Transportation Research Part C 56 (2015) 94–119

Contents lists available at ScienceDirect

Transportation Research Part C

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

Effect of speed limits in degradable transport networks

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ARTICLE INFO

Article history:
Received 19 November 2014
Received in revised form 27 March 2015
Accepted 27 March 2015

Keywords:
Degradable transport networks
Speed limit
Travel time budget

ABSTRACT

This paper studies how link-specific speed limits influence the performance of degradable transport networks, in which the capacity of each link is a degradable random variable. The distribution and cumulative distribution of link travel time have been presented with the effect of speed limits taken into account. The mean and variance of link and route travel time are formulated. Three link states have been classified, and their physical meanings have been discussed. The relationship between critical capacity, travel time and speed limit has been elaborated. We have proposed a Speed Limit- and Reliability-based User Equilibrium (SLRUE), adopting travel time budget as the principle of travelers' route choice. A heuristic method employing the method of successive averages is developed to solve the SLRUE in degradable networks. Through numerical studies, we find that for some networks both the mean and standard deviation of the total travel time could be reduced simultaneously by imposing some speed limits. The speed limit design problem has been studied, and it is found that imposing speed limits cannot always reduce the total travel time budget of a network.

1. Introduction

It is well known from the empirical studies that the three most important factors affecting travelers' route choice are travel time, travel time reliability and monetary cost (Abdel-Aty et al., 1995; Brownstone and Small, 2005; Uchida, 2014). Thus, in the past years more and more attentions were given to the travel time reliability as well as network design in uncertain transport network (Taylor, 2013; Chen et al., 2011a; Ukkusuri et al., 2007).

In an uncertain transport network, route travel times are stochastic on account of two reasons: supply and demand sides. Supply sides such as the capacity variations are resulted from traffic accidents, road works, traffic signals and weather. Chen et al. (2002) have proposed the capacity reliability as the probability that the network capacity can accommodate a given traffic demand at a certain service level. Recently, using the non-uniform origin–destination (OD) growth approach, two network capacity models related to the concepts of ultimate capacity and practical capacity have been developed to estimate alternate capacity reliability measures (Chen et al., 2013).

Many user equilibrium models have been proposed to study the degradable transport networks. Lo and Tung (2003) formulated a probabilistic user equilibrium (PUE) model which takes degradable links that have predetermined link capacity distributions into consideration. Lo et al. (2006) further extended the PUE and introduced the concept of travel time budget (TTB) to account for the traveler's reliability-based route choice behaviors. They assumed that travelers acquire the route travel time distributions by the past experiences, and choose the route to minimize their TTB. Yin et al. (2004) proposed

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http://dx.doi.org/10.1016/j.trc.2015.03.042

an expected travel disutility function, which takes into account the travel time delay, the uncertain of travel times and the consequent early or late arrival penalty. Nie (2011) formulated the percentile user equilibrium by minimizing the percentile travel time that ensures the preferred probability of on-time arrival. In the mean-excess traffic equilibrium model (Zhou and Chen, 2008; Chen and Zhou, 2010; Chen et al., 2011b; Xu et al., 2013, 2014a,b), travelers are assumed to minimize their mean-excess travel times defined as the conditional expectation of travel times beyond the TTB, which can be regarded as a combination of the buffer time measure and the tardy time measure. The former ensures the reliability aspect of on-time arrival and the latter represents the unreliability aspect of encountering worst travel times beyond the acceptable travel time. Tan et al. (2014) have investigated the Pareto efficiency of the various reliability-based traffic equilibria and the risk-taking behavior of travelers. They have examined reliability indexes mentioned above in terms of the mean and standard deviation of travel times. Wang et al. (2014) proposed a bi-objective user equilibrium model to minimize both expected travel time and standard deviation of travel time.

Demand sides are mainly from the travel demand fluctuations. Travel demand between a specific OD pair varies between times of the day, days of the week, and seasons of the year. Waller et al. (2001) showed that using expected demand tends to overestimate performance of the network and could lead to erroneous choice of improvements. They explored an approach in which the demand is inflated. Benefits in terms of selecting improvements with lower expected total system travel time have been yielded, and significant reductions in the variance associated with this measure have been achieved. Shao et al. (2006) presented a reliability-based stochastic user equilibrium traffic assignment model in view of the day-to-day demand fluctuations for multiclass transportation networks. Clark and Watling (2005) proposed a technique to estimate the probability distribution of total network travel time, in the light of normal day-to-day travel demand variations. A solution method based on a single run of a standard traffic assignment model has been presented. Nakayama and Watling (2014) proposed a stochastic network equilibrium model, in which stochastic demands and route choices are formulated as a fixed point problem.

There are also works concerning both supply and demand sides. Siu and Lo (2008) have studied the doubly uncertain transportation network considering both degradable capacity and stochastic demand. Lam et al. (2008) considered adverse weather conditions which will influence both supply and demand sides and proposed a novel traffic assignment model. Zhang et al. (2011) proposed an expected residual minimization model under stochastic demand and supply, with an emphasis on the planner's perspective.

A high speed could bring about drivers' less control of cars, less decision time, less reaction time and longer braking distances, which have a great impact on the risk of crashes (see, e.g., Garber and Graham, 1990; Kloeden et al., 2001). Speed limits regulations are applied to roads all over the world mainly due to high fatal crash rates in high speed. For instance, Yu and Abdel-Aty (2014) investigated the feasibility of utilizing a variable speed limit system to improve traffic safety on freeways. Moreover, speed limits are applied for the purpose of reducing fuel consumption and emissions (Eerens et al., 1993). Studies show that both vehicular emissions and fuel consumptions are non-monotonic functions of vehicular speeds (Yin and Lawphongpanich, 2006; Chen and Yang, 2012) and it means neither low speed nor high speed is preferred. Variable speed limits are also used together with ramp metering to control traffic flow on freeway networks to mitigate traffic congestion and prevent traffic breakdown (Hegyi et al., 2005; Carlson et al., 2010, 2014). Montella et al. (2015) proposed a procedure for consistently setting speed limits with point-to-point speed enforcement systems. Grumert et al. (2015) studied the potential benefits of variable speed limit system by introducing infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits. Chen and Ahn (2015) has developed a theoretical framework is developed for variable speed limit control in order to improve the performance of severe bottleneck.

Compared to large amount of studies about travel time reliability-based assignment problems, the traffic assignment problem related to speed limit has been investigated until very recently. Yang et al. (2012) firstly studied how the link-specific speed limits influence the traffic flow in an equilibrium manner at a macroscopic network level. They found that a target flow pattern can be decentralized by a toll charge scheme and a speed limit scheme if the equilibrium link flow pattern is unique. Wang (2013) examined the impact of speed limits on network efficiency, in terms of total travel time of all road users, and equity among road users from different OD pairs, in terms of the change of travel time after imposing a speed limit scheme. Yang et al. (2013) proposed a tri-objective bi-level programming model to design optimal link-specific speed limits that minimize system travel time, number of expected accidents and traffic exhaust emissions simultaneously. Yang et al. (2015) investigated the local and global impact of speed limits by considering road users' non-obedient behavior in speed selection.

This paper investigates how the link-specific speed limits influence the traffic flow in a degradable transport network, and proposes a Speed Limit- and Reliability-based User Equilibrium (SLRUE) model. We have presented the distribution and cumulative distribution of link travel time, and calculated the mean and variance of link and route travel time, considering both the speed limit and the degradable link capacity. Three link states have been classified, and their physical meanings have been discussed. The relationship between critical capacity, travel time and speed limit has been elaborated. We have adopted the travel time budget as the principle of travelers' route choice. A heuristic method employing the Method of Successive Averages (MSA) is developed to solve the SLRUE. In particular, a naive expectation is that speed limit would affect the network in a way that the mean of total travel time may increase but its standard deviation decreases. However, for some networks, we find that proper speed limits may optimize the network by reducing the mean and standard deviation of the total travel time simultaneously.