections of the route, etc. These factors can bias the estimation unless they are accounted for. The paper identifies and categorizes the most important sources of bias. The proposed methodology uses ideas from kernel-based estimation (e.g. Hastie et al., 2009) and takes into consideration the particular features of network routes and FCD observations to correct for these biases.

Another potential bias when using FCD from vehicle fleets to estimate general traffic conditions is the representativeness of the sample with respect to driver behavior and traffic regulations applicable to the vehicles in the fleet.

A case study using FCD from 1500 taxis in Stockholm, over a period of one year, is used to illustrate the proposed method. Data from ANPR on selected routes is also available. The results from the FCD compare well with the ANPR travel data (which provide direct observations of route travel times, but at a very limited spatial coverage). The results also illustrate that the proposed approach deals effectively with the identified biases. Furthermore, the case study is used to evaluate the sampling bias (not being representative) in the Stockholm region. A significant amount of this bias is explained by the use of bus lanes by taxis (while regular vehicles are not allowed to use them).

The fact that estimation is route-specific places high demand on computational efficiency for on-demand (real-time) applications where the route is provided as part of a request. The computational complexity of the proposed method is evaluated, and a framework for distributed computation is presented. It is demonstrated that, in addition to off-line applications, the method is suitable for real time applications where short response times are required, even for large data sets.

The main contributions of the paper are:

- Identifies important biases introduced when FCD are used for the estimation of path travel times.
- Develops efficient methods for their correction and demonstrates their effectiveness.
- Uses ANPR data for comparison purposes (which is probably one of very few papers that have done so). It also uses ANPR data to correct for sampling biases (i.e. the sample of taxis is not representative of the population of drivers).
- Proposes a computationally efficient implementation that is scalable and can support real time applications with large data sets.

The paper is organized as follows. Section 2 introduces the basic concepts and discusses the nature of FCD observations. Section 3 presents the travel time estimation methodology. Section 4 discusses the application of the methodology in a case study with taxi FCD from Stockholm, with results in Section 5. The computational performance of the method and approaches to its efficient implementation are presented in Section 6. Section 7 concludes the paper.

2. Preliminaries

2.1. Network route travel time

A *network route* is defined as a path $\pi = (k_s, k', \ldots, k'', k_e)$ connecting the beginning and end links k_s and k_e, and two offsets o_s and o_e, where o_s (o_e) is the distance from the start of link k_s (k_e) to the start (end) location of the route. A route may thus begin and end at points in the interior of links and not necessarily at the beginning or end of links. The path π is assumed to be acyclic. The length of overlap between the network route and link k, denoted by a_k, is