European Journal of Operational Research 229 (2013) 281–302

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

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

Invited Review

A review of urban transportation network design problems

Reza Zanjirani Farahani [a,*], Elnaz Miandoabchi [b], W.Y. Szeto [c], Hannaneh Rashidi [d]

[a] Department of Informatics and Operations Management, Kingston Business School, Kingston University, UK
[b] Logistics and Supply Chain Research Group, Institute for Trade Studies and Research (ITSR), Tehran, Iran
[c] Department of Civil Engineering, The University of Hong Kong, Hong Kong, China
[d] Department of Industrial Engineering, Mazandaran University of Science and Technology, Iran

ARTICLE INFO

Article history:
Received 7 March 2012
Accepted 2 January 2013
Available online 9 January 2013

Keywords:
Transportation
Urban transportation network design problem
Road network design
Transit network design and frequency setting problem
Multi-modal network design problem

ABSTRACT

This paper presents a comprehensive review of the definitions, classifications, objectives, constraints, network topology decision variables, and solution methods of the Urban Transportation Network Design Problem (UTNDP), which includes both the *Road Network Design Problem* (RNDP) and the *Public Transit Network Design Problem* (PTNDP). The current trends and gaps in each class of the problem are discussed and future directions in terms of both modeling and solution approaches are given. This review intends to provide a bigger picture of transportation network design problems, allow comparisons of formulation approaches and solution methods of different problems in various classes of UTNDP, and encourage cross-fertilization between the RNDP and PTNDP research.

1. Introduction

Transportation is important in the sense that it allows people to take part in human activities. With an increasing population, the demand for transportation is also increasing. More and more traffic is on roads, which in turn creates more and more mobility-related problems such as congestion, air pollution, noise pollution, and accidents; especially in city centers where the level of human activities is high. Governments need to plan transport networks properly and control urban traffic movements to ensure mobility and mitigate mobility related problems simultaneously. A higher population also leads to more expensive land, especially in city centers and hence more people living in new towns or suburbs, thereby requiring new transportation infrastructures for serving new towns or improving existing transportation structures to cope with the increasing population in the suburbs. These planning, design and management issues are traditionally addressed in UTNDP. This problem can actually include the design problems in suburban areas in addition to those in urban areas, because the methodology involved is basically the same. Moreover, this problem can involve transit networks in addition to road networks, since transportation includes both public and private transport.

UTNDP has been continuously studied during the last five decades, and the number of related publications has grown over time, probably because the problem is highly complicated, theoretically interesting, practically important, and multidisciplinary. Reviews have been published by Boyce (1984), Magnanti and Wong (1984), Friesz (1985), Migdalas (1995), Yang and Bell (1998a), Desaulniers and Hickman (2007), Guihaire and Hao (2008), and recently by Kepaptsoglou and Karlaftis (2009). Some of these reviews deal with general network design problems, but some focus specifically on urban network design or on one part of urban transportation networks. For example, the first five reviews only focus on RNDP, while the last three reviews only focus on PTNDP. As a result, the similarities and differences of the formulation approaches and solution methods between RNDP and PTNDP cannot be addressed in these reviews, and this does not encourage the cross-fertilization of the two research areas. Moreover, the problem that considers the interaction between road and public transit network designs has been ignored in these reviews.

This paper attempts to provide a holistic view of UTNDP and its classifications by uniting the decisions for improving transportation networks. With regard to this, the current paper covers both problem categories, and presents a third problem category for the joint decisions in road and public transit networks with at least two modes, which considers the interactions of these modes. This paper also contains updated literature for both fields to early 2011. This contrasts to the last review paper on RNDP which was published in the late 1990s, and the previous reviews of PTNDP which cover the literature until 2007. The main aim of this paper is to cover problems related to urban transportation network topology and its configuration. In this regard, only the *strategic* level and a number of *tactical* level decisions related to *network topology* are

* Corresponding author. Tel.: +44 020 8517 5098; fax: +44 020 8417 7026.
E-mail address: zanjiranireza@gmail.com (R.Z. Farahani).

0377-2217/$ - see front matter
http://dx.doi.org/10.1016/j.ejor.2013.01.001

covered in this paper; those papers not related to network topology decisions, such as operational level decisions and tactical decisions that are not related to network topology, will not be covered unless they are considered together with network topology decisions. Problems such as traffic signal setting, parking pricing, toll setting, and public transit ticket pricing are important sub-problems of UTNDP and even some of these have a long history with many important features and developments. These sub-problems deserve to be examined and reviewed in a comprehensive manner in future review papers and hence are excluded from this paper. Traffic signal setting has the strongest relevancy with network configuration decisions, as the network topology directly affects the flow pattern and the conflict points at intersections. This sub-problem has been studied extensively and there is a relatively large body of literature (e.g. Cantarella et al., 1991; Meneguzzer, 1995; Wong and Yang, 1999; Wey, 2000; Cascetta et al., 2006).

Moreover, this review focuses on deterministic transport networks and deterministic travel demand. That is, we focus on papers that assume no supply and demand uncertainty. For example, there is no randomness in travel demand and road capacity considered in the reviewed papers. Nevertheless, we can still identify current trends and gaps as shown later, and highlight new research directions in this field as shown in the last section.

Other than reviewing UTNDP, we also review the solution methods. This allows comparisons of solution methods of different problems in various classes of UTNDP and proposes new algorithmic research directions. This algorithmic review and the new directions are particularly important, given that these methods are required to solve practical design problems, and their problem sizes have become larger and larger. Real case studies are also reviewed to give insight about the size of the networks for each problem catalogue currently considered and give some hints on the future requirement of the solution methods for practical problems.

The rest of the paper is organized as follows: Section 2 explains the key definitions, classifications, and general formulations of UTNDP; Section 3 reviews the specific problem studied in the literature; Section 4 depicts the solution methods used in the literature; Section 5 describes the application to real case scenarios; and Section 6 presents an overall view of the research development of UTNDP. Finally, the summary and further research directions are presented in Section 7.

2. Definitions, general formulations and classifications of UTNDP

2.1. Definitions of UTNDP

There are at least three different definitions of UTNDP in the literature:

1. UTNDP is concerned with building new streets or expanding the capacity of existing streets (Dantzig et al., 1979). This definition is quite common in the literature, but most studies use other names for this problem catalogue such as the Road Network Design Problem (RNDP), the transportation network design problem, and the network design problem.
2. UTNDP is to determine the optimal locations of facilities to be added into a transportation network, or to determine the optimal capacity enhancements of existing facilities in a network (Friesz, 1985). In this definition, the facilities may be represented by either nodes or links. Therefore, this definition is wider than the first one.
3. UTNDP deals with a complete hierarchy of decision-making processes in transportation planning, and includes strategic, tactical and operational decisions (Magnanti and Wong, 1984). *Strategic decisions* are long-term decisions related to the infrastructures of transportation networks, including both transit and road networks; *tactical decisions* are those concerned with the effective utilization of infrastructures and resources of existing urban transportation networks; and *operational decisions* are short-term decisions, which are mostly related to traffic flow control, demand management or scheduling problems. Fig. 1 gives examples of strategic, tactical and operational decisions in UTNDP: the shaded items are related to network topology. This definition has the widest scope among the three, since it includes the management aspect at the tactical and operational levels in addition to the planning aspect at the strategic level.

In order to create a comprehensive and integrated collection of classifications under a single umbrella, this paper adopts the third definition of UTNDP, but mainly limits itself to the decisions specified in the second definition – the decision related to network topology. Actually, we believe that this definition encompasses both the *Road Network Design Problem* (RNDP) and the *Public Transit Network Design and Scheduling Problem* (PTNDSP) in which the term 'public' will be omitted in the rest of paper for the sake of brevity, that determines the optimal transit routes, frequencies, and time-tables, because transport networks include both transit and road networks. In addition, we believe that this definition includes two big classes of UTNDP: (1) the problem of developing a new network via adding links, which is related to strategic decisions and (2) the problem of improving or managing the current network, which is related to the tactical and operational decisions.

2.2. General framework of UTNDP

UTNDP differs from network design problems in other disciplines such as telecommunication, because the reaction of travelers has to be taken into account when designing a transportation network. Moreover, designing a network is associated with certain transport policy. Regarding these two facts, analyzing and modeling in UTNDP involves two issues: (1) policy-making for network improvement and (2) predicting the network user behaviors in response to the formulated design policies. The rest of this section will discuss the problem from the mentioned aspects.

2.2.1. General mathematical model for UTNDP

The problem is usually formulated as a bi-level problem or a leader-follower problem. The upper level problem is the leader's problem, the design problem, or the problem of the decision-maker, (e.g. the government), who plans or manages the transport network. This upper-level problem is related to the policy discussion in practice and includes the measurable goal (e.g. reducing total travel time), restrictions (e.g. political, physical, and environmental constraints) and the design decisions to be made (e.g. new roads to be built). This upper-level problem assumes that the leader can predict the behavior of the travelers. The lower-level problem is the followers' problem or the problem of travelers who decide whether to travel, and if so, their travel modes and routes. The bi-level structure allows the decision-maker to consider the reaction of the travelers and improve the network to influence the travel choice of travelers but has no direct control on their choice. This structure does not allow the travelers to predict the decision of the leader, but only allows them to determine their choice after knowing the decision of the leader. Mathematically, the problem can be represented as follows:

$$(U0) \quad \min_{u} \quad F(u, v(u)) \tag{1}$$

$$\text{s.t.} \quad G(u, v(u)) \leqslant 0 \tag{2}$$