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A novel comprehensive macroscopic model for time-dependent vehicle routing problem with multi-alternative graph to reduce fuel consumption: A case study

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ABSTRACT

Vehicle routing problem (VRP) has attracted the attention of many researchers in recent years, but in spite of its application, researchers have shown little interest in the time-dependent vehicle routing problem. In recent years, much attention has been paid to the reduction of environmental emissions and reduction of fuel consumption. In this paper, the factors effective in the fuel consumption in time-dependent vehicle routing have been comprehensively studied and by considering factors such as load, vehicle speed, road gradient, and urban traffic, a novel comprehensive macroscopic model is presented to calculate fuel consumption in time-dependent vehicle routing problem. Additionally, the multi-alternative graph which enjoys great importance in time-dependent routing problem is also considered in the model presented. With regard to the issue that proposed problem belongs to the class of NP-hard problems, to find suitable routes with the least fuel consumption, an improved algorithm based on Gaussian Firefly algorithm is proposed. The results obtained from the proposed algorithm in comparison to Gaussian and basic Firefly algorithms show the appropriate performance of the suggested algorithm. Ultimately, one of the distribution companies in one of the cities of Iran (Esfahan) is studied as a case study.

1. Introduction

In environments with high congestion like city centers, failing to pay attention to urban traffic in routing, leads to non-optimal solutions to the problem, because in environments with traffic congestion, the time required to traverse the road depends not only on the distance of the road, but also on the starting time of travel. On the other hand, in recent years, much attention has been paid to the reduction of environmental emissions and consumption of fossil fuels. According to the following equation, fuel consumption is directly related to the amount of emissions from vehicles (Bektas & Laporte, 2011).

$$F = \mu_1 E + \mu_2 \tag{1}$$

In this equation, E is the amount of emission; F is the amount of fuel consumption; and μ_1 and μ_2 are the constants. Therefore, paying attention to the reduction of fuel consumption in time-dependent vehicle routing problem not only can reduce the distribution costs, but it can also reduce environmental emissions.

In the vehicle routing problem, the distance between two nodes is usually specified through the shortest route between the two nodes. But, in the time-dependent routing problem, the time traversed between the two nodes depends on the travel starting time; therefore, at the time of reaching a node, the shortest route might have a high traffic congestion, and traversing a longer route might require less time. Therefore, considering one alternative between the two nodes, inefficient answers might be obtained.

The innovations of this paper can be summarized for the following issues. With regard to the knowledge of the authors of this paper, it is the first time that the use of multi-alternative graph in time-dependent routing is brought up. Also, by a comprehensive study of the factors affecting the fuel consumption in the time-dependent vehicle routing problem, a macroscopic comprehensive model is presented for the problem to reduce the fuel consumption. The presence of several traffic patterns and the "first-in–first-out" (FIFO) property, which have been of little interest to researchers, are also considered in the presented model. Then, Considering to this issue that proposed problem is NP-hard and in order to find routes with the least amount of fuel consumption, a

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metaheuristic algorithm based on Gaussian Firefly algorithm has been presented. Ultimately, one of the distribution companies in one of the cities of Iran (Esfahan) is selected for the case study.

The remainder of this paper and in Section 2, the literature regarding the issue is presented and in Section 3, the problem is defined. Then, the multi-alternative graph, which is the new issue in routing topic, is studied and the factors affecting fuel consumption are investigated; also, the importance of considering several traffic patterns and the FIFO property are described in this section. In Section 4, the algorithm for the calculation of fuel consumption in a tour is explained. In Section 5, the algorithm proposed for the intended problem is expressed in detail. Following that, Section 6 is devoted to the solution of the test problems and the results are analyzed. Then the case study is presented; and ultimately, the conclusion is offered in Section 7.

2. Literature review

The time dependent vehicle routing problem (TDVRP) is one of the vehicle routing problems, which has not attracted much attention by researchers in the literature in spite of its applicability. Most researches regarding VRP assume that the travel speed or travel time between related locations (distribution centers and retail stores) are fixed (Malandraki & Daskin, 1992). In fact, in more congested regions like city centers, travel speed (time) during the day varies with regard to the congestion during rush hours (Fleischmann, Gietz, & Gnutzmann, 2004). Malandraki and Daskin (1992) studied time dependent vehicle routing problem and time dependent traveling salesman problem and proposed a mixed integer programming formulation with time windows and waiting time. Also Hill and Benton (1992) and Malandraki and Dial (1996) examine the time dependent vehicle routing problem. Chen, Hsueh, and Chang (2006) formulated a mixed integer programming model for TDVRP and developed a heuristic to solve it. The major weakness of these papers is that they do not satisfy the FIFO property. The FIFO property guarantees when a vehicle leaves node b for node c at a given time, then an identical vehicle leaving node b for node c at a later time will arrive later at node c and vice versa. The FIFO assumption is satisfied by follow papers: Ichoua, Gendreau, and Potvin (2003) proposed TDVRP with minimizing total time and lateness. They tested their model in a static and a dynamic setting, using parallel tabu search algorithm. Fleischmann et al. (2004) consider the derivation of travel time data from traffic information systems that present a general implementation of time-varying travel times in various vehicle routing algorithms. In their modeling for time-varying travel times they also modeled calculating the start time for a given arrival time and FIFO property was considered in their model. Savings algorithm, Savings algorithm with insertion and Sequential insertion algorithm that forming one route at a time had been used with the adaption for time-varying travel times and time windows constraints. They consider traffic information system in a city Berlin. Haghani and Jung (2005) solved TDVRP with genetic algorithm. They validated it with an exact algorithm. Donati, Montemanni, Casagrande, Rizzoli, and Gambardella (2008) discussed the optimization of starting time and the optimization of the routs in the time dependent routing. Kuo, Wang, and Chuang (2009) proposed an optimization method for solving goods assignment and vehicle routings based on time- dependent travel speeds. In their optimization method, the FIFO property was considered. They proposed an algorithm for FIFO property that travel time was obtained considering changes in time periods. A case study 3C warehousing company and a large simulated problem were studied to examine the proposed method. In their paper a procedure was proposed to assign customers to vehicles and calculate total transportation time that for optimizing this procedure a TS algorithm was used. For generating initial solution they considered two methods about shortest distance search (SD) and clockwise search (CW). Balseiro, Loiseau, and Ramonet (2011) considered time dependent vehicle routing problem with time windows. Also they suggested an ant colony system algorithm hybridized with insertion heuristics.

In recent years, much attention has been paid to a decrease in environmental emissions and consumption of fossil fuels. In this regard, green logistic deals with different strategies of distribution by measuring the environmental effects, decrease in energy and fuel consumption and emissions (Sbihi & Eglese, 2007).

The emissions models are divided into two major macroscopic and microscopic models. The apparent specification of macroscopic models is that their data are obtained on the basis of the road measurements originated from the real world. The macroscopic models are also known as the emission models based on regression. The microscopic models are analytical models estimating the amount of emissions on the basis of the features of the engine and environment (Demir, Bektas, & Laporte, 2013). The following are among researches that have used the macroscopic models to calculate the amount of emissions: Kim, Janic, and Van Wee (2009) studied fright transport costs and CO_2 emissions. They related CO_2 emissions to speed and distance traveled. Maden, Eglese, and Black (2010) considered time varying speeds to planning routes; therefore they reported a 7% reduction of CO_2 emissions. Nevertheless their model emphasizes on minimizing total travel time more than reducing emissions. Figliozzi (2010) investigated the emissions vehicle routing problem (EVRP) with objective of minimization of emissions costs, which related to travel speed and distance traveled. Also three traffic classes were considered: uncongested, somewhat congested and congested traffic conditions. The author suggested that traveling in uncongested conditions cause reducing emissions on average, but sometimes opposite trend was observed. Jabali, Van Woensel, and de Kok (2012) referred to the congestion that a vehicle has to drive slowly so that emitting more CO_2 emission. They investigated travel times and CO_2 emissions in TDVRP by considering the effect of limiting vehicle speed. They used tabu search algorithm to solve their model. Their results indicated reduction of 11.2% in emission on average cause 14.8% increased in travel time.

The following are among researches, which have employed microscopic models to calculate the amount of emissions: Palmer (2007) studied vehicle routing problem with time windows considering CO_2 emissions. Results showed by minimizing CO_2 emission instead of travel time, reduction of 5% can be achieved. Urquhart, Hart, and Scott (2010) focused on the CO_2 savings, distance and required number of vehicles in VRPTW using evolutionary algorithms. They suggested that savings of about 10% depending on the problem instance and the ranking criterion used in the evolutionary algorithm can be achieved. Bektas and Laporte (2011) considered a pollution Routing Problem with minimization of the cost of carbon emissions, costs of drivers and fuel consumption but their model assumed a free- flow speed of at least 40 (km/h), which is contrary to congestion conditions. Demir, Bektas, and Laporte (2012) identified that emissions reduction can be achieved by varying speed over a network. They considered optimum speed that can vary due to speed limits and traffic congestion. Franceschetti, Honhon, Van Woensel, Bektaş, and Laporte (2013) suggested conditions that it is optimal to wait idly at a specified place to avoid congestion resulting in reducing the cost of emissions. Results showed 20% reduction in the cost of fuel, CO_2 emissions and driver cost.

There are also researches, which have not used the two approaches mentioned above; rather, they have employed innovative methods in order to make models. The following cases can be