Transportation Research Part C 57 (2015) 206–223

Contents lists available at ScienceDirect

Transportation Research Part C

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

A practice-ready relocation model for free-floating carsharing systems with electric vehicles – Mesoscopic approach and field trial results

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A R T I C L E   I N F O

Article history:
Received 18 March 2015
Received in revised form 24 June 2015
Accepted 29 June 2015
Available online 9 July 2015

Keywords:
Carsharing
Vehicle imbalance
Relocation
Real world field test

A B S T R A C T

This paper introduces a relocation model for free-floating Carsharing (FFCS) systems with conventional and electric vehicles (EVs). In case of imbalances caused by one-way trips, the approach recommends profit maximizing vehicle relocations. Unlike existing approaches, two types of relocations are distinguished: inter zone relocations moving vehicles between defined macroscopic zones of the operating area and intra zone relocations moving vehicles within such zones. Relocations are combined with the unplugging and recharging of EVs and the refueling of conventional vehicles. In addition, remaining pure service trips are suggested. A historical data analysis and zone categorization module enables the calculation of target vehicle distributions. Unlike existing approaches, macroscopic optimization steps are supplemented by microscopic rule-based steps. This enables relocation recommendations on the individual vehicle level with the exact GPS coordinates of the relocation end positions. The approach is practice-ready with low computational times even for large-scale scenarios.

To assess the impact of relocations on the system's operation, the model is applied to a FFCS system in Munich, Germany within three real world field tests. Test three shows the highest degree of automation and represents the final version of the model. Its evaluation shows very promising results. Most importantly, the profit is increased by 5.8% and the sales per vehicle by up to 10%. The mean idle time per trip end is decreased by 4%.

1. Introduction

Carsharing (CS) systems contribute to solving problems in transportation, land use, environment and society (Shaheen et al., 2012). They offer an advantageous alternative to private vehicle ownership. During the last 30 years, CS systems have become innovative mobility concepts all over the world. CS membership rates are steeply rising. In Germany, more than 750.000 registered users had access to almost 14.000 CS vehicles in 2013 (Bundesverband CarSharing e. V., 2014). Originally, CS systems were station-based. A fleet of vehicles is distributed throughout a network of CS stations with different capacities. The CS operator owns or leases the vehicles. The CS members reserve the automobiles before using them at time-dependent and often distance-dependent fees (Shaheen et al., 2012). At the end of the trip, the user generally has to return the vehicle to its home station. This prevents stations from running out of vehicles or flowing over. However, some operators allow for one-way trips to other stations. Imbalances in vehicle stocks at stations are caused by the gravitational

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http://dx.doi.org/10.1016/j.trc.2015.06.024

effect due to vehicle stock tendencies of stations and the tide phenomena due to demand oscillations (Waserhole and Jost, 2013). For instance, Hondas Diracc system in Singapore already had to stop operation due to those phenomena (The Straits Times, 2008).

During the last decade, the station-based systems were supplemented by the new so-called "free-floating" or "flexible" CS systems (FFCS). Those systems allow trips to almost any parking spot within a defined operating area. The customer does not have to reserve in advance and is not bound to stations. The fee is time-dependent. Like for station-based one-way systems, one-way trips are likely to cause imbalances between vehicle supply and demand. The prediction of the system behavior is more complex as the customers access the vehicles spontaneously without reservation and do not specify their destinations in advance. Weikl and Bogenberger (2014) have proven that vehicle imbalances occur for FFCS systems. Data of a FFCS system in Munich, Germany was used exemplarily. Vehicles were missing in central zones of the operating area on Monday mornings as they conglomerated in southern zones during the weekends. The reason were different usage patterns on weekends and workdays. Another study showed for the same FFCS system, that the main trip purposes on Sundays are "driving home", "leisure activities" and "picking someone up". In contrast, on workdays shopping trips and trips to work dominate (Lenz and Bogenberger, 2014).

Firnkorn and Mueller (2011) highlighted that the goal of global megacities that citizens predominantly abstain from private vehicles requires a solution to the challenging logistic problems of FFCS systems. If serious vehicle imbalances cannot be avoided, they have to be eliminated by dynamically relocating vehicles from oversupplied to undersupplied regions.

1.1. Vehicle imbalance problem – state of the art and research gaps

1.1.1. Station-based vehicle sharing systems

In the past, the focus was on vehicle imbalances of station-based one-way vehicle sharing (VS) systems. Table 1 summarizes the most important studies. For a more comprehensive overview of existing literature on CS systems with the focus on demand modeling and the vehicle imbalance problem of one-way CS systems see Jorge and Correia (2013). Morency et al. (2011) stated that the degree, to which relocations are necessary in Bikesharing (BS) systems, is related to the stations' locations. The same assumptions apply for CS systems. Consequently, CS vehicle stock imbalances can be partly avoided or reduced by deploying the optimal fleet size, the optimal number of stations and their locations as well as the optimal station capacities. Some studies treating this topic are listed in the first part of Table 1. The focus is on how to avoid deviations between supply and demand by optimal system design rather than on how to eliminate existing imbalances during operation.

Other studies concentrated more intensely on relocation strategies for station-based one-way CS systems. Two different approaches were distinguished: operator-based relocation strategies with CS vehicle movements between stations conducted by the operator and user-based relocation strategies shifting this task to the CS users. The second part of Table 1 lists relevant papers. Operator-based approaches recommend vehicle relocations between stations to the operator. User-based strategies offer incentives to the customers to change their travel behaviors. For operator-based strategies, one question remains: how are the vehicle movements most efficiently conducted by a specific number of relocation workers? This is a complex many to many pickup and delivery problem. In the past, this aspect of the relocation problem of one-way CS systems was highlighted by some authors (see third part of Table 1).

The existing relocation algorithms for station-based systems are complex with high computational times. Mostly, aspects of the overall problem are treated without combining demand prediction, relocation algorithm and staff operation planning. Target vehicle distributions are mostly taken as given. Relocations are mostly conducted periodically at the end of the day. Some models assume a priori information on the users' destinations and reservations well in advance, which is not always given in reality.

1.1.2. Free-floating carsharing systems

For solving the relocation problem, FFCS systems could be transformed to station-based systems by defining artificial CS stations, e.g. by theoretically dividing the operating area into station-like zones. Transferring the existing relocation models for station-based systems to FFCS systems is however restricted, as the new systems have other dynamics resulting from spontaneous usage without reservation, without stations and without a priori information on the users' destinations.

First, the existing models for station-based systems mostly consider relocations at the end of the day. However, trips in FFCS systems are usually shorter and the number of trips per vehicle is higher. Imbalances might occur more often and relocations might have to be conducted dynamically throughout the whole day. This implies that future demand has to be known for smaller time steps than 24 h.

Second, the algorithms for the efficient execution of the proposed relocation movements are only partly transferable to FFCS systems. They act on a station basis. Mostly, a specific number of relocation workers get a list of stations to visit successively as well as the number of vehicles to move between stations. As the number of CS stations is limited, the problem size is manageable. In FFCS systems, each vehicle that has to be relocated possibly has a different origin and destination position. A single team of relocation workers thus has to visit much more different positions increasing the problem size. Moreover, the order execution algorithms for station-based BS systems are not suitable for FFCS systems as several bicycles can be moved altogether on a bicycle carrier. In FFCS systems, each vehicle has to be brought to its destination separately unless vehicles are connected with a tow-bar or build platoons.