Transportation Research Part D 65 (2018) 438–457

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Static green repositioning in bike sharing systems with broken bikes

Yue Wang, W.Y. Szeto*

Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
The University of Hong Kong, Shenzhen Institute of Research and Innovation, Shenzhen, China

ABSTRACT

Bike-Sharing Systems (BSSs) and environmental concerns have been receiving increasing popularity in transportation operations. In BSSs, the distribution of bike demand often mismatches with bike supply and there are broken bikes. Usable bikes are needed to redistribute between stations to satisfy the demand and all broken bikes need to be carried back to the depot for repairs. Both types of bikes are often transported by fossil-fueled vehicles but using these vehicles for the operation may damage the environmental creditability of BSSs. A methodology is needed to mitigate the environmental impact of this operation.

This study aims to propose a methodology to reposition both good and broken bikes in a bike-sharing network in order to achieve a perfect balance between bike demand and supply at each station and make sure that all broken bikes are moved back to the depot. The objective of this repositioning operation is to minimize the total CO_2 emissions of all repositioning vehicles. A Mixed Integer Linear Program (MILP) model is presented to formulate the problem mentioned above and a commercial solver is used to solve it for small applications. Using example applications, problem characteristics and the factors that affect the CO_2 emissions are discussed. The results indicate that allowing multiple visits can reduce vehicle emissions. Moreover, when the percentage of broken bikes in the system increases, the CO_2 emissions increase. Furthermore, if there is a tolerance for meeting the demand target, when this tolerance increases, the CO_2 emissions decrease. In addition, when the distance of a link in an optimal route increases, the resultant emissions may remain unchanged. Besides, when the vehicle capacity increases, the CO_2 emissions decrease. The real world instances of Citybike Vienna are used to compare emission and distance minimization solutions and investigate the runtime complexity of the proposed model. The results demonstrate that a shorter distance may not necessarily lead to lower emissions. The results also show that as the number of vehicles increases, the total emissions and runtime increase. A clustering method based on the nearest neighbor heuristic together with a commercial solver is used to solve a large real-world instance. This result confirms the possibility of using the clustering approach to reduce the running time for large network instances with multiple vehicles.

1. Introduction

Cycling is an environment-friendly and healthy transport mode. It has received increasing attention in recent years. To encourage cycling, many cities have introduced public BSSs such as Velib in Paris, Villo in Brussels, Citi-Bike in New York City, and Santander Cycles in London. As of 16 September 2018, public BSSs were available in about 1780 cities (Meddin and DeMaio, 2018). In a classical BSS, registered users can rent a bike at a bike station, ride the bike, and return it to any station. Due to the asymmetrical distribution of bike flows, the deficient supply of both lockers and bikes often occur in these systems. The former situation leads to extra travel distances for some bike users to find available lockers while the latter one causes unsatisfied demand. To cater to the demands for both lockers and bikes, bike repositioning is essential.

In general, there are two types of bike repositioning: static and dynamic. Static bike repositioning (e.g., Li et al., 2016; Cruz et al., 2017; Ho and Szeto, 2017; Schuijbroek et al., 2017) usually focuses on the nighttime repositioning because, during that time, system

* Corresponding author.
E-mail addresses: yuewhku@hku.hk (Y. Wang), ceszeto@hku.hk (W.Y. Szeto).

https://doi.org/10.1016/j.trd.2018.09.016

usage and the congestion impact can be ignored. The target is to meet the demands in the next morning. Dynamic bike repositioning concerns with the daytime situation when the system is in high usage and the demand of each station will change during the repositioning period (e.g., Caggiani and Ottomanelli, 2012; Contardo et al., 2012; Kloimüllner et al., 2014; Ghosh et al., 2017; Caggiani et al., 2018; Shui and Szeto, 2018). Both types of repositioning can be found in practice.

Both types of bike repositioning are commonly performed by fossil-fueled vehicles. Using these vehicles for the operation may damage the environmental creditability of BSSs (Wiersma, 2010) because these vehicles emit pollutants and greenhouse gases. Other than the unmet demands for both lockers and bikes, environmental objectives should be duly considered in the repositioning operation. However, in the literature, except Shui and Szeto (2018), environmental objectives are rarely considered in bike repositioning studies.

Another important consideration is broken bikes. Broken bikes are regularly found in BSSs (Kaspi et al., 2016, 2017). The presence of broken bikes in the systems means not only a waste of resources but also causes user dissatisfaction. Broken bikes occupy lockers and reduce the parking spaces for users to return bikes. Moreover, broken bikes cannot be used to satisfy bike users' demand. In addition, broken bikes are always transported back to depots for repairs and use up some of the capacity of repositioning vehicles for usable bikes, making the repositioning of usable bikes less effective. It is therefore important to consider the repositioning of both usable and broken bikes simultaneously. However, no studies, except Alvarez-Valdes et al. (2016), considered this type of repositioning. Moreover, to the best of our knowledge, no studies simultaneously considered both broken bikes and an environmental objective at the time of this writing.

In this paper, we study a static green Bike Repositioning Problem (BRP) in the presence of broken bikes. This problem determines the route and the corresponding loading or unloading instructions for each repositioning vehicle to balance a BSS with broken bikes. The objective is to minimize the total CO_2 emissions of all the vehicles. An MILP model is proposed to formulate the problem, which is then solved using a commercial solver. Numerical experiments are carried out on small example networks to clearly illustrate the problem characteristics and investigate the factors that affect the vehicle emissions. The real world instances of Citybike Vienna are also used to compare emission and distance minimization solutions and investigate the runtime complexity of the proposed model. A clustering method based on the nearest neighbor heuristic and a commercial solver is used to solve the large real-world instance with 90 stations. The computational time required and solution quality obtained by this method are also demonstrated.

The contributions of this paper lie on the following:

1. to introduce a new and practical BRP—a static green BRP with broken bikes;
2. to present a model to formulate the problem, and;
3. to illustrate the problem properties and point out critical factors that affect vehicle emissions.

The remainder of the paper is organized as follows. Section 2 reviews the literature on BRPs and fuel consumption and CO_2 emission modeling. Section 3 presents a mathematical model for the studied problem. Section 4 describes the numerical studies and discusses the results. Section 5 discusses different approaches to solving large-scale BRPs. Finally, Section 6 concludes this paper and gives future research directions.

2. Literature review

In this section, we will first briefly introduce the objectives used in BRPs. Moreover, we will describe how current research addresses the fuel consumption and CO_2 emissions, especially the factors considered in mathematical models. Afterward, we will discuss the literature about broken bikes and the modeling assumptions in BRPs. Finally, we will depict the existing formulation approaches to BRPs.

2.1. Objective functions in BRPs

User satisfaction has been commonly considered as the primary objective in BRPs. It is mainly measured by the number of due date violations (e.g., Brinkmann et al., 2015), unsatisfied demand including both docks and bikes (e.g., Contardo et al., 2012), penalty costs (e.g., Ho and Szeto, 2014), and so on. Repositioning costs are also considered in most studies, such as travel costs including travel time or distance (e.g., Benchimol et al., 2011; Angeloudis et al., 2014; Dell'Amico et al., 2014, 2016; Cruz et al., 2017), maximum tour distance (e.g., Schuijbroek et al., 2017), total travel and handling costs (e.g., Erdoğan et al., 2014), total redistribution cost (e.g., Nair et al., 2013), and total relocation and lost user costs (e.g., Caggiani and Ottomanelli, 2012). Besides single objective optimization, some studies considered the weighted sum of various measures, including the cost of unsatisfied demand and the coefficient of variations of the duration of all routes (e.g, Alvarez-Valdes et al., 2016), the total absolute deviation from the target number of bikes, the total number of loading/unloading quantities, and the overall time required for all routes (e.g., Di Gaspero et al., 2013, 2016; Raidl et al., 2013; Rainer-Harbach et al., 2013, 2015), total travel time and penalty cost (e.g., Ho and Szeto, 2017), total vehicle travel cost and the expected user dissatisfaction in the system (e.g., Zhang et al., 2017), the total number of unsatisfied customers and the vehicle's total operational time (e.g., Szeto et al., 2016), and travel, imbalance, substitution, and occupancy costs (e.g., Li et al., 2016). However, existing objectives have rarely considered environmental objectives. Indeed, repositioning operations are commonly carried out by fossil-fueled vehicles, which emit pollutants and greenhouse gases. These emissions can damage the environmental creditability of BSSs (Wiersma, 2010). It is therefore important to capture environmental objectives in BRPs. To the best of our knowledge, Shui and Szeto (2018) were the pioneers to capture an environmental objective in