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Discrete Optimization

A bi-objective turning restriction design problem in urban road networks

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ABSTRACT

This paper introduces a bi-objective turning restriction design problem (BOTRDP), which aims to simultaneously improve network traffic efficiency and reduce environmental pollution by implementing turning restrictions at selected intersections. A bi-level programming model is proposed to formulate the BOTRDP. The upper level problem aims to minimize both the total system travel time (TSTT) and the cost of total vehicle emissions (CTVE) from the viewpoint of traffic managers, and the lower level problem depicts travelers' route choice behavior based on stochastic user equilibrium (SUE) theory. The modified artificial bee colony (ABC) heuristic is developed to find Pareto optimal turning restriction strategies. Different from the traditional ABC heuristic, crossover operators are captured to enhance the performance of the heuristic. The computational experiments show that incorporating crossover operators into the ABC heuristic can indeed improve its performance and that the proposed heuristic significantly outperforms the non-dominated sorting genetic algorithm (NSGA) even if different operators are randomly chosen and used in the NSGA as in our proposed heuristic. The results also illustrate that a Pareto optimal turning restriction strategy can obviously reduce the TSTT and the CTVE when compared with those without implementing the strategy, and that the number of Pareto optimal turning restriction designs is smaller when the network is more congested but greater network efficiency and air quality improvement can be achieved. The results also demonstrate that traffic information provision does have an impact on the number of Pareto optimal turning restriction designs. These results should have important implications on traffic management.

1. Introduction

Congestion is one of the most representative aspects of urban road traffic problems, and has become one of the most important factors that influence people's mobility and travel cost in daily life. Meanwhile, road traffic leads to some intractable problems that attract wide attention from the whole society, such as road safety, environmental pollution, and energy consumption. Traditionally, traffic control, such as signal control, lane allocation, turning restriction, and road pricing, mainly aim to improve traffic efficiency and alleviate traffic congestion. Nowadays, especially in developing countries, the environmental pollution problem caused by vehicle emissions attracts more and more attention in the transportation engineering field and becomes a hot issue for studies (see Chung, Weaver, & Friesz, 2013; Demir, Bektaş, & Laporte, 2012, 2014; Gokhale, 2012; Mayeres, Ochelen, & Proost, 1996; Ng & Lo, 2013; Orubu, 2004; Pandian, Gokhale, & Ghoshal, 2009; Zhu, Lo, & Lin, 2013 for example).

Vehicle emissions, such as carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOC), have been shown to have a variety of negative effects on public health and the natural environment (Szeto, Jaber, & Wong, 2012). Compared to the emissions from industry, power plants, space heating, refuse disposal, etc., vehicle emissions play the most important role in contributing air pollutants in typical urban centers (Bach, 1972). Empirical studies show that transportation is identified as a highly significant contributor, accounting for well over 50% of total air pollutants in some countries (Fu, Hao, He, & He, 2001; Goyal, Ghatge, Nema, & Tamhane, 2006; Orubu, 2004). In some developing countries, this percentage is expected to increase quickly in the future because the vehicle growth has not been properly regulated by the government authorities. For example, the motor vehicle population continued to increase at an annual rate of approximately 10% in mega cities in China (Chan & Yao, 2008). This calls for the needs to control the situation. In fact, there are many means that have been successfully adopted to reduce vehicle

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emissions, such as tightening vehicle emission standards, reducing travel demand (e.g., pricing) and vehicle ownership (e.g., vehicle quota systems), improving traffic management and control (e.g., signal control), etc.

Turning restriction is one of the commonest traffic management techniques and an effective, low cost traffic improvement strategy for urban road networks. Turning restrictions are applied to a group of intersections where travelers are prohibited to drive into restricted downstream links. Long, Gao, Zhang, and Szeto (2010) proposed a turning restriction design problem (TRDP), which is the problem of determining a set of intersections to implement turning restrictions to minimize the total system travel time (TSTT). It has been demonstrated that implementing turning restrictions can effectively improve traffic efficiency by reducing the TSTT. However, the influence of turning restrictions on environmental pollution has not been examined yet. In fact, when a turning restriction is implemented, some drivers need to travel at a longer distance to reach their destinations as their original, shortest routes are not permitted to use. The vehicle emissions and the corresponding monetary values (i.e., the cost of vehicle emissions) are usually more as a result. Although the overall TSTT is reduced, there may be a tradeoff between minimizing the cost of total vehicle emissions (CTVE) and TSTT. Therefore, this paper investigates a bi-objective TRDP (BOTRDP), which aims to reduce not only the TSTT, but also the CTVE by implementing turning restrictions.

Turning restrictions are implemented by traffic managers, but the implementation should take travelers' route choice behavior into account. A new turning restriction in road networks directly influences some travelers' route choice, because their original routes include the restricted turning and are infeasible after implementing the turning restriction. As a result, the original traffic equilibrium state is disrupted and some travelers adjust their routes. A new equilibrium is realized again only when all travelers cannot be better off by unilaterally changing their routes. Similar to the original TRDP (Long et al., 2010) and the traditional network design problems (see Farahani, Miandoabchi, Szeto, & Rashidi, 2013 for a comprehensive review), the BOTRDP can be mathematically formulated as a bi-level problem. The upper level problem (ULP) of the BOTRDP is a bi-objective optimization problem that minimizes both the TSTT and the CTVE. The lower level problem (LLP) formulates travelers' route choice behavior as the SUE assignment problem, which is more realistic than the deterministic user equilibrium (DUE) assignment problem (Chen & Alfa, 1991b).

Whether a turning restriction is implemented or not can be represented by a binary variable. Hence the ULP of the BOTRDP is a discrete optimization problem, and the BOTRDP is a bi-objective nonlinear bi-level mixed integer programming problem, which has been recognized as one of the most difficult and challenging problems in the transportation research area due to its computational difficulty. In general, all Pareto solutions of the BOTRDP cannot be obtained by using the exact solution methods when the number of binary variables is large. As a result, meta-heuristic methods are always used to find good, but not necessarily Pareto optimal solutions within a reasonable amount of computing time. During the past several decades, many meta-heuristic approaches were developed to tackle the multi-objective optimization problems (see Jones, Mirrazavi, & Tamiz, 2002 for a comprehensive review). The most popular meta-heuristics for multi-objective optimization problems include genetic algorithms (GAs) (Cantarella & Vitetta, 2006; Chen, Kim, Lee, & Kim, 2010; Chen, Subprasom, & Ji, 2006; Gen, Cheng, & Lin, 2008; Konak, 2012; Miandoabchi, Daneshzand, Szeto, & Farahani, 2013; Miandoabchi, Farahani, Dullaert, & Szeto, 2012; Miandoabchi, Farahani, & Szeto, 2012; Sharma, Ukkusuri, & Mathew, 2009; Shepherd & Sumalee, 2004; Sohn, 2011; Szeto, Wang, & Wong, 2014; Teklu, Sumalee, & Watling, 2007; Xu, Wei, & Wang, 2009; Yin, 2000, 2002), evolution strategies (Deb & Sinha, 2010; Zheng, Wan, & Wang, 2011), simulated annealing (Friesz et al., 1993; Suppapitnarm, Seffen, Parks, & Clarkson, 2000; Xu et al., 2009), tabu search (Armentano & Claudio, 2004; Jaeggi, Parks, Kipouros, & Clarkson, 2008; Uno & Katagiri, 2008), etc.

The artificial bee colony (ABC) algorithm is a swarm-based meta-heuristic algorithm that was introduced by Karaboga (2005) for solving numerical optimization problems. This algorithm is motivated by the foraging behavior of honey bees. Compared to existing evolutionary algorithms such as GA, one merit of the ABC algorithm is that the ABC algorithm has a better local search mechanism to improve the solution quality. Indeed, the ABC algorithm has been applied to solve other single objective optimization problems with great success (Karaboga, 2009, 2010; Karaboga & Basturk, 2008; Singh, 2009; Szeto & Jiang, 2012; Szeto, Jiang, Wang, & Sumalee, 2013; Szeto & Jiang, submitted for publication; Szeto, Wu, & Ho, 2011). Recently, the ABC algorithm has also been applied to solve the multi-objective optimization problems (Akbari, Hedayatzadeh, Ziarati, & Hassanizadeh, 2012; Omkar, Senthilnath, Khandelwal, Naik, & Gopalakrishnan, 2011; Zhang, Zhu, Zou, & Yan, 2012). It is worthwhile to evaluate the performance of the ABC algorithm for solving the BOTRDP.

In this paper, a bi-level programming model for the BOTRDP is introduced, and the ABC algorithm is developed to solve the BOTRDP. Rather than directly applying the ABC algorithm proposed by Karaboga (2005), this paper improves the ABC algorithm by enhancing its global search ability. For this purpose, crossover operators that are normally used in GA are incorporated in the ABC algorithm. The resulting ABC algorithm has both the strength of the original ABC algorithm and GA. The computational experiments show that the inclusion of the crossover operators can indeed improve the performance of the ABC heuristic, and that the proposed heuristic significantly outperforms the non-dominated sorting genetic algorithm (NSGA) even if various operators are randomly selected and adopted in the NSGA as in our proposed heuristic. The results also demonstrate that the Pareto optimal turning restriction strategy can obviously reduce both TSTT and the cost of total vehicle emissions. It is also found that the number of Pareto optimal turning restriction designs is smaller when the network is more congested but greater network efficiency and air quality improvement can be achieved. The results also illustrate that traffic information provision does have an impact on the number of Pareto optimal turning restriction designs.

The contributions of this paper include the following. (1) This paper proposes a new bi-objective, bi-level problem, which is NP-hard. (2) A modified ABC heuristic is proposed for solving the proposed problem, and the heuristic outperforms the NSGA. (3) The tradeoff between the TSTT and the CTVE under the implementation of turning restrictions is pointed out and illustrated. (4) The effects of demand levels and traffic information provision on the number of Pareto-optimal solutions are demonstrated and discussed.

The rest of the paper is organized as follows: In the next section, a BOTRDP is formulated as bi-level programming model. The modified ABC algorithm is presented in Section 3 to solve the proposed bi-objective problem. In Section 4, numerical examples are given. Finally, conclusions are drawn in Section 5.

2. A bi-level programming model for the BOTRDP

2.1. Notations

Consider a multi-destination and connected network G. N denotes the set of nodes whereas A denotes the set of arcs (links). R and S denote the sets of origin and destination nodes, respectively. The following notations are adopted throughout this paper: