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Optimization of Station-based Carsharing Networks: Increasing Sustainability through Heterogeneous Fleets and Emission Control

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Impact (ceteris paribus) of … on	**Number of stations**	**Number of vehicles**			**Profit**
		In total	**Electric**	**Petrol**	
Costs for stations ↑	→	→	→	→	↓
Costs for parking lots ↑	→	→	→	→	↓
Costs for electric vehicles ↑	→	→	↓	↑	↓
Costs for petrol vehicles ↑	→	→	↑	↓	↓
Demand ↑	↑	↑	↑	↑	↑
CO_2-emission limit ↓	→	→	↑	↓	↓
Price per kWh ↑	→	→	↓	↑	↓
Price per liter petrol ↑	→	→	↑	↓	↓
Max. distance ↑	↓	↓	↓	↓	↑

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Abstract

The positioning and dimensioning of carsharing stations have already been addressed in several optimization models applying homogeneous fleets. Yet, carsharing organizations increasingly apply mixed fleets of vehicles with different propulsion methods. We introduce a model, which permits a combination of differently powered vehicles and the option to include fleet emission constraints to satisfy customer expectations and governmental requirements. It supports decision makers in solving the challenge of fulfilling demands while maximizing profit. With an applicability check, the proposed model is evaluated. Extensive sensitivity analyses are presented and discussed indicating how a profitable operation of heterogeneous fleets can be established.

Keywords

Station-based Carsharing, Transportation, Urban Mobility, Network and Fleet Optimization, Sustainability.

1 Introduction and Motivation

A growing level of eco-consciousness in public as well as business sectors evokes a rethinking of car usage and personal vehicle ownership (Shaheen and Cohen, 2013). In this context, carsharing addresses both, the environmental and economic concerns of conventional vehicle usage (Alfian et al., 2014). This leads to reduced emissions and grants carsharing clients access to a fleet of relatively new and thus environmentally friendly vehicles on a pay as-needed basis (Shaheen et al., 2010). As carsharing profitability depends on demand, carsharing services are typically offered in urban areas where car ownership can (partly) be dispensed with. With an increasing percentage of the world population living in cities and a rapidly rising number of people using carsharing, new opportunities for carsharing organizations arise (Dedrick, 2010). Supported by technological progress and a variety of available optimization approaches, carsharing organizations are able to better plan their networks as well as their fleet sizes and offer simplified operational services at high service levels to their customers (Hayashi et al., 2014; Kaspi et al., 2014). The scope of literature dealing with the functionality of different carsharing concepts, the analyses of these concepts, and investigations of use and users is manifold. Introduced optimization models focus on diverse goals and support the creation or expansion of station-based carsharing networks. But even though potentially crucial to success, the implementation of a heterogeneous carsharing fleet has not yet been intensively researched on existing models. The option of installing a heterogeneous fleet is deemed important as it allows a carsharing organization to leverage the benefits of diverse propulsion methods and thus address a larger customer pool. While a pure electric fleet contributes towards environmental protection, it creates high costs for vehicle charging infrastructures and leads to idle times during charging cycles under present-day conditions (Speranza, 2018). While a combustion engine fleet allows for increased capacity utilization, this results in higher emissions. The positive effects of reduced emissions and reduced energy consumption can thus be reinforced by including alternatively powered vehicles in the carsharing fleet (Shaheen et al., 2013). In addition, many of these alternatively powered vehicles already meet the requirements of so far mostly voluntary environmental labelling programs, which in turn represent a beneficial marketing aspect for carsharing organizations (Millard-Ball et al., 2005).

Real-life application examples further support the concept of heterogeneity. Especially the combination of electric vehicles with petrol-powered vehicles is a growing mixture in today's carsharing fleets. Zipcar, the main provider in the U.S., already successfully applies a heterogeneous vehicle approach with vehicle type and propulsion method varying depending on the location of offer (Zipcar, 2020). Other providers follow suit and start to partially replace existing fleets with electric vehicles, e.g., ShareNow (ShareNow, 2020).

While increasing the flexibility and availability of vehicles, electric fleets require vehicle charging infrastructures. Consequently, the integration of electric vehicles makes round-trip carsharing (also called two-way) most feasible for a carsharing network. This means that vehicles have to be returned to their designated parking lot or, in the case of electric vehicles, their respective charging infrastructure. This is rather limited possible for one-way modes, in which vehicles can be driven between designated stations, as more charging infrastructure and relocation costs incur decreasing the profitability of a carsharing organization. Regarding free-floating carsharing, which allows a vehicle to be left at any allowed parking space within a designated area, these cost-effects are even higher. Based on the number of potential carsharing users, the three carsharing operation modes are typically established within different city sizes. As free-floating is usually operated in cities with at least 500.000 inhabitants, round-trip carsharing is also suitable for towns with more than 50.000 inhabitants as it is less cost-intense to install and no costs for relocation incur. A summary of the above is given in Table 1, which shows the specific characteristics of the carsharing modes.

Table 1: Advantages and disadvantages of different carsharing operation modes

	One-way	Round-trip	Free-floating
Network structure	Station-based; vehicle can be picked up and dropped off at any station	Station-based; vehicle needs to be returned to a designated station / parking lot	Vehicle can be picked up and dropped off at any allowed parking space in the area of operations
Advantages for the carsharing organization	• Relocation is predictable because of typically required pre-booking	• No relocation costs • Prevents crowded stations/areas • No operational management • Planning reliability (e.g., utilization, maintenance, cleaning)	• No station costs
Advantages for the customer	• Fixed location for vehicles • Pre-booking is limited possible • Cost reductions may be applied to support relocation • Spontaneous trips possible • Round trips possible	• Fixed location for vehicles • Pre-booking possible • Spontaneous trips possible • Predictable with regard to long-term scheduling	• Door-to-door service is possible • High flexibility
Disadvantages for the carsharing organization	• Station costs • Relocation costs (staff vs. user incentives) • Crowded/vacant stations	• Station costs • Loss of demand for door-to-door service	• Relocation costs (staff vs. user incentives) • Parking costs in some areas • Crowded/vacant areas
Disadvantages for the customer	• No vehicle available at nearest/preferred station • Preferred destination station may be occupied	• Lower flexibility than free- floating/one-way • Payment of idle times (e.g., for parking)	• No vehicle available in nearby area (limited availability) • No pre-booking possible • Search for parking lot
Typical field of application	• Cities up to metropolises	• Towns up to metropolises	• Large cities and metropolises
Implications regarding electromobility	• Unlimited suitability for pure electric fleet • Limited suitability for heterogeneous fleet → Limited availability of vehicle charging infrastructure → Relocation necessary	• Unlimited suitability	• Limited suitability → Ineffective and expensive → Relocations necessary for charging

With the goal of reducing the overall emissions of a carsharing fleet, while at the same time maintaining a customer friendly and yet profit maximizing approach, the above considerations favor a unified fleet deploying different propulsion methods, such as electric, hybrid, or combustion engine vehicles in a round-trip mode. Thus, the research questions of this paper is:

How can an optimization model for strategic and tactical station-based carsharing be designed to maximize profit while applying a heterogeneous fleet and obtaining a maximum CO_2-threshold?

The paper is structured as follows: work regarding carsharing networks and its optimization is described the following section 2. Section 3 introduces our optimization model and explains the underlying assumptions as well as the input parameters. Section 4 explains our approach towards dataset creation, provides benchmarks, and resulting evaluations and generalizations. We complete our article with conclusions and an outlook.

for electric vehicles, which require renewable energy not only for the charging process but also for the production of the vehicles. This represents a simplification of real life situations.
Due to the requirement of charging infrastructures for electric vehicles, a station-based round-trip carsharing approach is considered which takes into account all the advantages and disadvantages given in Table 1. One-way trips generate significantly more costs due to the requirement of additional charging infrastructures at each station as well as staff or user incentives for relocation. However, the implementation of a one-way option with higher prices to cover the additional costs could increase flexibility and attract additional users. This option may be limited to non-electric vehicles, as already offered by Zipcar (Zipcar, 2020).
Further improvements of the set optimization gap of 3% are possible with additional computing time. As our model addresses strategic and tactical planning, computing time is not a critical aspect. However, the set optimization gap used in our benchmarks may lead to small biases between the results.

5 Conclusions and Outlook

Carsharing organizations offer their services in an increasing number of cities worldwide. With a growing public environmental awareness, the number of carsharing users continues to rise rapidly and the aspect of sustainability becomes more and more important. As a consequence, the integration of vehicles with alternative propulsion methods such as electric vehicles into existing fleets depicts an ongoing trend in this business sector. To successfully integrate differently powered carsharing vehicles in a city, station locations, their sizes, and an optimal number of different types of vehicles have to be determined. Round-trip modes are especially advantageous as they can be used in almost any city regarding their requirements concerning population density.
We introduced a MILP to support the challenging task of network and fleet planning as well as optimization for heterogeneous fleets with the overall objective of profit maximization under consideration of ecological sustainability. We evaluated our model using the example of San Francisco. Our benchmarks reveal that the identification of realistic demand levels has a significant influence as to whether carsharing is profitable or not. They further show that slight adjustments in parameters can have a notable impact on how to optimally disburse the carsharing network of a heterogeneous fleet. In doing so, we contribute to station-based carsharing and its planning as well as its optimization. Further, we present a possibility to estimate the demand without having actual user data on hand. Although certain limitations have been identified, it was possible to verify the applicability and usefulness of the optimization model.
Benefit could be drawn from more detailed empirical evaluation in this field; as demand represents the most crucial factor to success, additional information regarding typical carsharer and support for the currently used aspects could further validate and enhance our approach. The optimization model itself could be refined by adding aspects not yet considered, such as the implementation of additional multi-mobility constraints, demand-related prices, or a one-way option including relocation procedures. We emphasize that the potential of including alternative propulsion methods in carsharing applications is considerable, as this approach serves to increase sustainability while maintaining profitable installation. In conjunction with further enhancements, our work can therefore contribute to supporting a cleaner environment and a greener future.

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