Transportation Research Part C 82 (2017) 1–23

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

A copula-based approach for estimating the travel time reliability of urban arterial

Min Chen, Guizhen Yu, Peng Chen *, Yunpeng Wang

School of Transportation Science and Engineering, Beijing Key Laboratory for Cooperative Infrastructure System and Safety Control, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 24 November 2016
Received in revised form 13 June 2017
Accepted 13 June 2017

Keywords:
Urban arterial
Travel time distribution
Travel time reliability
Segment correlation
Copula

ABSTRACT

Estimating the travel time reliability (TTR) of urban arterial is critical for real-time and reliable route guidance and provides theoretical bases and technical support for sophisticated traffic management and control. The state-of-art procedures for arterial TTR estimation usually assume that path travel time follows a certain distribution, with less consideration about segment correlations. However, the conventional approach is usually unrealistic because an important feature of urban arterial is the dependent structure of travel times on continuous segments. In this study, a copula-based approach that incorporates the stochastic characteristics of segments travel time is proposed to model arterial travel time distribution (TTD), which serves as a basis for TTR quantification. First, segments correlation is empirically analyzed and different types of copula models are examined. Then, fitting marginal distributions for segment TTD is conducted by parametric and non-parametric regression analysis, respectively. Based on the estimated parameters of the models, the best-fitting copula is determined in terms of the goodness-of-fit tests. Last, the model is examined at two study sites with AVI data and NGSIM trajectory data, respectively. The results of path TTD estimation demonstrate the advantage of the proposed copula-based approach, compared with the convolution model without capturing segments correlation and the empirical distribution fitting methods. Furthermore, when considering the segments correlation effect, it was found that the estimated path TTR is more accurate than that by the convolution model.

1. Introduction

Travel time reliability (TTR), defined as consistency of travel time over time by SHRP 2 Reliability research (SHRP 2 Report S2-L02-RR-2, 2014), has been increasingly recognized as an important measure for assessing the operation efficiency of road facilities, evaluating alternative traffic management strategies (SHRP 2 Report S2-L07-RR-2, 2014) and providing travelers with timely and reliable route guidance (SHRP 2 Report S2-L14-RW-1, 2014). Bates et al. (2001) suggested that the analysis of TTR is as important as, if not more important than, the traditional analysis of average travel time. To fully characterize TTR, travel time distribution (TTD) needs to be determined as a prior, which helps measure the risk for on-time arrival probability and find a reliable path for risk-averse travelers (Zeng et al., 2015). Ma et al. (2016) also stated that better understanding of TTD is a prerequisite for exploring the causes of unreliability.

* Corresponding author.
E-mail addresses: chenmin_cn@163.com (M. Chen), yugz@buaa.edu.cn (G. Yu), cpeng@buaa.edu.cn (P. Chen), ypwang@buaa.edu.cn (Y. Wang).

http://dx.doi.org/10.1016/j.trc.2017.06.007

Compared to uninterrupted freeway facilities, the interrupted nature of travel flows on arterials make TTD estimation much more challenging. Due to complex interactions between volatile traffic regimes and signal control strategies, as well as the correlation between neighboring segments, the resulting travel times on arterials often present various distributions under different levels of congestion (Chen et al., 2013). The state-of-practice approaches for arterial TTD estimation have focused on developing models for estimating the average travel time. Detailed introduction and discussion of these average travel time models have been provided by Highway Capacity Manual (2010), Skabardonis and Geroliminis (2005, 2008), and Liu and Ma (2009). However, less effort has been made to quantify the variability of either segment-level or path-level TTD and analyze the interdependence between segment TTDs along signalized arterials. A review of the related research is provided below.

Segment-level TTD on arterials can capture the interrupted nature of traffic flow under signal control and has various applications in practice, including evaluation on the level of service of intersections, congestion and incident detection, and real time dynamic control of traffic systems. Ji and Zhang (2013) utilized high-resolution bus probe data to estimate travel times on urban streets for short segments, and revealed predominantly bimodal TTD at the segment level, with one mode corresponding to travels without delay and the other travels with delay. Then, a hierarchical Bayesian mixture model was used to characterize such bimodal TTD, analyze traffic operation and identify congestion. Zheng and van Zuylen (2010) investigated urban segment-level TTD by mainly focusing on the delay distribution at signalized intersections. A probabilistic delay distribution model was developed considering both stochastic arrivals and departures at signals. The key influencing factors, e.g., arrival process, degree of saturation, saturation flow rate, were examined in detail. The results indicated a temporal correlation between arrival time and segment travel time, and demonstrated the evolutions of delay distribution on a cycle-by-cycle basis. Mohammad et al. (2015) proposed a probabilistic travel time model for a single segment, which was compatible with the algorithms developed to compute the probability density function (PDF) of a path.

In terms of route guidance, path-level TTD is of more concern to travelers than segment-level TTD. The state-of-art studies on path-level TTD put significant effort into identifying the best statistical model for fitting travel time observations. Unimodal distributions, e.g., Normal, Lognormal, Gamma, Weibull, Exponential and Burr distributions, were often used to characterize TTD for a given path, as can be found in the literature (Eman and Al-Deek, 2006; Uno et al., 2009; Susilawati et al., 2013). However, increasing researchers (Guo et al., 2010; Feng et al., 2012; Kazagli and Koutsopoulos, 2012; Chen et al., 2014) pointed out a unimodal distribution may not sufficiently represent the variation of path TTD. For example, travel times under free-flow conditions and under congested conditions can differ substantially. Guo et al. (2010) proposed a multi-state model to fit a mixture of Gaussian distributions into travel time observations along one arterial at San Antonio, Texas. Feng et al. (2012) adopted a mixture of normal distributions to estimate TTD for arterial routes using GPS probe vehicles. Kazagli and Koutsopoulos (2012) used a mixture of two lognormal distributions to model TTD on urban routes in Sweden based on AVI data. Chen et al. (2014) further presented a finite mixture of regression model with varying mixing probabilities (weights) to gain a better understanding of urban path TTD through consideration of signal timings. The essence of the above multi-state mixture models is to establish a connection between TTDs and the underlying travel time states, which allows for the quantitative evaluation of the probability of each state and results in better fitting. However, such distribution fitting methods are largely dependent on the path-level travel time observations, which may not be available in large-scale urban network. Considering that various paths may exist between one Origin-Destination (OD) pair and one path may include multiple segments, it is more realistic in practice to estimate path-level TTD based on individual segment TTDs given the commonly available data sources at segment-level. The route choice is then made by choosing the best path from all feasible paths according to certain reliability measures.

To date, a fundamental assumption imbedded in most reliability research upon segment-level or path-level TTD in a road network is the independence of individual segment travel times (Iida, 1999). If one is only interested in a deterministic measure of travel times, e.g., average segment travel time or path travel time, this assumption is generally acceptable. However, when focused on TTD, the assumption of segment independence is evidently unrealistic. He et al. (2002) mentioned that the assumptions made for long-term (such as peak hours, non-peak hours, daily and seasonal) TTD estimation, i.e., (1) travel times on all separate route sections are independent and (2) trip times per unit distance on all sections are identically distributed, may not be valid for the short-term estimation of route TTD. They investigated the temporal and spatial variations and correlations of travel times in short term based on vehicle tracking data from Paramics simulation. Strong evidence of significant correlation was found between segment travel times. The results suggested that the estimation of path TTD needs to account for the correlation between individual segments and it is necessary to include both temporal and spatial variability of travel times when developing advanced route guidance systems.

To model the dependency and correlation of segment TTDs, Pattanamekar et al. (2003) suggested that in order to estimate the conditional mean and variance of one segment travel time given the observation of the other, the joint PDF is needed. However, instead of estimating the function in detail, the authors only used a three-point polynomial approximation to estimate average travel time. Rakha et al. (2006) pointed out that the assumption of segment travel time independence ignores any covariance across segments and they tried to estimate the variance of freeway path travel time by modeling dependence between segment travel time variances. This method makes the results tractable; however, the limitation is that the variances cannot fully characterize the travel time characteristics. Geroliminis and Skabardonis (2006) estimated the variance of one urban route travel time by assuming linear correlations between successive segment travel times. In fact, the dependence between successive segment travel times is complex. Herring et al. (2010) proposed a Coupled Hidden Markov Model to model the dynamics of segment travel times in urban network based on probe vehicle data. It is assumed that each seg-