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Transportation Research Procedia 3 (2014) 366 – 373

Transportation Research Procedia

www.elsevier.com/locate/procedia

17th Meeting of the EURO Working Group on Transportation, EWGT2014, 2-4 July 2014, Sevilla, Spain

Analytical formulation of the trip travel time distribution

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Abstract

This paper validates an analytical and tractable approximation of trip travel time variance for general topology networks. The main challenge in the derivation of such an approximation is to account for spatial between-link dependencies in an analytical yet also tractable manner. The approximation considered in this paper achieves tractability by extending Little's law for higher-order moments of finite capacity Markovian queueing networks. This paper presents a detailed validation of this approach. We compare the analytical approximations of path travel time variance to simulation-based estimates for two general topology queueing networks. Ongoing work, to be presented at the conference, uses this approach to address an urban traffic signal control problem that explicitly accounts travel time variability.

Selection and peer-review under responsibility of the Scientific Committee of EWGT2014

Keywords: Little’s law; spillback; path travel time.

1. Introduction

Urban traffic management strategies are typically formulated such as to improve first-order performance metrics (e.g. expected trip travel times, expected link speeds). They have the potential to further enhance performance by accounting for higher-order distributional information, such as to improve, for instance, network reliability and network robustness. Enhancing the reliability of our networks is currently recognized as a critical goal in the US and in Europe [24, 25, 9]. The main challenge in addressing reliable or robust formulations of traditional transportation problems is the need to provide an analytical and tractable formulation of the trip travel time distribution, or of its first- and second-order moments. The complex between-link spatial-temporal dependency patterns makes analytical modeling of dependency, and hence accurate modeling of path metrics, a great challenge.

Numerous methods have been proposed for the approximation of expected trip travel time [23, 11, 3]. For a review, see Vlahogianni et al. [26]. The approximation of trip (or path) travel time variance has received less attention [6]. Nonetheless, empirical studies indicate the importance of path travel time variability in various travel

Selection and peer-review under responsibility of the Scientific Committee of EWGT2014
doi:10.1016/j.trpro.2014.10.017

choices such as departure time choice and route choice [28]. A recent stated preference (SP) survey indicates that for certain users the value of travel time variability is more than twice that of average travel time [4]. Another SP survey found that 54% of 564 morning commuters in Los Angeles (USA) considered travel time variability as either the most important or the second most important attribute in their commuting route choices [1].

Analytical approximations of path metrics are mostly derived based on simplifying, or even omitting, spatial temporal dependencies. The most common assumption is that of link independence [17], which typically underestimates path travel time variance for congested road networks [22]. Recent work that accounts for spatial between-link dependencies includes Westgate [27], Xing and Zhou [28], Charle et al. [6], Fu and Rilett [10], Rakha et al. [22].

Another approach to address reliable or robust traffic management problems is the use of stochastic traffic simulators. The latter can approximate the full distribution of the main network performance measures, making them suitable tools to design traffic management strategies that improve higher-order metrics. Recent work has designed a simulation-based optimization (SO) algorithm that allows designing traffic management strategies that improve both first-order (i.e., expectation) and second-order (i.e., variance) information of link travel times [8]. More importantly, the algorithm is computationally efficient, meaning that it can identify such strategies within few simulation runs.

In order to design a computationally efficient algorithm that embeds inefficient traffic simulators, information from other more efficient and tractable traffic models is used throughout the optimization process. In particular, information from the simulator is combined with information from an analytical differentiable traffic model. The latter combines ideas from traffic flow theory and queueing network theory [19, 18]. The role of the analytical model is to provide analytical problem-specific structural information to the generic SO algorithm. It is this combination of information from a simulation-based traffic model and an analytical traffic model that enables good short-term algorithmic performance.

We have extended this SO approach in order to address a signal control problem that aims at reducing both the expectation and the variance of link travel times [8]. The analytical traffic model used is a queueing network model, where each lane of an urban road is modeled as a set of finite space capacity M/M/1/K queues. Nonetheless, this work assumes between-link independence of travel times. The latter is a strong assumption that rarely holds for congested urban networks.

This paper considers an analytical traffic model that approximates the first- and second-order moments of trip travel time while accounting for the between-queue dependency. We validate the results using simulation-based estimates of trip travel time. As part of ongoing work we are embedding this analytical model within the SO framework of Osorio and Bierlaire [20] and using it to address a simulation-based signal control problem that improves trip travel time variability.

2. Methodology

Path travel time variance is defined as a function of the first- and second-order moments of path travel time. In queueing theory, Little's law [14] describes the relationship between the expected number of users (e.g., travelers) in a network, E[L], and the expected time a user spends in the network E[W]. The law is given by:

$$E[L] = \lambda E[W],$$

where λ is the arrival rate of users to the network.

Little' law holds under very general conditions [15, 14]. Higher-order formulations of Little's law have been proposed [13, 5, 12, 16]. For Poisson arrivals to the network, the higher-order law is given by:

$$E[L(L-1)\dots(L-r+1)] = \lambda^r E[W^r], r = 1,2,\dots$$

This higher-order law holds for a single M/ G/ 1 queue where: a) the arrival process is stationary; b) there is no overtaking (i.e., the first-in-first-out discipline holds); c) the time in the system of a user is independent of the arrival process of any arrivals after it. Keilson and Servi [13] proved that for a single M/ G/ 1 priority queue (infinite capacity and FIFO discipline) with two classes of customers, the second-order Little's law holds for each class of