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Rental bike location and allocation under stochastic demands

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ABSTRACT

In this research, we develop four planning models for leisure-oriented public bicycle rental systems under deterministic and stochastic demands, respectively. Time-space network models are employed to determine the locations of bike rental stations, bike fleet allocation and bike routing. These models are formulated as mixed integer programs that are characterized as NP-hard. While the two deterministic models can be solved directly using CPLEX, a threshold-accepting-based heuristic is developed to efficiently solve the stochastic models. Finally, numerical tests using operating data from the New Taipei City Public Bike program are performed to evaluate the models and the solution algorithm. The test results show that the proposed models and solution algorithm are useful for practices.

1. Introduction

Growing concerns over climate change and global energy security have led to an explosive interest in sustainable transportation modes such as the sharing of public bicycles and bicycle rentals. Public bicycle systems are not only viewed as an innovative inner-area transportation mode that can meet many user needs and be integrated with other public transit systems, but also as part of an ambitious program to cut traffic, reduce pollution, and enhance the area's image as a greener and quieter pace with a better way of life. The purpose of this research is to formulate a bicycle rental station location and bike redistribution model for leisure-oriented public bicycle rental systems where uncertain demand and unbalanced flows exist. The key design decisions considered are: the location of the public bicycle rental stations, the bicycle inventory levels at each rental station in each period, and how the available (un-rented) bicycles should be redistributed to replenish the inventory pool of bicycles available for rent at each rental station. The planning decisions are made as a result of taking into consideration the fixed costs of opened bike stations, the fixed costs of bicycle investment, the operating costs of running the system and the service levels (measured by unmet demand in each period). The number of opened rental station locations is assumed to be known and the travel demands of each pickup/drop-off pair are assumed to vary with time. The major concerns in this model are long-term investment decisions regarding the location of the bicycle rental stations, the size of the bicycle fleet and operational decisions regarding the redistribution of bicycles within a planning horizon.

Traditional bicycle rental programs are a most common method of making bicycles available for tourists in recreational areas. Unlike public bicycle sharing systems aimed at commuters in dense urban areas, traditional leisure-oriented bicycle rental programs are aimed at recreational riders in recreational areas. The leisure-oriented bicycle rental programs differ from the public bicycle sharing systems in several ways. The bicycle rental programs are normally operated by for-profit private businesses. Riders typically rent bikes for longer trips ranging from an hour to several days. Bikes are checked out and returned at a single staffed bike rental station (not allowing for one-way trips). However, not allowing for one-way trips may discourage a leisure bicycle rider from sightseeing. Tourists may wish to ride a bike to an attraction point but hike, drive or shuttle back. A bike rental program that does not allow for a one-way trip will discourage tourists from using the bikes. To make bikes more convenient, comfortable, and attractive for tourists visiting a recreational area, it is important to combine the concept of public bicycle sharing systems – allowing for one-way trips. Allowing for one-way trips requires establishing a bike rental system with more bike rental stations at more convenient locations.

For a leisure-oriented bicycle rental system that combines the concept of public bicycle sharing (for simplicity, we refer to it as a public bicycle rental system), it is crucial for the success of the system that users find bike rental stations in convenient locations and in sufficient numbers. The system needs sufficient stations for

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users to pick up a bicycle close to their origin and to drop it off close to their destination. The bike stations should not be located too far from important traffic origins and destinations (lodgings, parking lots, public transit stations, trail heads, or sightseeing points). The larger the number of bike rental stations, the more easily users can find bikes close to their origins/destinations. However, the local government (or the recreational area managers) may not have enough funding to open all the required bicycle stations because of budget limitations. Therefore, in this study we assume that the number of opened bike rental stations is known and fixed to reflect the budget constraint.

On the other hand, it is also important for the success of the system that the system guarantee the availability of a bicycle. Each rental station must carry enough bicycles to increase the possibility that each user can find a bicycle when needed. Existing systems show that users feel frustrated when they cannot find a bicycle when they need one. The availability of bicycles is directly related to the number of bicycles invested in the system. The larger the number of the bicycles, the greater the possibility that users can find a bicycle when they need one. Determining the optimal number of bicycles requires a trade-off between the ownership costs of the bicycles and the penalty costs associated with not meeting some demands. In addition, serving one-way-trip demands results in the relocation of bicycles. Existing systems show that pick-ups and drop-offs by users over the planning horizon (a week in this study) often lead to an unequal distribution of bicycles throughout the system. In this case, a re-distribution of un-rented bicycles over the system from the rental stations at which they become idle and can be reused is required to enhance the availability of the bicycles. Thus, the bicycle pool, which is available for rent at each rental station at any given time, depends on the bicycle redistribution strategy.

Thus the optimal planning of a public bicycle rental system requires an integrated view of the strategic decisions regarding the bicycle rental stations, bicycle stock investments and operational decisions on how to redistribute bicycle stocks between rental stations. The purpose of this study is to create a formal model that provides such an integrated view. Based on our review of the related literature, we have not found any studies that address the network design of leisure-oriented public bicycle rental systems incorporated with operational decisions regarding bike redistribution. This study therefore develops a mathematical model for the strategic network design of a public bicycle rental system. This has so far not been proposed in the literature.

Public bicycle sharing systems are aimed at commuters in dense urban areas; by contrast, public bicycle rental systems are aimed at recreational riders in recreational areas. Although both systems can bring great benefits to the area and the users, most of the studies focus on bicycle sharing systems only. Studies related to bicycle sharing in the literature include the promotion of policy and safety issues (Aultman-Hall & Kaltenecker, 1999; Martens, 2007), the history and development of public bicycle systems (DeMaio, 2009; Shaheen, Guzman, & Zhang, 2010), and the analysis of bicycle temporal and geographical usage patterns (Kaltenbrunner, Meza, Grivolla, Codina, & Banchs, 2010). Lin and Yang (2011) addressed the network and facility location design problem for public bicycle sharing systems from the perspective of strategic planning, taking into consideration user travel costs, system investment as well as coverage quality. Due to the nature of low user demands, Lin, Yang, and Chang (2013) took into further consideration the bicycle stocks at each bicycle terminal and developed a solution procedure for the problem. Past studies related to the distribution of shared bicycles include Nair and Miller-Hooks (2011), Sayarshad, Tavassoli, and Zhao (2012), Lu (2016), Raviv, Tzur, and Forma (2013), Shu, Chou, Liu, Teo, and Wang (2013), Fricker and Gast (2014), Ho and Szeto (2014), and Forma, Raviv, and Tzur (2015).

In the design and operation of transportation service networks, there are three important questions of interest to answer: the number of facilities and their locations, how many vehicles there should be in the fleet (the fleet sizing decision) and how the empty vehicles should be redistributed elsewhere to provide service (the vehicle allocation decision). To ensure that the transportation network can effectively handle the traffic through its facilities given the uncertain demand, each open facility location needs to carry enough vehicle (or product) inventories to ensure that the desired service level is maintained while determining the optimal facility locations. Related studies in strategic logistics systems design include those by Cole (1995), Nozick and Turnquist (1998, 2000, 2001), Daskin, Coullard, and Shen (2002), Shen, Coullard, and Daskin (2003), Miranda and Garrido (2004), Shu, Teo, and Shen (2005), and Lin, Nozick, and Turnquist (2006). In addition, related studies in strategic public bicycle sharing system design include Lin and Yang (2011) and Lin et al. (2013).

The fleet sizing and vehicle allocation decisions are highly interrelated. The proposed public bicycle distribution system problem can be viewed as a stochastic dynamic fleet sizing and vehicle allocation problem. Therefore, we will briefly review the previous studies in this field. Some studies focus on dynamic vehicle allocation problems (Cheung & Powell, 1996; Frantzeskakis & Powell, 1990; Hall, 1999; Jordan & Turnquist, 1983; Powell, 1987). For a comprehensive review, please refer to Powell, Carvalho, Godfrey, and Simao (1995). While some studies focus on the fleet sizing problems (Golden, Assad, Levy, & Gheysens, 1984; Imai & Rivera, 2001; Salhi & Rand, 1993; Turnquist & Jordan, 1986), only a few studies, however, jointly consider the fleet sizing and vehicle allocation problem. Beaujon and Turnquist (1991) described a non-linear network optimization model for fleet sizing and vehicle allocation in railroad operations where uncertain demand and travel time exist. Du and Hall (1997) applied inventory and queuing theory to determine the fleet size and to redistribute empty equipment in a hub-and-spoke system. Köchel, Kunze, and Nieländer (2003) combined simulation with genetic algorithms to solve the problem. Song and Earl (2008) determined the fleet size and vehicle allocation decisions analytically for a two-depot system. Dong and Song (2009) considered joint fleet sizing and empty containers in liner shipping systems. Li and Tao (2010) developed a model to determine the optimal fleet size and vehicle transfer policy for a car rental company. A time-space network flow approach has been popularly employed to solve the joint fleet sizing and fleet allocation problem. Related studies include Yan, Wang, and Wu (2012), Sayarshad et al. (2012), Lu (2016), Yan, Lin, and Chen (2014), and Yan, Chu, Hsiao, and Huang (2015). A notable study that has attempted to apply the time-space network flow approach to integrate the location of strategic depots with the distribution of operational vehicles is that by Correia and Antunes (2012). However, to the best of our knowledge, there is no study that addresses the integration of strategic location decisions with operational bicycle distribution decisions for public bicycle rental systems. This has encouraged us to carry out this study.

The rest of this paper is organized as follows. In Section 2, we introduce the models. In Section 3, the solution algorithms are developed. In Section 4, numerical tests are performed. Finally, we conclude in Section 5.

2. Modeling approach

In this section, we discuss our network structure and the mathematical formulation for determining the best location and size of rental stations under stochastic demands. A time-space network model is employed to denote the locations of rental stations, as well as the bike fleet allocation and bike routing. Based on the