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Optimal signal-setting for road network with maximum capacity

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ABSTRACT

A signal-controlled road network with maximum capacity is considered while route choice of users is taken into account. This problem can be formulated as an optimization problem by taking user equilibrium as a constraint. A min–max bilevel program is formulated for a signal-setting problem. A new hybrid search heuristic is proposed to exploit the maximum capacity of road network using delay-minimizing signal settings. For a road network with maximum capacity, a tractable computation scheme is presented to effectively determine a delay-minimizing signal-setting. Numerical computations are performed at two benchmark signal-controlled road networks. The proposed heuristic has been demonstrated successfully to solve the min–max signal-setting problem. As compared to conventional alternatives, the proposed heuristic has been empirically demonstrated highly effective in terms of delay rate reduction.

1. Introduction

In signal-controlled road networks, planning to both exploit maximum capacity of road network and reduce total travel delay incurred by road users has long been recognized as one of the most important issues in literature [3–12,16–19,21,27–29,33,35,37]. Recently, Chen and Kasikitwiwat [5] presented a bilevel mathematical model to capture demand variations for a passenger transportation system. In the presence of travel demand changes, capacity flexibility of a road transportation system becomes one of the important performance measures needed to deal with demand variations. The capacity flexibility allows road users to have route choice when evaluating the maximum capacity of road networked system in the presence of uncertain demand. In order to exploit maximum capacity of road networked system, Miandoabchi and Farahani [23] proposed a mixed-integer bilevel mathematical model to address the problem of designing of street directions and lane additions in urban road networks. A hybrid genetic algorithm and an evolutionary simulated annealing algorithm are introduced to solve the model together with computational results for a number of variations. He and Hou [18] presented an ant colony algorithm to solve traffic signal timing problem. Numerical computations and comparisons are made with conventional signal-setting algorithm and good results are obtained. More recently, Zhang et al. [37] investigated a robust signal-setting optimization model. A bi-objective optimization model is proposed to minimize travel delay and the risk involved with human exposure to traffic emissions. The bi-objective optimization model is solved via a simulation-based genetic algorithm. Numerical example is given using field data from a selected real-world arterial network. It indicates that traffic flows and travel delay are strongly influenced by correct operations of signals. Whilst

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many researchers have theoretically investigated this problem via technique of optimization [1,3,4,7–12,15–17,19–21,23,24,35], computational tractability of signal-setting still becomes a formidable challenge to traffic engineers in practice [6,7,18,28]. In this paper, we intend to fill this gap both from theoretical prospect and from empirical prospect. For a signal-controlled road network, a good performance measure can be effectively achieved by optimizing a chosen objective function with respect to signal-setting variables. The road users between specified origin–destination pairs are supposed to choose the minimal travel time route, which are in turn dependent on the choice of chosen signal-setting variables. Therefore, in the optimization process for a signal-controlled road network, not only signal-setting needs to be considered but also the resulting effect on traffic flows caused by signal-setting needs to be taken into account. The underlying behaviour of road users' route choice is supposed to follow Wardrop's principle [32]. In this regard, Allsop and Charlesworth [3] were the first ones to propose a mutually consistent calculation for signal-setting problems. The resulting signal-setting and traffic flows will, however, in general be a non-optimal solution as has been discussed in literature [14,17] and demonstrated empirically [6,7].

Another alternative to solve a signal-setting problem is a bilevel programming approach [15,19,24,30,35]. Heydecker and Khoo [19] proposed a linear constraint approximation (LCA) to the equilibrium traffic flow and solved the problem as a constrained optimization problem. As it reported, the linear constraint approximation method has obtained good results. Yang and Yagar [35] presented a sensitivity analysis based (SAB) method to solve the signal-setting problem only approximately. Because the constraint for user equilibrium traffic assignment is non-linear, which causes the signal-setting problem to be non-convex, only local optima can be found. These two simple computation schemes can only solve the signal-setting problem locally and are incurred with intensive computational overheads even at small-scaled road networks. Since signal-setting problem may contain several local optima, the gradient-based methods like LCA and SAB are not effective to achieve a global solution. A signal-setting problem is in nature a non-convex problem and meta-heuristic based algorithms are often preferred such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) [2,6,28,30,34,31]. For example, Ceylan and Ceylan [6] presented a hybrid harmony search and hill-climbing heuristic to improve system performance of a stochastic equilibrium network design problem. In Ceylan and Ceylan's model, a meta-heuristic Harmony Search (HS) algorithm is employed as a global search method while the hill climbing routine is used for fine-tuning. It has been applied to an example signal-controlled road network. The effectiveness of the hybrid harmony and hill-climbing heuristic over other alternatives has been demonstrated with considerable travel cost savings.

In order to solve a class of nonlinear bilevel programming problems, Wan et al. [30] presented a novel evolutionary algorithm. In [30] the lower level problem is a convex programming problem for each given upper level decision. Without requiring the differentiability of the objective function, Wan, Mao and Wang proposed a novel algorithm to address the nonlinearity of the bi-level programming problems with non-differentiable upper level objective function and constraints. Xing and Qu [34] considered a bi-objective network coding based multicast routing optimization problem with respect to the cost and delay. A non-dominated sorting GA is used for the proposed problem with adjustments. Experimental results indicated that adopted adjustment contributes to the problem concerned and outperforms a number of multi-objective evolutionary algorithms. More recently, Abdul-Rahman et al. [2] presented an adaptive binary coded GA for constrained optimization problems. The performance of proposed GA has been numerically compared with various benchmark problems. As it demonstrated in [2], the proposed GA achieved good effectiveness against common problems. On the other hand, Particle Swarm Optimization (PSO) has long been recognized as an effective tool to solve variant real-world optimization problems. Wang et al. [31] presented a hybrid PSO using a diversity mechanism and neighborhood search strategies to circumvent premature convergence of PSO when solving high-dimensional problems. A comprehensive experimental study was conducted on a set of benchmark functions and promising performance of test problems was obtained.

In this paper we intend to bridge this gap between solution effectiveness and computational efficiency of a signal-setting problem. The signal-setting plan is defined by a common cycle time, the start and duration of greens. The performance index (PI) can be defined as the sum of a weighted linear combination of rate of delay and number of stops as introduced in [8]. A min–max bilevel program is presented. At the upper level a decision maker with the leader determines a signal-setting which can be regarded as parameter for the lower level problem. At the lower level a road user with the follower minimizes his journey time with respect to route choice under these parameters. In other words, the upper level optimizes the system performance with respect to signal-setting subject to a given traffic flow. The lower level solves a user equilibrium traffic assignment problem in the presence of a determined signal-setting. The dependence of traffic flow on signal-setting is regarded as a constraint for the upper level and is solved by the lower level problem. Therefore, a signal-setting problem can be regarded as a constrained optimization problem. As a step toward finding solutions to this signal-setting problem, a HybRid Search (HRS) heuristic is presented. HRS combines a locally optimal search and a global search heuristic. For a locally optimal search, a projected conjugate gradient approach (PCGA) is introduced. A descent direction is found along which the PI value is progressively decreased. For a global search heuristic, making equal and simultaneous changes in the starts of green for all signal settings at any one junction provides a wide search across the feasible region. Accordingly, a better signal-setting can be identified. In order to enhance the robustness of HRS against sensitivity of initial signal-setting, a hybrid search with extension (HRS-T) is presented. Integrated with parallel tangents (PARTAN) of objective function, HRS-T exploits past computed gradients of objective function and greatly improves local optimal search of HRS. Combining PCGA and PARTAN, HRS-T adopts a favorable descent direction in search for an optimal signal-setting.

For a min–max signal-setting problem, the performance measure of road network with maximum capacity can be regarded as an upper bound for a signal-setting problem. And the performance measure of a signal-setting problem can serve