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RESEARCH PAPER

Multi-period Bi-level Programming Model for Regional Comprehensive Transport Network Design with Uncertain Demand

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Abstract: By exploring of the multi-period network design problem of comprehensive transport, the paper proposes a bi-level programming model with uncertain demand. The upper level problem is to maximize the consumer surplus of all demand scenarios with budget constraint. While under the network investment decisions of the upper level problem, the lower level problem is to maximize the consumer surplus of every demand scenario with consideration of the collaborations of transportation modes, traffic load balancing and capacity constraints. Then, a numerical example is given to verify the effectiveness of the model and algorithm. Compared with the existing research, the proposed model can simultaneously optimize the final form of the comprehensive transport network and construction timing. The model considers all the annual coordination between transportation infrastructure construction and demand. It reflects the cooperation and balanced development of transportation modes, and makes the decision support more effective for the gradual improvement of the regional comprehensive transport network.

Key Words: integrated transportation; comprehensive transport network design; bi-level programming; uncertain demand; multi-period

1 Introduction

In recent years, with the rapid growth in total scale of transportation infrastructure and the continuous expansibility of transportation networks, the transportation network in China has been improved continually. However, on the whole, the transportation infrastructure still cannot meet the transportation needs of national economic and social development. The structural problems are still outstanding and every transportation mode that is developed in dispersion, which lacks coordination, cooperation, organic linking and integrated operation. And these problems resulted in poor connections and services, which seriously reduced the overall integrated transport efficiency and increased transportation costs. Constructing an integrated transport infrastructure network with reasonable division of transport tasks, complementary advantages and organic linking is a basis for building a perfect comprehensive transportation system, that is, a system that is environmentally friendly and has an efficient operation. With increasingly urgent constraints of resources, environment and ecology, how to make the passenger and freight transport of each transportation develop in phase under limited funds has been becoming increasingly prominent.

Integrated transport network design is the key content of regional transportation system strategy management, whose decision-making process needs to consider the interaction between government departments and the public. Thus the bi-level programming model has become an ideal tool for transport network design problems, and made great progress in urban transport network design[1]. In recent years, bi-level programming model has began to be applied in the studies of integrated transport and multimodal transport network design[2–4]. These studies have laid a good foundation for this paper, but they mostly took network design under mid long term fixed demand as the research object.

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The construction of an integrated transport network is a gradual process under budget constraints. Because of huge investment, long investment recovery period and strong public interest in transportation infrastructure, financing difficulties have become a prominent realistic problem. In this case, considering the constraints of capital budget of each period and achieving effective use of limited funds to meet the transport demand as much as possible is closer to the decision-makers' need in the practice of investment decision-making. The existing literature on transportation projects timing does not fully consider the impacts of construction time sequence on the integrated transport network. Some of the existing literature in the road transport network design model has considered the multi-period problem[5–7]. Using these ideas for references, this paper analyzes the multi-period problem in integrated transport network design, studies investment allocation among transport modes under network environment, comprehensively considers the dynamic relationship between passenger and freight traffic, and reflects the random nature of OD demand and the impact of elastic demand, which can provide a decision support for coordinated development of various modes of transport and transport infrastructure orderly building in the integrated transport network.

2 Consumer surplus with elastic demand

The objective of bi-level programming model in transport network design generally includes[8]: (1) to minimize total system travel time with fixed demand; (2) to maximize network reserve capacity with fixed demand; (3) multi-objective optimization, such as comprehensively considering total system travel time, construction cost, environmental impact, and so on; (4) to maximize consumer surplus with elastic demand. Consumer surplus is the difference between the willingness to pay and actual travel cost, which can be used to evaluate the social benefits of transportation systems bringing to consumers of transport. With consumer surplus as the objective of network design, the impact of transport network improvement measures on commuter/shipper behavior can be examined. Therefore, this study takes the consumer surplus with elastic demand as the objective of programming.

In reality, the transport demand per origin–destination (OD) pair and its transport cost interact with each other. The changes in transport cost result in an increase or decrease in travel demand per OD pair. The paper allows for the assumption of elastic demand for the overall trip demand. Compared with fixed demand, the traffic assignment model with elastic demand gets feedback from the transport cost. The potential demand level between rs for user type k can be written as Eq. (1)[7].

$$d_{rsk}^{t,\omega} = D_{rsk}^{t,\omega} \exp(-\theta_k \pi_{rsk}^{t,\omega}) \quad \forall rs \in A,\ t \in T,\ \omega \in W,\ k \in K \tag{1}$$

where $D_{rsk}^{t,\omega}$ denotes the forecast value of demand between rs for user type k at time t under the demand scenario ω, which is a constant value. $d_{rsk}^{t,\omega}$ is the simulation value of demand between rs for user type k at time t under the demand scenario ω, which is a stochastic variable. The user type k can be used to separate passenger transport demand (while k=1) and freight transport demand (while k=2). $\pi_{rsk}^{t,\omega}$ is the minimum travel cost between rs for user type k at time t under the demand scenario ω. θ_k is a constant value reflecting the sensitivity level of elastic demand to transport cost changes.

The minimum travel cost between rs for user type k at time t under the demand scenario ω can be written as

$$\pi_{rsk}^{t,\omega} = \frac{1}{\theta_k}\left[\ln\left(\frac{D_{rsk}^{t,\omega}}{d_{rsk}^{t,\omega}}\right)\right] \tag{2}$$

The system consumer surplus (SCS) for user type k at time t under the demand scenario ω is

$$SCS_k^{t,\omega} = \sum_{rs\in A}\int_0^{d_{rsk}^{t,\omega}} \pi_{rsk}^{t,\omega}(\varpi)d\varpi - \sum_{rs\in A} d_{rsk}^{t,\omega}\pi_{rsk}^{t,\omega} \tag{3}$$

where the first term in Eq. (3) represents the willingness to pay for travelling from r to s. The second term is the minimum travel cost.

$SWP_k^{t,\omega}$ is used to denote the system willingness to pay for user type k at time t under the demand scenario ω. Substituting Eq. (2) into Eq. (3), thus it can be obtained:

$$SWP_k^{t,\omega} = \frac{1}{\theta_k}\sum_{rs\in A}\left[d_{rsk}^{t,\omega}\left(\ln\left(\frac{D_{rsk}^{t,\omega}}{d_{rsk}^{t,\omega}}\right)+1\right)\right] \tag{4}$$

The system consumer surplus (SCS) for user type k under the demand scenario ω in the planning period is denoted by SCS_k^{ω}. Substituting the Eqs. (2) and (4) into Eq. (3), Eq. (5) is obtained:

$$SCS_k^{\omega} = \frac{1}{\theta_k}\sum_{t\in T}\sum_{rs\in A}\frac{D_{rsk}^{t,\omega}\exp(-\theta_k\pi_{rsk}^{t,\omega})}{(1+\rho)^t} \tag{5}$$

where ρ is the social discount rate.

3 Bi-level programming model

3.1 Assumption

In this research, we have the following pretreatment and assumptions.

(1) Regional integrated transport network design problem is a hybrid network design problem. By taking discrete network design as the research object, we make choices in a given set of integrated transport infrastructure projects.

(2) It is assumed that the investment on common highway and expressway between nodes is used to upgrade and renovate the existing road.

(3) It is assumed that passengers and cargo owners always tend to select the most effective traffic paths and transportation modes, therefore the model is based on the principle of utility maximization to achieve the distribution of traffic flow in integrated transport network.