Transportation Research Part B 93 (2016) 268–299

Contents lists available at ScienceDirect

Transportation Research Part B

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

Joint design of parking capacities and fleet size for one-way station-based carsharing systems with road congestion constraints

Lu Hu, Yang Liu*

Department of Industrial and Systems Engineering, National University of Singapore, 1 Engineering Drive 2, 117576, Singapore

ARTICLE INFO

Article history:
Available online 3 August 2016

Keywords:
One-way carsharing
Fleet size
Reservation policy
Parking capacity
Mixed queueing network
MVA algorithm

ABSTRACT

This paper formulates one-way station-based carsharing systems as a mixed queuing network model and proposes a profit-maximization model for the joint design of fleet size and station capacities. We explicitly model the road congestion by formulating each route as a queue where the travel time is an increasing function of the state. The booking process is also modeled in the rental station queue so that the efficiency loss caused by the reservation policy can be captured. The mixed queuing network falls into Baskett, Chandy, Muntz and Palacios (BCMP) networks with unique product-form equilibrium distribution. We derive the asymptotic behavior as the parking capacities and fleet size grows, and show that the performance of carsharing systems will be proportionally bounded by that of the bottleneck route. The exact mean value analysis (MVA) algorithm and the approximate Schweitzer-Bard mean value analysis (SB-MVA) algorithm are extended here to solve networks with different sizes. The numerical experiments reveal some interesting findings: (1) The higher customer service rate (the smaller pick-up time window) will generate the optimal design with lower parking capacities and lower fleet size; (2) Neglecting the efficiency loss due to reservation will lead to an overestimate of the profit and other system performances as well; and (3) Given different levels of congestion on the existing road network (the non-shared car traffic), the net revenue is maximized when the existing traffic congestion is moderate.

1. Introduction

Carsharing has been recognized as a sustainable and efficient alternative that can improve the utilization of land and energy. It can let users enjoy the convenience and the flexibility of sharing cars without suffering the high cost of owning and maintaining a car in a city. It also can potentially enhance the connectivity to suburb areas with no access to public transport, and thus can potentially improve the accessibility and mobility of an entire urban transportation system. At the same time, from the social perspective, its social and environmental benefits include (1) reducing the overall car ownerships, (2) saving parking space and improving utilization of land resources, (3) relieving congestion, and (4) reducing the overall vehicle emissions. In recent years, carsharing has been progressively developed around the world. As of 2014, global car sharing market has reached an estimate of 4.94 million memberships over 92,200 shared cars (Frost and Sullivan, 2014).

* Corresponding author.
E-mail address: iseliuy@nus.edu.sg (Y. Liu).

http://dx.doi.org/10.1016/j.trb.2016.07.021
0191-2615/

Moreover, in the long run, carsharing may influence travel behavior and commuting habits, and reduce the total number of trips and the total travel distance by automobile (Zhao, 2010). Hereafter, "car" or "vehicle" all refer to the shared car or the shared vehicle in the system unless otherwise specified.

The carsharing industry involves decision-making of multiple stakeholders, i.e., operators, public sectors and commuters. The for-profit operators typically aim to expand the market share in the short run and maximize the profits in the long run. The primary forms of the carsharing models are round-trip station-based trip (cars are returned to the same station where they were picked up, e.g., the early operation model of Zipcar), one-way station-based trip (cars can be returned to any station, e.g., the one-way electric vehicle sharing system in Paris by Autolib'), one-way free-floating trip (cars can be returned to any legal on-street parking space, e.g., Car2Go at Seattle), and peer-to-peer model (participating car owners instead of the operators make their private vehicles available for participating renters, e.g., iCarsclub at Singapore).

While practitioners in the carsharing industry have been dealing with these challenges, with various levels of success, there are still many exciting and difficult scientific questions at the design and operation levels, that need further investigation.

First, the fundamental design problem is to determine the proper locations of the stations, the optimal parking capacity and the optimal fleet size. Those problems have been extensively studied in the literature in the vehicle rental problems (Beaujon and Turnquist, 1991; Savin et al., 2005; Song and Earl, 2008, to name a few). For one-way station-based carsharing system, de Almeida Correia and Antunes (2012) develop a mixed-integer optimization approach to determine the best number, location and capacities of stations. Their model accounts for vehicle stock imbalances by relocating vehicles at the end of the day. George and Xia (2011) use a closed queuing network model to tackle the fleet sizing problem with the objective of the profit maximization. Waserhole et al. (2012) present a fluid approximation of a closed queueing network model to study the one-way vehicle sharing optimization problems. Barrios and Doig Godier (2014) adopt an agent-based model to optimize the fleet size, and the goal is to maximize the number of trip by incorporating the vehicle redistributions. Boyacıet al. (2015) develop a multi-objective mixed integer linear programming for the design of an electric one-way carsharing system which maximizes the net revenue for both the operator and the users. They determine the fleet size, and the number and location of the required stations by considering the dynamic relocation process. Nourinejad et al. (2015) use two integrated multi-traveling salesman models to optimize vehicle relocation and staff rebalancing simultaneously which minimizes the total cost including the amortized fleet cost, amortized salary of staff members, relocation cost, and rebalancing cost. Li et al. (2016) develop a continuum approximation model to determine the optimal station locations and fleet size for a one-way electrical vehicle sharing system. Their model is aimed at minimizing the comprehensive system cost including vehicle balancing by considering daily vehicle operations. In the bike-sharing system, the rented bicycle can be returned to any public bike station, which is similar to the one-way station-based carsharing system. Hence, we also review some relevant literature. Lin and Yang (2011) address the combined problem of the optimal locations and bicycle paths network in a city in order to minimize the total travel costs of all customers. Nair et al. (2013) quantitatively study, the bike sharing system in Pairs, the Vélib system's interdependency with its public transit system, and the flow imbalances between stations. Shu et al. (2013) use the proportional network flow model to study optimal locations of bikesharing docks and the optimal bike allocations at each dock. They show a linear integer model can approximate the stochastic system well. Chow and Sayarshad (2014) propose a new framework using time-expanded network and multiobjective optimization to design transportation networks in the existing networks. And it is applied to the joint design of station location and parking capacity for the bikesharing system in the existing transit system. The goal is to minimize the costs of bikesharing and transit networks including user travel and schedule delay costs and bike relocation costs. Fricker and Gast (2014) study the optimal fleet sizing of the bikesharing system given identical station capacities. They show that the optimal fleet size is approximately half of the station capacity.

Next, optimizing the system operations is another key theme in studying carsharing. When the flexibility of the one-way trip is allowed, the imbalance problem becomes more severe, mainly due to the fact that travel demand is generally concentrated in one direction rather than both ways. So that some oversupplied stations are accumulating excessive inbound vehicles and some stations have vehicle shortage (incoming demand cannot be satisfied). Therefore, it is difficult but necessary to balance the system continuously across time and space dimension in order to match the demand and the supply for both cars and parking. Fan et al. (2008) formulate the profit-maximization problem which incorporates the system uncertainty and solves the vehicle allocation strategy. Kek et al. (2009) use the time-expanded network with static demand and formulate it as a mixed-integer program to generate manpower schedule and vehicle allocation plan. Nair and Miller Hooks (2011) propose a stochastic mixed-integer program which explicitly models a probabilistic distribution of demand and produces the least-cost redistribution plan. Di Febbraro et al. (2012) propose a user-based relocation method in a rolling horizon which provides greater flexibility to customers and reduces the number of staffs simultaneously, and thereby increases the operator's profit. Fan (2013) develop a stochastic linear programming model which solves the dynamic relocation problem in current stage by considering the probabilistic demand in future stage. For the free-floating carsharing system, Weikl and Bogenberger (2015) formulate an integrated model and examine the effectiveness of the detailed relocation plans in Munich. Forma et al. (2015) propose a heuristic-based method for solving the static large-size reposition problem which responds to the fluctuations in demand for bikes and lockers. de Chardon and Caruso (2015) propose the aggregate models to estimate the spatial and temporal distribution of bike-sharing trips using historical data. Spieser et al. (2016) use simulation, where the actual rental data of a free-floating carsharing system is embedded, to analyze the relationship among the key performance, fleet size, and rebalancing policies from the perspective of the fleet operator.