Transportation Research Part B 81 (2015) 555–576

Contents lists available at ScienceDirect

Transportation Research Part B

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

Transportation network design for maximizing space–time accessibility

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ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 2 August 2015
Accepted 2 August 2015
Available online 14 August 2015

Keywords:
Accessibility
Space–time network
Network design
Lagrangian relaxation

ABSTRACT

One of the goals of transportation system construction and management is to improve individuals' *accessibility* or the ease of reaching desired activities, destinations and services. However, many transportation network design models instead focus on maximizing individuals' *mobility* or the ease of movement within the network. By adapting a space–time prism analysis framework, this paper aims to address a new urban network design problem to maximize the system-wide transportation accessibility between major activity locations, subject to a given highway construction budget. By constructing a time-dependent space–time network, we formulate the problem as a linear integer programming model to maximize the number of accessible activity locations within travel time budget for road users. A Lagrangian relaxation solution framework effectively decomposes the original complex problem into classical subproblems such as knapsack and time-dependent least cost problems. Various examples and discussions are provided to consider the effectiveness of the proposed method in modeling accessibility-enhancement strategies such as congestion mitigation and land use policies.

1. Introduction

As an essential performance measure for transportation systems, *accessibility* refers to the ability for travelers and freight shippers to reach desired activities, destinations and services. This contrasts with *mobility*, or the ease of movement within the network. Traditional transportation planning methods, including network design methods, focus on improving mobility-based measures such as speed and travel times. However, a mobility-oriented approach to transportation planning can induce travel demand and lead to traffic congestion (Handy, 2005). Although planning for mobility can improve network accessibility, accessibility-based planning expands the range of potential solutions compared to mobility-oriented strategies (Litman, 2003). Urban transportation planning for accessibility is a challenge for the metropolitan planning organizations (MPOs). One obstacle is a lack of methods for addressing accessibility directly rather than mobility in transportation network design (Santos et al., 2008).

In this paper, we formulate and solve the transportation network design problem with a focus on maximizing temporal and spatial accessibility. We introduce a new class of network design problem for maximizing the accessibility given travel time budget (TTB) constraints. By constructing a time-expanded network to model the space–time prism, a sensitive

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http://dx.doi.org/10.1016/j.trb.2015.08.002
0191-2615/

measure of individual accessibility (Hägerstrand, 1970), we develop a network design model with time-dependent arcs, while the equivalent optimization goal is to minimize individual inaccessibility between major activity locations in the space–time network. To address the computational efficiency issue for real-world large-scale applications, we develop a Lagrangian relaxation algorithm for effective problem decomposition.

The remainder of this paper proceeds as follows. The next section provides background on accessibility measures and network design for accessibility. In Section 3, a conceptual illustration is presented to describe the definition and calculation procedure of network accessibility under space–time network structure. Section 4 develops a linear integer programming model for the network design problem that aims to maximize system accessibility. Section 5 describes the Lagrangian relaxation solution framework and Section 6 provides discussions on various issues related to applying the accessibility-oriented network design model in planning practices. In Section 7, several demonstrative examples are presented to model various accessibility-enhancement strategies. The final section concludes the paper with some brief remarks.

2. Background

2.1. Accessibility measures

In transportation planning, accessibility is first defined by Hansen (1959) as the potential of opportunities for traveler interaction. Typically, accessibility captures the extent of attractiveness of each potential destination and some researchers represent accessibility as amount of activity potential reachable within a given travel time from an origin location (Chen et al., 2011b). Most existing measures of accessibility can be further classified into the following categories.

i. *Cumulative opportunity measures* count the number of potential opportunities that can be reached by each location within a given travel distance or travel time; locations with larger number of opportunities have higher accessibility (Wachs and Kumagai, 1973; Vickerman, 1974; El-Geneidy and Levinson, 2006).
ii. *Spatial interaction-based measures* balance the attractiveness of each opportunity against it travel cost from a given location (Hansen, 1959;Wilson, 1971; Williams, 1976; Erlander, 1977; Weibull, 1976, 1980; Geertman and Ritsema Van Eck, 1995). Benefit measures use the economic concepts of utility theory and consumer surplus to measure accessibility (Ben-Akiva and Lerman, 1979, 1985; Neuberger, 1971; Small and Rosen, 1981; Williams, 1976, 1977).
iii. *People-based accessibility measures* are sensitive to social, economic, cultural and demographic differences in accessibility imposed by differences in scheduling and location constraints as well as transportation resources. The space–time prism (Hägerstrand, 1970) is a central concept, and modelers can either directly or indirectly incorporate prism-based space–time constraints into other measures such as spatial interaction or benefit measures (Miller, 1991, 1999).

Many studies use accessibility measures in different transportation applications. Daganzo (2010) analyzes the structure of urban transit network for increasing accessibility. Hou and Li (2011) and Chen et al. (2014) study the impact of transport infrastructure development; Sohn (2006), Chen et al. (2007) and Taylor (2008) perform transportation network vulnerability analyses under network disruption scenarios, due to traffic incidents or flood damage. In these studies, the accessibility measure is typically used to represent the node-to-node connectivity, and researchers have been focusing on the evaluation or analysis of different strategies.

Many MPOs are seeking for viable models and approaches that can better design and improve the transportation networks to provide comprehensive services/utilities to general demand in an urban setting (Waddell, 2002; Litman, 2003, 2011; Curtis and Scheurer, 2010). The accessibility perspective has been widely adopted in the transportation planning field. It is used as a collective indicator for evaluating the overall transportation system performance (e.g., El-Geneidy and Levinson, 2006; Handy, 2005; Litman, 2011) and representing the general traveling opportunities. Other topics of interest for accessibility planning is how to jointly improve the sustainability and accessibility of cities through public transportation services, that is, offer feasible transit routes from major origins to desirable destinations within the available time frame. In our proposed research, we particularly consider the planning or optimization aspect of the network design process, with a special focus on the integration of space–time accessibility measures in general activity-travel decisions.

2.2. Network design and accessibility

In the field of operations research, the network design problem was first formulated by Dantzig (1963) as a fixed charge transshipment problem, and this class of problems has been well studied with a full spectrum of strategic, tactical, and operational decision-making situations. When it comes to transportation planning, the network design problem aims to find an optimal allocation and utilization of resources to achieve a certain goal (Crainic, 2000), such as improving traveler mobility, reducing air/noise pollution, avoiding accident and increasing accessibility. Magnanti and Wong (1984) review various integer programming-based network design models; a more up-to-date survey by Crainic (2000) focuses on the classification and formulations of various service network design models for freight transportation. For the design and scheduling of transit network, Guihaire and Hao (2008) present a unified review of the crucial strategic and tactical steps of transit planning. A