Transportation Research Part C 19 (2011) 320–337

Contents lists available at ScienceDirect

Transportation Research Part C

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

Modeling heterogeneous network user route and departure time responses to dynamic pricing

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ARTICLE INFO

Keywords:
User responses to pricing
Dynamic traffic assignment
Simultaneous route and departure time user equilibrium
Dynamic road pricing
User heterogeneity

ABSTRACT

The ability to realistically capture trip-makers' responses to time-varying road charges is essential for network equilibrium assignment models typically applied to predict network flows in the presence of dynamic road (congestion) pricing. User responses to pricing are governed by individual trip-makers' preferences, such as their value of time (VOT), and the cost they attach to late vs. early arrival relative to the destination. These behavioral characteristics vary across users. This paper presents a joint route and departure time network equilibrium assignment model explicitly considering heterogeneous users with different preferred arrival times at destinations, VOT, and values of early and late schedule delays (VOESD and VOLSD). The model is formulated as an infinite-dimensional variational inequality and solved by a column generation-based algorithmic framework that embeds: (i) an extreme non-dominated alternative-generating algorithm to obtain combinations of VOT, VOESD, and VOLSD subintervals (or breakpoints) that define multiple user classes, and the corresponding least trip cost alternative (joint departure time and path) for each user class, (ii) a traffic simulator to capture traffic flow dynamics and determine experienced travel costs; and (iii) a multi-class alternative flow updating scheme to solve the reduced multi-class simultaneous route and departure time user equilibrium problem defined by a subset of feasible alternatives. Application to an actual network illustrates the properties of the algorithm, and underscores the importance of capturing user heterogeneity and temporal shifts in the appraisal of dynamic pricing schemes.

1. Introduction

The ability to realistically capture trip-makers' responses to time-varying road charges is essential for predicting network flows under dynamic road (congestion) pricing. In general, trip-makers facing time-varying charges on a facility would not only change route but also adjust departure time so as to minimize the total associated trip cost. Some analytical studies (e.g., Arnott et al., 1990) have found that time-varying tolls generally yield greater efficiency gains than static tolls because the former reduce queueing delays by altering travelers' departure times as well as routes. User responses to pricing, including the shift in the timing of trips and the change in travel routes, are governed by individual trip-makers' preferences, such as their value of time (VOT), and the cost they attach to late vs. early arrival relative to the destination. These behavioral characteristics vary significantly across users (e.g., Brownstone and Small, 2005). Capturing the heterogeneity of users in this regard is critical in predicting the impact of dynamic pricing schemes (e.g., Lu et al., 2008).

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doi:10.1016/j.trc.2010.05.017

While several models propose to find simultaneous route and departure time user equilibrium (SRDUE) in a network (e.g., Friesz et al., 1993; Janson and Robles, 1993; Ziliaskopoulos and Rao, 1999; Huang and Lam, 2002; Szeto and Lo, 2004), few have considered the heterogeneity of users in the underlying departure time and path choice decision framework (e.g., Ran and Boyce, 1996; Ran et al., 1996a, 1996b). This paper proposes a framework to incorporate joint consideration of route and departure time, as well as user heterogeneity in a wider range of behavioral characteristics, in dynamic network equilibrium assignment. A multi-criterion SRDUE (or MSRDUE) model is presented, along with a simulation-based heuristic intended for practical network applications. The model explicitly considers heterogeneous users with different VOT and values of (early or late) schedule delay (VOESD or VOLSD), in their choice of joint departure time and path alternatives characterized by a vector of trip attributes including travel time, out-of-pocket cost, and schedule delay cost, where schedule delay is determined by the difference between actual and preferred arrival times (PAT). The MSRDUE problem is formulated as an infinite-dimensional variational inequality (VI) problem, and solved by a column generation-based algorithmic framework comprised of: (i) an (extreme non-dominated) alternative-finding algorithm to obtain combinations of VOT, VOESD, and VOLSD subintervals that define multiple user classes, and the corresponding least trip cost alternative for each user class, (ii) a traffic simulator to capture traffic flow dynamics and determine experienced travel costs; and (iii) a multi-class alternative flow updating scheme to solve a reduced MSRDUE problem.

In the modeling framework typically adopted in discrete time, deterministic SRDUE models, each trip-maker is assumed to choose an alternative, a combination of departure time (interval) and path, that minimizes his/her generalized trip cost (or alternative cost), defined as the sum of travel cost, travel time weighted by VOT, and early schedule delay weighted by VOESD or late schedule delay weighted by VOLSD. With this assumption, it is necessary for SRDUE algorithms to construct a set of feasible alternatives on which trip-makers are to be equilibrated. While some studies (e.g., Huang and Lam, 2002; Szeto and Lo, 2004) assumed that the complete set of feasible alternatives are known a priori (justified in light of their focus on theoretical insights and/or equilibration methods), time-dependent shortest path algorithms can be applied to generate representative subset of feasible alternatives. Nevertheless, because the trip's schedule delay cannot be determined until arrival at the destination, applying a time-dependent least cost path algorithm to compute the least generalized cost path for each departure time interval might not find the least trip cost path for an origin–destination (OD) pair. Furthermore, it is inappropriate to assume the path trip cost as the sum of generalized costs of its constituent links, because of the schedule delay cost. This non-additive nature of trip cost could preclude direct application of existing departure time-based time-dependent shortest path algorithms which are often adopted in DTA procedures for determining feasible descent directions. Few studies had attempted to solve for commuters' best paths with penalties for early or late arrivals (e.g., De Palma et al., 1990).

In order to obtain a set of least trip cost alternatives, without loss of generality, this study considers an alternative as the combination of arrival time interval and the corresponding least generalized cost path (that arrives the destination at that arrival time interval) and develops an algorithm for computing time-dependent least cost paths for all possible arrival time intervals. This modeling approach would facilitate finding the least trip cost alternative, because for an OD pair and a PAT interval, given all possible (early or late) schedule delays, the least trip cost alternative can be found by computing the least generalized cost paths for all possible arrival time intervals. Once the best alternative is selected, the corresponding departure time can be readily determined by subtracting the path travel time from that arrival time. Therefore, modeling trip-makers' selections of arrival time interval is equivalent to modeling their departure time choices.

This paper is organized as follows. Section 2 presents the assumptions, definitions and statement of the MSRDUE problem, followed by the infinite-dimensional VI formulation in Section 3. Section 4 describes the structure of the column generation-based solution algorithm. A sequential parametric analysis method (SPAM) for alternative-finding is presented in Section 5, and Section 6 details a multi-class alternative flow equilibration scheme. Section 7 reports the experimental results, and Section 8 concludes this paper.

2. Assumptions, definitions, and problem statement

Consider a network $G = (N, A)$, where N is the set of nodes and A is the set of directed links (i, j), $i \in N$ and $j \in N$. The time period of interest (planning horizon) is discretized into a set of small time intervals, $S = \{t_0, t_0 + \sigma, t_0 + 2\sigma, \ldots, t_0 + M\sigma\}$, where t_0 is the earliest possible departure time from any origin node, σ a small time interval during which no perceptible changes in traffic conditions and/or travel cost occur, and M a large number such that the intervals from t_0 to $t_0 + M\sigma$ cover S. Without loss of generality, associated with each arc (i, j) and time interval t are two essential time-dependent arc travel impedances: time ($d_{ij}(t)$) and cost ($c_{ij}(t)$), which are required to travel from node i, in time interval t, to node j. The link generalized cost perceived by a trip-maker with VOT α from node i in time interval t to node j is defined as:

$$g_{ij}(t) = c_{ij}(t) + \alpha \times d_{ij}(t). \tag{1}$$

The VOT represents how much money a trip-maker is willing to trade for a unit time saving. The following notation and variables are used in this paper.