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A robust urban traffic network design with signal settings

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ABSTRACT

An urban traffic network (UTN) accounting for signal setting and link capacity expansion under uncertain travel demand is considered. In order to mitigate vulnerability of UTN system, a robust bi-level model is firstly presented. A trust-region cutting plane projection (TCPP) is proposed in this paper to solve the proposed robust bi-level model. Numerical computations for proposed bi-level model were performed using various test road networks. Computational comparisons for proposed approach were also made with other heuristics. It indicates that the proposed approach can substantially enhance greater system performance of UTN system as compared to other alternatives while incurring less CPU time. In particular, in comparison with a recently proposed heuristic, the proposed approach improved robustness of UTN system with significance whilst maintaining optimality of nominal solutions.

1. Introduction

For most urban traffic networks, severe travel delays would be incurred by all road users as a result of inappropriate design of signal settings and insufficient provision of link capacity particularly under uncertain travel demand. To deal with growing travel demand and alleviating traffic congestion with success for most urban traffic networks (UTNs), a bi-level programming (BLP) model has been employed [6,8,11–13,19,21,22,31,40,46–48]. For example, [11] proposed a general bi-level programming approach for continuous transportation network design problem. [21] proposed a non-linear constrained bi-level program for urban network design where both directions of existing roads and signal settings at junctions were taken into account. A scatter search algorithm based on a random descent method was proposed to solve the proposed bi-level program. Numerical tests were conducted on a real dimension network. The local optimal solution can be found by reasonable computation times. Recently, [19] presented a comprehensive review for urban transportation network design problem which includes a variety of definitions, classifications, objectives, constraints, and solution methods of road network design and public transit network design problems. [46] also proposed a BLP for a continuous network design problem with tradable credit scheme and equity constraints. At the upper level, the government chooses optimal capacity enhancement for some existing links to minimize the total system costs under a budget constraint. The lower level chooses the optimal route based on the generalized cost. A relaxation algorithm was proposed to solve the proposed BLP model.

To deal with compromises among interacting decision entities distributed throughout a multi-level hierarchical system which appears quite often in many real-world applications, [23] presented a tri-level decision-making model with multiple followers. The Stackelberg equilibrium in a three-level vertical structure and the Nash equilibrium among multiple followers at the same horizontal level can be achieved using a fuzzy programming approach. To exploit maximum reserve capacity of UTN system, [12] proposed a min–max bi-level programming problem for urban city traffic signal design. A new hybrid strategy using

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delay-minimizing signal settings was proposed to mitigate travel delay to all road users. The merits of proposed strategy have been numerically demonstrated with two moderate road networks when compared to other alternatives. More recently, [6] proposed a bi-level programming model to solve multi-modal bus lane design in transportation road networks. The upper level problem aims to minimize average travel time of road users and the difference of passengers' comfort among all bus lines is minimized via optimal design of bus frequencies. The lower level problem is a multi-modal transportation network equilibrium model for the joint modal split and traffic assignment problem. A simple numerical test has been conducted using a column generation algorithm combined with the branch-and-bound method. Good results have been reported with regard to the objective of effectively reducing travel times for all users and balancing transit service level among all bus lines. To address optimal road capacity expansion of existing links under uncertainty, [40] proposed a reliability-based bi-level traffic network design model with advanced traveler information system. The objective at the upper level is to maximize the reliability of the total travel time whilst drivers' travel time uncertainty at lower level is being effectively reduced via traffic information provided by advanced traveler information systems. The proposed reliability-based bi-level network design model was solved by the particle swarm optimization and primary results were reported using the Sioux Falls real data network.

As it has been widely recognized from literature [2,18,29,32,35,38], the BLP is generally a non-convex problem due to the implicit form in constraints. Ways of characterizing the implicit function form in constraints for BLP can be achieved by a gap function as investigated in [28,31,45]. Employing a certain form of gap function, Meng et al. [31] gave an equivalent continuously differentiable model for BLP. An augmented Lagrangian method was proposed to solve the problem. Since in general the gap function is non-convex, optimal solutions for the BLP turn out to be fairly difficult to obtain in practice. In this regard, [28] proposed a viable global optimization method to solve the BLP model effectively. Based on selected gap functions, the proposed BLP model in [28] with continuous variables can be conveniently transferred into a sequence of single-level concave sub-problems. A combination of multi-cutting plane approach and penalty method was proposed to solve the BLP. Due to intensive computational efforts in solving sub-problems, however, the approach presented in [28] may simply solve very modest networks only. Instead of solving the BLP directly, [45] on the other hand presented a mixed transportation network design model using a global optimization approach with equilibrium constraints. The user equilibrium condition in [45] was characterized by a path-based complementarity problem. A BLP model was transferred into a single-level optimization problem with a set of mixed-integer constraints. Because it is generally challenging to calculate all path flows for a moderately large network, the techniques developed by [45] were relatively not deemed practicable when performed on a road network of realistic size.

The difficulty inherent to the BLP makes attractive the use of heuristics. One meta-heuristic algorithm such as Genetic Algorithm (GA) is often preferred as an alternative to solve the BLP [9,21,42,44]. In order to solve a class of nonlinear BLPs, [44] presented a novel evolutionary algorithm. In [44], the lower level problem is a convex programming problem for each given upper level decision variable. A novel algorithm was proposed to address the nonlinearity of the BLPs with non-differentiable upper level objective function and constraints without requiring the differentiability of the objective function. For urban traffic networks, [42] presented a GA-based heuristic to optimize traffic signals with promising results from empirical studies. [9] also employed a hybrid harmony search and hill-climbing heuristic to improve system performance of UTN with stochastic flows. The effectiveness of proposed GA-based heuristics has been demonstrated numerically with example test networks. Recently, [50] presented a bi-objective optimization model for coordinated traffic signals. A signal timing optimization model was presented to simultaneously optimize the cycle length, offsets, green splits and phase sequences to minimize traffic delay and the risk associated with human exposure to traffic emissions. The Pareto optimal solutions for bi-objective optimization model were solved by GA with a numerical example.

Robust optimization is often employed as an effective tool to hedge against uncertainty [3–5,14,24,43]. In order to mitigate vulnerability of UTN system, for instance, [14] proposed a robust optimization approach [3–5] for traffic network design problem ([14,15,24,33,34] and references therein). A linear programming model was presented by [14] to solve a UTN system design together with numerical test results at a small toy network. Considering a UTN system under uncertain travel demand, [43] proposed a robust system optimal signal control and conducted numerical results. More recently, [24] proposed a robust optimization approach for dynamic traffic signal control together with emission considerations. A mixed integer linear program was proposed to explicitly capture vehicle spillback, and minimizes travel delay together with reduced emissions. In order to perform against the worst-case scenario without loss optimality of nominal solution, [49] presented a set-based model to determine robust optimal signal timings. A cutting plane solution algorithm was employed to minimize travel delays in the presence of the worst-case scenario of travel demands. Computational results were conducted at simple small isolated signal-controlled junctions. Moreover, [15] considered a BLP dynamic congestion pricing problem under travel uncertainty. A BLP cellular particle swarm optimization approach was proposed to find optimal congestion pricing when traffic flows correspond to dynamic user equilibrium on the network. Numerical comparisons for BLP dynamic congestion pricing problem were made with two other robust dynamic solution approaches. As it was shown from numerical results, the proposed approach considerably outperformed other alternatives both in terms of solution quality and computational efficiency. More recently, [37] proposed an integrated model to tackle BLP with signal-settings under uncertain travel demand. A bi-objective BLP model was presented to determine the Pareto solutions. Although the proposed signal settings are less sensitive to fluctuations of traffic flow, the network effect of route choice from travelers has not yet been taken into account and therefore solutions obtained are only sub-optimal. For a general BLP, because of the non-linearity of equilibrium constraint with respect to design variables, most solution heuristics mentioned above [14,15,24,43,49] can simply solve the BLPs only locally.

Considering a UTN system under uncertain travel demand, at the best of author's knowledge, there is very limited work in the literature to contribute in this area except a more recent preliminary study in [13]. The work given in [13] was, however,