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A new cut-and-solve and cutting plane combined approach for the capacitated lane reservation problem ☆

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ABSTRACT

This paper investigates a capacitated lane reservation problem with residual capacity. The focus of the problem is to design time-guaranteed paths for a set of transportation tasks via lane reservation with respect to the residual capacity issue. The lane reservation can ensure the time-guaranteed travel but has negative impact on the normal traffic. Thus, the objective of the problem is to minimize the impact of such lane reservation by optimally selecting lanes in the network to be reserved. For this NP-hard problem, an exact approach based on the cut-and-solve and cutting plane methods is developed. New separation algorithms are proposed to find appropriate valid inequalities according to the characteristic of the problem to accelerate the optimal convergence of the resolution approach. Numerical computational results show that the developed approach is efficient as compared with state-of-the-art algorithms in the literature and the IP solver CPLEX.

1. Introduction

With the economic development, human's daily travel demand and industrial products' movement are increasing rapidly nowadays. Consequently, transportation planning and scheduling have drawn much attention and many transportation problems, such as vehicle routing problem (Azi, Gendreau, & Potvin, 2007; Pisinger & Ropke, 2007; Tasan & Gen, 2012), facility location problem (Farahani, Asgari, Heidari, Hosseininia, & Goh, 2012; Zhu, Chu, & Sun, 2010) and inventory-routing problem (Bard & Nananukul, 2009; Raa & Aghezzaf, 2009) haven been extensively studied over the past decades. However, a widespread problems, such as traffic accidents, energy waste and environment issues, arise from traffic congestion due to an increasing number of vehicles (Banister, 1996). Therefore, traffic managers think up different ways to achieve efficient transportation for solving these problems. The lane reservation strategy, to reserve lanes on some road segments (in some time periods) for only special road users, is a traffic management way that has been applied in real-life in recent years. For example, the exclusive bus lanes (XBLs) can provide public buses priority over other vehicles to pass through congestion regions so as to enhance the bus attractiveness (Smith & Hensher, 1998). Many bus rapid transit (BRT) systems based on XBLs have been developed during the past decades around the world (Falbel, Rodriguez, Levinson, Younger, & Misiewicz, 2006; Levinson, Zimmerman, Clinger, & Rutherford, 2002). Moreover, temporary lane reservation on an existing network as a flexible and economic option can adapt rapidly to special situations, such as sport events (Black, 2004) and emergencies evacuation (Cova & Johnson, 2003).

The major advantage of the lane reservation is to provide a relatively congestion-free environment for the special vehicles on them. And time-guaranteed transportation tasks can usually be ensured. However, due to the disallowed use of reserved lanes by general-purpose vehicles, adjacent non-reserved lanes may be more congested and negative impact such as increase of travel time on them may be caused. Since the lane reservation strategy is becoming an increasing used transportation management way, it is necessary to well investigate it so as to minimize its impact on normal traffic. It is worthwhile to note that in the literature there are few quantitative studies on the optimal decision of which lanes on the road segments should be reserved or not. Wu, Chu, Chu, and Wu (2009) firstly formulated a mathematical model to study a lane reservation problem (LRP). The LRP is aimed to ensure time-guaranteed transportation tasks via optimally selecting lanes to be reserved during great sport events, with the objective of minimizing the impact of such lane reservation. A heuristic is proposed

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to obtain near-optimal solutions. Wu and Wu (2010) then proposed a metaheuristic algorithm based on tabu search to obtain better solutions for LRP. Wu, Che, and Chu (2013) proposed a quantum evolution based algorithm to solve large sized LRP with acceptable computational time, as compared with the IP solver CPLEX. Moreover, some new extended LRPs are studied and solved by exact algorithms based on a cut-and-solve method. Fang, Chu, Mammar, and Che (2011) and Fang, Mammar, Chu, and Che (2011) followed the pioneer work of Wu et al. (2009) and studied some extended LRPs that were proved NP-hard, then they extended the work for intelligent transportation system and automated truck freight transportation (Fang, Chu, Mammar, & Zhou, 2012; Fang, Chu, Mammar, & Che, 2013), respectively. To well apply the lane reservation strategy to different realistic scenarios, Fang, Chu, Mammar, and Che (2012, 2013) respectively proposed two new different models to study the dynamic lane reservation problem (DLRP), in which dynamic link travel times were introduced instead of constant link travel times in the previous papers. Recently, Fang, Chu, Mammar, and Che (2014) proposed a cut-and-solve based approach to solve the DLRP. Besides the papers above, Zhou, Chu, Che, and Zhou (2013) investigated an LRP for hazardous material transportation with considering transport risk. They formulated the problem as a multiobjective integer programming model and proposed a resolution approach based on the ϵ-constraint method and fuzzy logic-based method.

This paper focuses on the capacitated lane reservation problem (CLRP) considering the residual capacity issue, which was only studied in Fang, Mammar, et al. (2011) and Fang, Chu, Mammar, and Zhou (2012). The CLRP is to make an optimal selection of lanes from an existing transportation network to be reserved and design a path for each special transportation task and given source–destination pair. Due to the exclusive right to use the reserved lanes, the vehicles of the special tasks can avoid being trapped in traffic congestion and the travel duration can be guaranteed. However, such lane reservation will cause the adjacent lanes more congested and general-purpose vehicles on them take more travel time. Then the objective of the CLRP is to minimize the total negative traffic impact of such lane reservation. In the CLRP, the residual capacity issue is considered. The residual capacity of a road segment (i,j) is defined as the capacity that can be used for the special transportation tasks on road (i,j) without lane reservation. For example, suppose that the residual capacity of a road (i_1,j_1) without lane reservation is 20 vehicles per unit time (denote by veh/u for short), and the vehicle flow of tasks A and B are 6 veh/u and 10 veh/u, respectively. Then the vehicles of both tasks A and B can pass road (i_1,j_1) without reserving any lane on it. If the residual capacity of another road (i_2,j_2) without lane reservation is 8 veh/u, then only the vehicles of task A can pass it because there is not enough residual capacity for task B to be used. However, in this case, a lane on (i_2,j_2) can be reserved for the only use of task B, as well as task A and other special tasks if necessary. It can be seen that the residual capacity issue involve the residual capacity of a road and the vehicle flow of the special tasks, which distinguishes the CLRP from the LRP and DLRP. It requires that the total vehicle flow of the tasks moving on a road without reserved lanes should not exceed its residual capacity. It is natural to consider the residual capacity issue for a transportation problem in realistic traffic situation. Although the CLRP was studied in Fang, Mammar, et al. (2011) and Fang, Chu, Mammar, and Zhou (2012), it becomes difficult to solve large sized problem and the computational time increases exponentially. It is necessary to resort to more efficient resolution approaches by analyzing the characteristics of the problem. The main contribution of this paper is the development of a new exact approach which is based on the cut-and-solve and cutting plane methods. New separation algorithms for the cutting plane method are proposed to find appropriate valid inequalities according to the characteristic of the problem so as to accelerate the optimal convergence of the resolution approach.

The rest of the paper is organized as follows. Section 2 describes the problem and presents the mathematical model. Section 3 develops the resolution approach, which is based on the cut-and-solve and cutting plane methods. Section 4 reports the computational results of numerical experiments. Finally, Section 5 concludes the paper and discusses some future work.

2. Problem description

In this section, the CLRP is formulated as an integer linear programming model. The CLRP is defined on a transportation network that can be represented by a directed graph $G = (N;A)$ with a set N of nodes and a set A of directed arcs. A node can be viewed as a road intersection and an arc can be viewed as a road link in the network.

To formulate the problem, the CLRP is described as follows. Given a set of tasks and corresponding source–destination (SD) node pairs, the CLRP is to select some lanes to be reserved in the network and design a path for each transportation task to guarantee that it can be completed within its prescribed travel duration and the total flow of the tasks moving on a link cannot exceed its residual capacity. The lane reservation is intend to provide a congestion-free travel environment for the special tasks. However, it has impact on the normal traffic due to the disallowed use of reserved lanes by other general-purpose vehicles. The objective of the problem is to minimize the total impact of all reserved lanes.

As stated in Fang, Chu, Mammar, and Zhou (2012), some assumptions are made to facilitate the formulation of the problem as follows: (1), there is at most one reserved lane on each road; (2), the capacity of a reserved lane which can be used by the special tasks is assumed large enough because it can be used only by the special tasks and can be shared by them; (3), the residual capacity issue is only considered for the links without reserved lanes as the case in Fang, Chu, Mammar, and Zhou (2012). The notations used to formulate the CLRP is defined as follows:

Sets and parameters

- A: set of directed arcs $(i,j), i \neq j \in N$
- K: set of transportation tasks, $k \in K$
- N: set of nodes
- a_{ij}: traffic impact caused by reserving a lane of arc $(i,j) \in A$
- c_{ij}: residual capacity on arc $(i,j) \in A$ without lane reservation
- d_k: destination node of task $k \in K$
- f_k: vehicle flow of task $k \in K$
- p_k: prescribed travel duration to complete task $k \in K$
- s_k: source node of task $k \in K$
- τ_{ij}: travel time on a reserved lane of arc $(i,j) \in A$
- τ'_{ij}: travel time on a non-reserved lane of arc $(i,j) \in A$

Decision variables

- x_{kij} $x_{kij} = 1$, if task k passes a reserved lane on arc (i,j); and otherwise $x_{kij} = 0, \forall k \in K, (i,j) \in A$
- y_{kij} $y_{kij} = 1$, if task k passes a non-reserved lane on arc (i,j); and otherwise $y_{kij} = 0, \forall k \in K, \forall (i,j) \in A$
- z_{ij} $z_{ij} = 1$, if there is a reserved lane on arc (i,j); and otherwise $z_{ij} = 0, \forall (i,j) \in A$

With the assumptions and notations given above, the CLRP can be formulated as the following integer linear programming model (Fang, Chu, Mammar, & Zhou, 2012).

$$P_c: \quad \min \sum_{(i,j)\in A} a_{ij} z_{ij} \tag{1}$$

$$\text{s.t.} \quad \sum_{i:(s_k,i)\in A} \left(x_{ks_ki} + y_{ks_ki} \right) = 1, \qquad \forall k \in K, \tag{2}$$