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Discrete Optimization

Time-dependent trip-chain link travel time estimation model with the first-in–first-out constraint

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ABSTRACT

Estimating network-wide time-dependent link travel time is a key problem in transportation management. During the examination of users' time-dependent route choice behaviors, the conditions and changes in traffic flow propagation in time–space networks must satisfy the first-in–first-out principle in order to be applicable for transportation planning. In this context, we developed a bilevel programming model with the first-in–first-out constraint for estimating time-dependent trip-chain link travel times under to examine users' trip-chain route choice behaviors. Subsequently, we derived a bilevel mathematical formulation and developed an iterative algorithm based on Lagrangian gradient projection. Several numerical examples are presented herein to explain the accuracy of the model. Finally, conclusions and suggestions are presented on the basis of the research findings.

1. Introduction

As smart transportation systems are developed and transportation demands in urban social and economic activities increase, accurately estimating the link travel times (LTTs) during different periods to satisfy vehicle dispatch schedules or travel plans is a key traffic management problem for businesses, logistics providers, and emergency response units. Analyses of the time-dependent LTT estimation problem from the perspective of road networks have indicated that traffic volumes in various links and during different periods affect actual travel times. The traffic volume differences result from the cumulative choices of origin–destination (OD) pairs that individuals make for their travel within the road network. Travelers engage in trip-chain route choice behaviors (RCBs) on the basis of the estimated LTTs for their chosen OD pair during different periods as well as the requirements of their social or economic activities. When users' route choice outcomes are incorporated into an LTT function, the links on a road network can be used to determine actual travel times. Then, the traffic propagations of these links can be depicted to reveal changes in the time–space propagations of these links' flows. Therefore, accurate time-dependent LTT estimations of a road network indicate that the LTT estimations are consistent with the actual travel times reflected in the users' route choice outcomes. Such estimations conform to users' RCB equilibrium when dealing with changes in time-dependent link flow.

From a macro perspective, reasonable LTT estimation outcomes should satisfy the first-in–first-out (FIFO) principle. If travelers use the same link at different departure times, the users that enter the link first typically also exit the link first; thus, overtaking is not permitted. Otherwise, if the LTT estimation model applies the first-in–last-out (FILO) principle, it is not applicable to practical problems. Studies have largely focused on using time-dependent link time functions to examine LTT estimations (Astarita, 1996; Carey, Humphreys, McHugh, & McIvor, 2014; Chen, 1999; Friesz, Bernstein, Smith, Tobin, & Wie, 1993; Nie & Zhang, 2005; Ran & Boyce, 1996; Wu, Chen, & Florian, 1998; Xu, Wu, Florian, Marcotte, & Zhu, 1999; Zhu & Marcotte, 2000). Among these studies, those that have developed time-dependent link time functions using linear cost functions have ensured that the models satisfy the FIFO principle. By contrast, those that have used nonlinear cost functions could not guarantee conformity with the FIFO principle. However, nonlinear functions are more suitable for developing time-dependent link cost functions. Notably, the FILO anomaly is difficult to avoid in cost function designs. To avoid inaccuracies in the practical application of the time-dependent LTT estimation outcomes, a time-dependent LTT estimation model should adhere to the FIFO constraint.

Traditionally, studies of user's travel choice behavior have focused on their choices of OD pairs; these research models have been developed on the basis of the user equilibrium principle. However, these OD-based network equilibrium models omit route changes made by users when traveling to satisfy incidental socioeconomic activities. In other words, trip chaining influences users'

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travel behaviors. Empirical studies have confirmed the presence of trip chaining in users' travel behaviors (Currie & Delbosc, 2011; Hensher & Reyes, 2000; McGuckin, Zmud, & Nakamoto, 2005). However, these studies have failed to account for the effects of trip chaining on users' route choices. Therefore, these models could not adequately reflect the time-dependent transportation demands of road networks and, thus, yielded erroneous network-wide LTT estimations during different periods. Numerous studies have focused on the trip-chain network equilibrium problem (Maruyama & Harata, 2005, 2006; Wang & Chen, 2016). However, these studies have developed traffic assignment models by assuming that a static network equilibrium exists when considering users' trip-chain behaviors. Therefore, these models could only measure the spatial flow of travelers, and they could not apply the LTTs obtained from users' time-dependent trip-chain travel behaviors. Thus, the results were limited to transportation planning and were unable to satisfy the operational requirements of businesses, logistics providers, and emergency response units.

In summary, the remainder of the paper is structured as follows. The FIFO principle is a key factor in the development of time-dependent LTT estimation models. Estimation models that do not adhere to the FIFO principle may generate network-wide time-dependent LTT estimations that are inadequate for practical applications. Therefore, developing a time-dependent trip-chain LTT estimation model with the FIFO constraint is a key task for traffic authorities in the development of intelligent transportation systems. Section 2 presents a problem analysis and literature review, and Section 3 presents the procedures involved in developing of a time-dependent trip-chain LTT estimation model with the FIFO constraint. Then, Section 4 presents the testing of the relevant mathematical properties of the model and the development of a solution algorithm. Section 5 explains the model solution procedures and presents the testing of the model against the numerical examples of a test network. Finally, conclusions and suggestions are offered.

2. Problem analysis and literature review

The purpose of the present study was to establish a time-dependent LTT estimation model that satisfies the FIFO principle on the basis of users' trip-chain RCBs and the network-wide time–space link flow and to estimate network-wide LTTs during different periods. Most studies have analyzed and discussed dynamic traffic assignment models or models of users' time-dependent route choices. Merchant and Nemhauser (1978) and Carey (1986) were the first to develop discrete, single-destination, nonlinear, and time-dependent system optimization models through mathematical programming to analyze users' dynamic travel behaviors on road networks and calculate link flows and LTTs. Friesz, Luque, Tobin, & Wie (1989), Luque and Friesz (1980), Matsui (1987), Ran and Shimazaki (1989a, 1989b), and Ran and Boyce (1994) have adopted optimization theory to implement time-dependent network equilibrium models. These models have been used to estimate the traffic flows and LTTs during different periods by analyzing users' dynamic RCBs. However, these models are complicated and cannot adhere to the FIFO constraint because they omit users' trip-chain RCBs. When addressing the temporal network equilibrium problem, the time–space changes in network-wide traffic flow must also be considered. Moreover, the flow of the preceding link affects that of the subsequent link. Thus, Chen (1999) revealed that the dynamic network equilibrium problem is asymmetric and that the associated Jacobian matrix is therefore not positive definite. In general, asymmetric problems cannot be formulated as optimization problems, because the temporal interactions between traffic flows are asymmetric. Alternatively, a variational inequality (VI) can be used to reformulate the equivalent optimization problem. The main difference between a VI problem and its equivalent optimization problem is that objective formulation of a VI is nonspecific. Moreover, the equilibrium solution must satisfy the following condition: for an equilibrium solution x^* and any feasible solution x, the inner product of the search direction vector $(x - x^*)$ and gradient vector $c(x^*)$ must be nonnegative. Therefore, the finite-dimensional VI problem is expressed as follows: determine a vector $x^* \in \Omega \subseteq R^n$ such that $c(x^*)^T \cdot (x - x^*) \geq 0 \forall x \in \Omega$, where c is a continuous function from Ω to R^n and Ω is a closed convex set. Friesz and Mookherjee (2006), Friesz et al. (1993), Friesz, Kim, Kwon, and Rigdon (2011), and Han, Friesz, and & Yao (2013) have adopted VIs to develop dynamic network equilibrium problems and used linear cost functions to ensure that the flow propagation satisfies the FIFO principle.

From a macro perspective, traffic that enters a link first typically also exits the link first; thus, overtaking is nonexistent. To ensure that traffic flow satisfies the FIFO principle, many studies have investigated the time-dependent travel cost function. Astarita (1996), Friesz et al. (1993), Xu et al. (1999), Zhu and Marcotte (2000), and Nie and Zhang (2005) have used linear cost functions to ensure that their dynamic network equilibrium models satisfy the FIFO constraint. Friesz, Bernstein, Suo, and Tobin (2001) proved that link flow estimations will satisfy the FIFO principle if the link cost function is a monotonic increasing linear function. Although linear cost functions satisfy the FIFO principle, they often produce the double-counting effect in a time–space network, and thus overestimate travel times (Nie & Zhang, 2005). Ran and Boyce (1996) and Chen (1999) have used nonlinear link cost functions to build dynamic network equilibrium models. However, these models fail to satisfy the FIFO principle. Wu et al. (1998) and Xu et al. (1999) have revealed high correlations between the inflow, outflow, and traffic flow rate of a link during different periods. Estimation models may violate the FIFO principle when the number of vehicles or inflow rate of a specific link differs significantly during the day or when the nonlinear cost function is not strictly increasing. Carey et al. (2014) used a simplified nonlinear cost function from the US Bureau of Public Roads (BPR) to examine a specific link. When the FIFO constraint was violated, they adjusted the maximum outflow rate (maximum capacity) and used the ratio of the outflow rate to the maximum outflow rate to calculate the delay cost, which was then used to recalculate the travel times according to the inflow rates during different periods. This approach prevented changes in the inflow rate from influencing the nonlinear cost function; thus, the model satisfies the FIFO principle. However, Carey et al. (2014) only analyzed a single link and the model could only affect the travel cost over time on a single link. Therefore, the results did not reveal travelers' equilibrium states. Chen (1999) argued that the FIFO principle could be incorporated as a side constraint and that the travel times reflected in the violation of the side constraint could be used to ensure that all forms of the link cost function conformed to the FIFO principle.

The aforementioned time-dependent or dynamic travel choice models, which were largely based on users' time-dependent RCBs when choosing OD pairs, have overlooked the fact that travelers may change their route choices to satisfy incidental socioeconomic activities. Hägerstrand (1970) introduced an activity-based theory on the basis that travelers often complete a series of activities within an OD pair. In other words, travelers not only travel from the origin to the destination but also complete activities within their selected links. This behavior, termed "trip chaining," is represented by a series of interconnecting links that form the OD pair. Empirical studies have identified trip-chaining behaviors in users (Currie & Delbosc, 2011; Hensher & Reyes, 2000; McGuckin et al., 2005). Holzapfel (1986); Thill and Thomas (1987), and Stopher, Hartgen, and Li (1996) have proposed definitions of trip chaining, and they have noted that users' homes are anchors within trip

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