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Reliability-based traffic network design with advanced traveler information systems

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ABSTRACT

As the demands on urban transportation networks grow rapidly, problems of network design have attracted a great deal of interest because of the need to effectively handle urban transport planning using information technology. A bi-level continuous network design model is proposed in this paper to address the optimal road capacity expansion of existing links. Based on the fact that every origin–destination demand is random and affected by traffic travel information, the network is subject to relatively minimal day-to-day events of stochastic link capacity variations. Therefore, the primary objective is to maximize the reliability of the total travel time, while the lower level model, utilizing the behaviors of stochastic route choice, is aimed at reducing drivers' travel time uncertainty through traffic information provided by advanced traveler information systems. The Particle Swarm Optimization algorithm is used to solve the suggested model, and a numerical example using the Sioux Falls network is provided. The computation results show that travel time reliability is improved by system optimization using traffic information.

1. Introduction

In modern society, the growth in transportation demand is much faster than the growth of urban transport systems, as the resources available for expanding system capacity remain limited. Therefore, it is necessary to plan and design an effective traffic network. It is, however, a well-known paradox that it is possible to make the network performance worse if traveler behaviors are not considered in the network design. Hence, describing choice behaviors is the basis of network design. Numerous studies have shown that travel time uncertainty and advanced travel information guidance in transportation networks affect travelers' route choice [22,27,16]. For example, bad weather and traffic incidents lead to road capacity variability and thus cause typical non-recurrent congestion. Under this condition, traffic information is an effective technology to make route decisions for drivers. Therefore, this paper tries to establish a new traffic network design model to improve network performance by considering the information and the travel demand uncertainty.

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1.1. Network design problems

The network design problem (NDP) involves the optimal decision on the expansion of the urban road and highway system in response to rapidly growing travel demand. Generally, this problem has been posed in two different forms: (1) the discrete form dealing with the additions of new road or roadway segments to an existing traffic network; and (2) the continuous form dealing with the optimal capacity expansion of existing urban roads. Regardless of the form, the objective of NDP is to optimize a given system performance measure, such as to reduce the total system travel cost [31]. The decisions of the road planner affect the route choice behavior of network users, which are normally described by a network user equilibrium model. Mathematically, bi-level programming is a good way to describe the hierarchical nature of the NDP with an equilibrium constraint: the lower level problem is to characterize the user equilibrium (UE) traffic flow pattern, while the upper level problem is aimed at minimizing the total system cost.

Due to the intrinsic complexity of the model formulation, the NDP has been recognized as one of the most difficult but challenging problems in transportation research. In fact, a large number of scholars have investigated the NDP over the past three decades [31]. Thus far, studies have been overwhelmingly focused on the continuous network design problem (CNDP) and substantial achievements in algorithmic development have been made. For instance, [8] proposed a globally convergent algorithm to solve the CNDP. Li [14] developed a viable global optimization method for the CNDP based on the concepts of gap function and penalty. An activity-based network design problem was proposed by Kang [11] using the location routing problem as inspiration without the demand information.

1.2. The reliability of the transportation network

To provide more effective and reliable transport problem solutions, transport analysts and engineers have to deal with different sources of uncertainty when modeling transportation systems and their main components, such as travel demand, transport supply, interaction between demand and supply and relevant analysis and assessments [20]. Therefore, flow assignments based on stochastic characteristics are both realistic and important and have become a focus of research. Sumalee and Xu [23] considered the effects of stochastic demand on network reliability, which has also been studied by multiple network demon approaches [25] and cooperative game approaches [26]. Tan et al. [15] studied a multistate network composed of multistate edges to study the relationship between transmission reliability and spare routing. Tan et al. [27] investigated the Pareto efficiency of the various reliability-based traffic equilibria proposed in the literature and the risk-taking behavior of travelers by considering different traveler behaviors. Han [9] found the maximum amount of flow from an uncertain network.

The need to assess the reliability of the transportation network has caused many researchers to develop various indicators, including travel demand reduction [19], travel demand satisfaction reliability [13], capacity reliability [4], travel time reliability [28] and so on. Sumalee et al. [22] considered the so-called reliable network design problem with stochastic demand. Chootinan et al. [5] proposed a reliability index that explicitly considers not only the average traffic flow conditions but also the variability of traffic flow conditions when designing a road network.

1.3. Factors affecting the traveler's route choice behavior

The reliability of route travel time plays an important role in a traveler's route choice behavior. Several studies found that reliability-related attributes are among the most important service attributes in a variety of situations [1,16,33]. Uchida [28] estimated the value of travel time and of travel time reliability based on the risk-averse driver's route choice behavior.

Moreover, the advanced traveler information system (ATIS) is another important factor affecting travel choice behavior. ATIS is generally believed to be efficient in alleviating traffic congestion and enhancing the performance of road networks, which can improve travelers' route choice decisions by providing them with the road network situation and navigational assistance [10]. Thus far, a number of studies have been conducted to model the effects of ATIS on commuting behaviors and to assess the relevant benefits and risks using laboratory experiments [17, 2], computer simulation [3] and analytical modeling [32,16,33,29].

Obviously, travelers equipped and unequipped with ATIS will behave differently in terms of their route choices due to different traffic information and variation in perception on travel disutility. In analytical modeling approaches, the three criteria, namely UE, system optimum (SO) and stochastic user equilibrium (SUE), are often used to model the commuters' route choice behaviors. Yang [32] developed a mixed equilibrium formula combined with UE and SUE to model the route choice behaviors for equipped and unequipped drivers. Lo and Szeto [16] and Yin and Yang [33] adopted the logit-based SUE principle to describe the route choice behaviors of all drivers. Their approaches are closer to reality because neither equipped nor unequipped drivers can accurately calculate the route travel disutility. Dong [6] proposed an improved congestion coefficient feedback strategy to an intelligent transportation system.

However, the aforementioned studies have not taken both the travel time reliability (TTR) and ATIS into consideration in the network design problem. In reality, the TTR can be improved greatly when using ATIS in the network. How advanced information affects the travelers' behaviors and then affects the TTR of the whole system is the main concern of this paper. Hence, to fill this gap, a bi-level programming model for CNDP considering both TTR and ATIS is proposed, which will improve the efficiency of the traffic system in traffic network design. Then, a PSO-based algorithm is developed to solve