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The Potential of Flexible Reservations in a Car Sharing System With an Auction Scheme

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ABSTRACT In the last 20 years car sharing has been a growing trend in personal mobility. Multiple aspects of these systems have been already discussed: different forms of car sharing, user's preferences and behavior, or benefits estimation. Nevertheless, the management of these systems needs to be continuously improved to remain a competitive alternative. In this work, we propose a reservation scheme to manage rental reservations of a two-way station-based car sharing system. It allows the operator to better plan the necessary vehicles at each station, and encourages the drivers to make better use of the existing vehicles, by showing flexibility in the starting rental time. The reservation scheme is organized with an auction, where drivers bet for their preferred rental start time. Drivers participating in the auction are offered a reduced rental fare, which is then complemented with the reservation fee that results from the auction. The auction is solved under Vickrey-Clarke-Groves (VCG) mechanism for combinatorial auctions, which guarantees the desired properties for the operator and a fair assignment for the drivers. The proposed scheme is tested on instances inspired by the Mobility car sharing system in Zürich, Switzerland. The results show that operators could decrease their fleets with low to no impacts on the overall rental revenues, especially when drivers show flexibility in their rental start times. For certain levels of demand price elasticity, even positive impacts on the overall rental revenues can be expected. Moreover, reservation fees are proven to partially compensate for the decrease in rental revenues provided to the auction users.

INDEX TERMS Car sharing, combinatorial auctions, reservation system.

I. INTRODUCTION

Shared mobility services have gained relevance since the mid-1980's and have developed in many forms and in many places around the world [1]. In particular, car sharing had approximately 15 million members and 157.000 vehicles worldwide as of 2016 [2]. In addition to the classical round-trip station-based vehicle sharing system, recently more flexible vehicle sharing alternatives have emerged, like one-way vehicle sharing [3], [4] or free-floating vehicle sharing [5], [6]. The revolution of autonomous vehicles is expected to further change mobility trends and change operating costs of the different transport alternatives. In any case, autonomous shared fleets will still remain with the lowest costs to operate [7].

Mobility patterns are known to show daily peak demand periods (e.g. morning or morning/afternoon peaks), where many trips occur simultaneously. In the case of car sharing, this pattern is also observed when analyzing data obtained in Zürich from Mobility (carsharing operator in Zürich) for the year 2010. Fig. 1a shows the relative usage of cars across multiple days over the maximum number of simultaneously used vehicles, which occurs at 15h. Also from Mobility data, the current behavior of drivers shows different levels of anticipation when reserving the vehicle (see Fig. 1b). Some drivers plan the rental weeks in advance, whereas others directly get the vehicle on site. Around 32% of the drivers reserve the vehicle more than 1 day in advanced, and an extra 11% the previous day.

Drivers' reservations, if properly managed, could be used to better design and operate the system. A reservation management scheme can be a tool to better use the available capacity providing a more efficient use of the resources.

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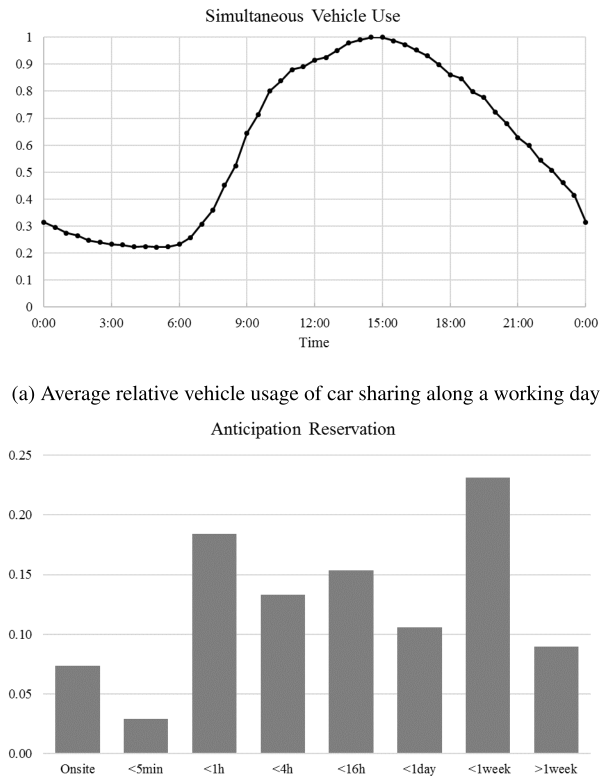


(a) Average relative vehicle usage of car sharing along a working day

(b) Anticipation for car sharing reservations

FIGURE 1. Properties of the car sharing data from the city of Zürich.

On the one hand, the operator might be able to adjust the capacity at the stations, or even perform relocations between stations to address different peak patterns. On the other hand, the drivers can be guaranteed a vehicle, and might obtain fare reductions as an incentive to use the reservation scheme.

In this paper, we propose a reservation scheme for a two-way station-based car sharing system. The operator can adjust the number of vehicles at each station using the information from the reservations. Drivers participating in the reservation scheme will be offered a reduced rental fare, which will then be complemented with a reservation fee. Drivers are offered to participate in a reservation auction, by placing their bids for using the vehicles at different starting rental times. Then, an auction provides the optimal assignment (i.e. under the criteria to maximize the overall drivers' utility) and charges a reservation fee. The reservation fee will be given as the minimum to guarantee the correct performance of the auction (e.g. in some cases it might be zero). The scheme can be easily implemented within the current drivers' reservation system.

Fig. 2 presents a comparison between the classical rental system and the proposed scheme where two drivers (A, B) place their reservations. With the classical rental system, the drivers rent their vehicles for the desired time. Driver A rents the vehicle from 9h until 13h and driver B rents the vehicle from 12h until 15h. Two vehicles are needed at the station and the operator can obtain the revenues according to the original rental fare. In the case only one vehicle is available, one of the drivers will not be able to complete his/her rental. With the proposed reservation scheme, the drivers place a flexible rental bid (dashed square indicates the time interval within which they are willing to rent the vehicle). In this case, both drivers are willing to rent the vehicles with 1 hour of flexibility, that is, either starting an hour before, or one hour later. In this case, the operator is able to serve both rentals with a single vehicle, that is using user A flexibility, and assigning the rental to start at 8h instead of at 9h. The revenues obtained from the rental are represented by $\$_A$ and $\$_B$, respectively. The revenues from the rental will decrease slightly (depending on the rental fare discount (%)). On the other hand, the revenues from the reservation will increase (i.e. with the classical system they are equal to 0, but with the proposed scheme they are positive (++)). Moreover, the costs of the operator can be reduced thanks to the reduction of the number of vehicles at the station. This figure illustrates an elemental comparison between the two systems, both in terms of the rental assignment, and the operator revenues and vehicles needed.

The rest of this paper is organized as follows. Section II lists and explains the existing relevant literature. Section III describes the reservation scheme, and the key metrics to analyze the performance of the system. Section IV discusses the potential benefits of the scheme under different scenarios. Section V summarizes the findings of this study.

II. STATE OF THE ART

Multiple aspects of vehicle sharing systems have been studied since these systems started to gain popularity two decades ago. Different forms of vehicle sharing have been analyzed, as well as many efforts have been made to characterize the user's preferences and user's behavior, or the estimated benefits of these more sustainable systems. On the operational side, some works have covered different aspects of the management of these systems, with a special focus on station location, fleet sizing, and fleet rebalancing. In this section, a brief review is presented. A complete review of the state of the art can be found in [8], where they indicated that there is limited work on using optimization tools in car sharing services.

Different vehicle sharing alternatives have appeared after the classical two-way station-based system, like one-way station-based and free-floating amongst others. [9] presented a framework for classifying multiple forms of car sharing, as well as highlighting the advantages of each. The worldwide perspectives were analyzed by [10], taking into account new market trends.

Several efforts have been made to understand user's groups, and the factors that influence the adoption of these systems [5], [11]–[14]. In particular, [12] concluded that dense urban areas are the most suitable markets for station-based car sharing, whereas [14] analyzed the impacts of different factors on the vehicle usage, with a case of study based on the city of Montréal, Canada. Special attention has been

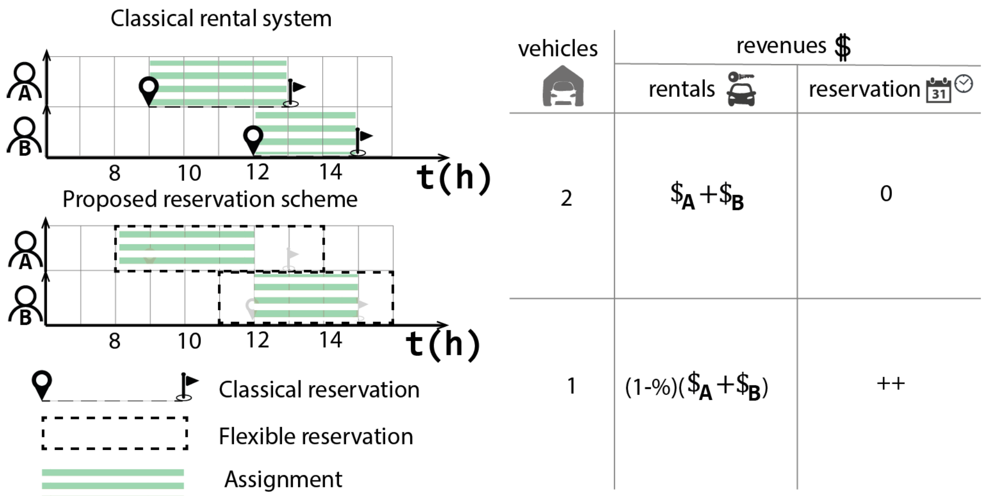


FIGURE 2. Classical rental system versus proposed reservation scheme with driver's flexibility, number of vehicles needed, and associated revenues.

devoted to demand estimation, [15] provided a good review. A comparison between station-based and free-floating car sharing demand estimation can be found in [16], with a test case study from Berlin, Germany. The work of [17] went further, investigating the effects of supply on demand of the round-trip service. The work used a multi-agent simulation tool (MATSIM) and applied it to the city of Zürich, Switzerland. It concluded that increasing the supply would increase the number of rentals, but might saturate the stations' capacity. Therefore, better management of the vehicles was suggested to optimize the service, with the aim to reduce the number of unused vehicles. A comprehensive approach was presented by [13], modelling car sharing as part of the whole urban mobility system.

Several approaches have also tackled the management of these systems, focusing on different aspects: fleet sizing [18]–[21], re-balancing [22], or including stochasticity and different levels of information [23]. [24] provided a decision support system for the optimization of car sharing stations location and size, that was applied to the city of Hannover, Germany. [23] proposed a stochastic optimization framework to address the dynamic vehicle allocation problem for car sharing systems, where both temporal and spatial vehicle allocation were optimized to maximize profits. More recently, a tradable permit mechanism was proved to be computationally viable for car sharing with temporal-spatial OD connection conditions [25]. Also, some works have studied the future operative systems of autonomous shared fleets [26]–[28], or their electric version [29]. Other works have considered modified pricing schemes in order to balance one-way systems [30], [31]. Self-regulated systems were studied on [30] through pricing schemes, with the aim to increase their performance. A more complex approach was presented on [31], with a mix-integer non-linear programming model to set the price in order to maximize the profit for one-way station-based systems.

Despite the abundance of works on car sharing systems, reservations have been considered recently, and just for the case of one-way free-floating car sharing systems [32]. In this setting, they proposed a relocation-based method to incorporate reservations without compromising the viability of the system. Additionally, two works have analyzed the benefits of reservation with car sharing related problems and one analyzed relocation strategies based on a constrained reservation policy. An integrated optimization-simulation framework for vehicle and personnel relocations of electric car sharing systems was studied in [33]. The benefits of reservation were assessed assuming the daily demand was known in advanced and the problem was solved with full information. The parking reservation problem associated to car sharing was studied in [3], where it was proved to improve performance in realistic systems. In [34] on-line proactive relocation strategies are analyzed accounting for reservations.

Reservation systems have been used in multiple industries, like airline and hotel booking, and also most recently analyzed in traffic management, for the reservation of roadway systems [35]–[37]. The parking reservation problem has also been studied extensively, for example [38] studied the parking allocation of curbside downtown with homogeneous durations, or [39] investigated the reservation of loading/unloading operations for logistic vehicles in urban areas. As an extension, [40] proposed an auction approach to prebook loading and unloading facilities.

Inspired by [40] this paper proposes an easily implementable reservation scheme for two-way station-based vehicle sharing systems to optimize the use of the vehicles at each station thanks to the reservation information. At the same time, drivers are given the opportunity to obtain a reduced rental fare if they offer any flexibility. The combination of the two factors allows to improve the overall efficiency of the system, balancing impacts to the revenues with the possibility to reduce the number of vehicles at the station. Nevertheless, the context of the previous work is significantly different from the one in this paper. In [40] the limited resources are the parking spots, which are located in public space and managed by the city authorities, and auction users are companies trying to park their vehicles in the urban logistics facilities. Whereas in here, the limited resources are the vehicles at a station, owned and managed by the operator company, and the auction users are car sharing drivers. The new context is somehow better suited for the auction approach for the following reasons: i) a more efficient use of the limited resources is in the best interest of the operator, increasing efficiency; ii) car sharing users are already used to reserve their vehicles through a digital system, in comparison with delivery drivers just going to multiple parking spots; and iii) car sharing users are not tight to a route schedule, which results in higher flexibility.

The use of customer's flexibility has been recently considered in car sharing systems, as a way to improve its efficiency [41], [42]. Both, spatial and temporal customer flexibility were leveraged in [41], to achieve better supply-demand alignment by evaluating both its value and cost with an offline and online optimization. They concluded that temporal flexibility has limited potential, whereas the combined temporal and spatial flexibility can bring up to 20% of fleet size reductions. The operator was assumed to minimize a combined objective function with the vehicle cost and the rewards for users's flexibility. The untapped potential for customer flexibility was revealed, and it was suggested to use smart assignment policies to expand the operation on these systems. [42] analyzed user's spatial flexibility in one-way systems, where users show flexibility within a reduced set of convenient stations.

A previous approach to balance supply and demand in other transportation services is through the implementation of dynamic pricing. For instance, airlines use revenue management to set flight prices [43] or the recent use of surge pricing in ride-sharing platforms [44]. Unfortunately, users are not guaranteed transparency nor fairness.

Our proposal aims to combine the benefits of a reservation system with drivers' offering temporal flexibility on their starting rental time. The proposed solution guarantees a fair solution for the drivers while improving the overall system efficiency. Moreover, our scheme can deal with the heterogeneous preferences of the users instead of equally rewarding all users for their flexibility.

III. RESERVATION SCHEME

Car sharing stations normally have a fix number of vehicles available for driver's reservation. Drivers need to first check the availability, and then proceed to reserve if there are available vehicles. There is no reservation priority, the rental works on a First Come First Serve (FCFS) basis. Drivers are able to make their reservations long in advance, but also just immediately before the rental. The rental fare is a linear combination based on the rental time and distance driven. The linear coefficients of the fare normally vary according to the vehicle type and members' subscription. According to [14], each additional vehicle at a station increases the likelihood of a booked reservation by 30%. For this reason, a way to increase reservations is by increasing the number of vehicles at stations, i.e. increasing availability. That being said, as it has already been mentioned, car sharing rental patterns are not uniform throughout the day (i.e. they have peaks). As a result, it is possible that operators end up with oversized stations, and a number of vehicles unused during most of the day. This large and unused fleet would increase the operator costs much more than its revenues.

The ultimate goal of the operator is to maximize profit. Essentially that is pursued by either maximizing revenues, minimizing costs, or both. Both revenues and costs depend on multiple system factors, such as vehicle availability, overall customer experience (e.g. reservation system, comfort), marketing strategy, pricing system (membership price and rental pricing), etc. Nevertheless, strategies need to account for users preferences. The implementation of some specific strategies to exploit users' flexibility, like dynamic or surge pricing [43], [44], recently used in other transportation alternatives, might lead to user dissatisfaction. In this paper, we propose a reservation scheme for round-trip station-based car sharing systems that can be used by operators in order to increase their profit, but at the same time gives freedom to drivers and guarantees them a fair assignment.

The proposed reservation scheme has multiple advantages. First, it will allow the operator to reduce their costs while maintaining a similar level of service and revenues. In-advance rental information can be used to better plan the usage of the existing vehicle fleet not only across time periods but potentially also across stations. Second, the reservation scheme will provide users a reduced rental fare in exchange for some flexibility. Such flexibility will also reduce the operator costs through a more efficient use of the vehicle fleet. Third, users will retain the ability to participate or not in the proposed reservation scheme. Users who participate in the reservation auction might have to pay a reservation fee under some conditions, but will always receive a reduced rental fare. Alternatively, they can pay the full rental fare and continue with the original rental service. Fourth, with a careful implementation, the reservation scheme is expected to attract a higher demand, ultimately leading to a further increase in revenues.

Inspired by [40], we implement an auction approach to solve the reservation problem. Drivers participating in the auction will be offered a reduced rental fare. Drivers' preferences for the different starting times can be represented with their individual utility function. This function is the drivers' valuation for getting a given starting time minus the price they will have to pay for it. According to this function, drivers participate in the auction placing their bids in advance for one or multiple starting times. The auction will determine how the different vehicles at the station should be assigned to the participating drivers, and an associated reservation fee. The assignment criteria will be to maximize the overall drivers' utility. Drivers participating in the auction will pay the reduced rental fare plus the reservation fee. Drivers place their bids to the different multiple starting times according to what they are willing to pay to start their rentals at the given starting time. Thanks to the auction design, the reservation fee will not be higher than the drivers bid. Therefore, drivers can control the maximum additional payment for the reservation fee by adjusting their bids. Drivers are also free to bid in a nonhomogeneous way, i.e. place different bids for different starting times. The reservation auction is then solved on a daily basis. After the auction, the remaining vehicles will be available according to the original reservation system and regular rental fare.

The reservation fee is not solely a revenue for the operator but also is given to drivers as an option to participate in the auction showing different levels of flexibility. Drivers participating in the auction increase their chances of getting a car in their desired time period and get a lower rental fare, and thanks to the design of the auction the reservation fee is the minimum that guarantees the fairness of the system. From the operator's perspective, the reservation scheme might allow to reduce the overall operator's costs in two ways: by adjusting the vehicle's fleet at the different stations, and by allowing a more efficient use of the vehicles.

A. RESERVATION AUCTION

We have the set of drivers N that would like to reserve one of the c vehicles of a vehicle sharing station for a given duration $(s_i,\ i \in N)$, during a time horizon (e.g. a day). The time horizon $[0, T]$ is considered as a discrete set $\Pi_r = \{t_0, t_1, \ldots, t_r\}$ of $r + 1$ time instances when the rentals may start. Denote $J_r = \{0, \ldots, r\}$ as the index set of the discrete time horizon Π_r. The problem needs to assign $n = |N|$ drivers to the Π_r time instants in the c vehicles, taking into account the duration of the drivers' reservations. Therefore, the resulting problem is of combinatorial optimization nature.

In contrast with the current rental system, drivers can consider different starting rental times based on their utility function. Instead of only bidding for the starting time that would give them the highest individual utility, they can place a bid for the multiple times they are willing to reserve. This flexibility brings a new potential to the system, which is able to make a more efficient use of the resources. Note that each driver can individually choose his level of flexibility with the bids, according to its utility function. In other words, a driver can decide to keep the bid only for a single starting time, whereas others might be fully flexible within a given time interval. It is also the driver's choice to place a higher/lower bid according to the willingness to pay for a reservation, or placing different bids for different starting times. For example, a driver can give priority to a certain starting time with a high bid, while at the same time placing lower bids for other less convenient times. It is assumed that the duration of the reservation is fixed and independent of the starting time. From the drivers' perspective, if offering flexibility comes with a longer rental trip, it is not reasonable to assume that it would be beneficial. From the operator's perspective, longer rental times mean that in exchange for flexibility, they would have the vehicles occupied for longer periods. That being said, the modelling framework could accommodate different durations of the reservation depending on the starting time by only adapting slightly the formulation.

Once drivers have placed their bids, the reservation problem needs to be solved. In summary, the reservation problem consists of finding a feasible assignment of the drivers to the vehicles, taking into account their bids and their rental duration. The problem is solved with the objective of maximizing the social welfare for the whole group of drivers. Here, the social welfare is the sum of the utilities obtained from all the drivers with the given assignment, i.e. the total utility across all the drivers. This way, a fair assignment is provided and drivers are incentivized [40]. To solve the reservation problem under the previous criteria, we propose to use an auction formulation based on the Vickrey-Clarke-Groves (VCG) mechanism for combinatorial auctions [45]. The proposed auction consists of two steps. In the first step, each driver i bids for a vehicle reservation, reporting a vector of bids $b_i = [b_{i0}, \ldots, b_{ir}]$ where each element b_{ij} represents the bid for reserving the starting rental at time t_j, and a rental duration s_i. In the second step, two problems are solved: 1) the assignment problem, which assigns drivers to vehicles and starting times, 2) a pricing problem, which determines the reservation fee that each driver needs to pay to get the assigned vehicle. Thanks to the inherited properties of a VCG mechanism, this scheme guarantees the desired properties of a fair system: i) the assignment is done with the objective of maximizing social welfare, ii) the system is truthful, i.e. best strategy for drivers is to place bids based on their true valuations of the starting times, iii) the utility of each driver is nonnegative, i.e. drivers do not suffer any loss by participating in the auction.

As already mentioned, the auction solves two problems: the assignment problem and the pricing problem. The assignment provides a solution that maximizes social welfare, which is the sum of all the bids from all the drivers. The problem is formulated using the following set of binary variables $x = [x_{ij},\ i \in N,\ j \in J_r]$, where $x_{ij} = 1$ if driver i is assigned to start rental time at t_j, and $x_{ij} = 0$ otherwise. The optimal allocation x^* is obtained by solving the following integer program:

$$\max_x \sum_{i \in N} \sum_{j \in J_r} b_{ij} x_{ij} \tag{1}$$

$$\sum_{j \in J_r} x_{ij} \leq 1, \quad i \in N \tag{2}$$

$$\sum_{i \in N} \sum_{k \in \mathcal{T}_{ij}} x_{ik} \leq c, \quad j \in J_r \tag{3}$$

$$x_{ij} \in \{0, 1\}, \quad i \in N,\ j \in J_r \tag{4}$$

where $\mathcal{T}_{ij} \subseteq J_r$, with $j \in J_r$ and $i \in N$, such that $\mathcal{T}_{ij} = \{k \in J_r | t_k \geq 0, t_k < t_j, t_k > t_j - s_i\}$.

The assignment problem is defined by the solution of the integer programming problem with (1)–(4). The starting rental times are assigned with the objective of maximizing total social welfare (1), while fulfilling the capacity restriction of the number of vehicles. Constraints (2) impose that for every driver at most one vehicle is assigned, and constraints (4) ensure that decision variables are binary. Constraints (3) guarantee that at any given time instant, at most c drivers are using vehicles simultaneously (i.e. the capacity of the station is not exceeded). When a driver is assigned a vehicle at a given starting rental time, that does keep the vehicle used for the duration of the reservation of that driver.

In addition to the assignment problem, the pricing problem needs to be solved. This is achieved by defining p_i in (5) as the fee driver $i \in N$ needs to pay for reservation.

$$p_i = \sum_{h \neq i} \sum_{j \in J_r} b_{hj} y^*_{hj} - \sum_{h \neq i} \sum_{j \in J_r} b_{hj} x^*_{hj} \tag{5}$$

where, x^* is the optimal solution of the assignment problem, and y^* is the optimal solution to the following pricing problem for each driver $i \in N$:

$$\max_{y} \sum_{\substack{h \in N \\ h \neq i}} \sum_{j \in J_r} b_{hj} y_{hj}, \tag{6}$$

subject to

$$\sum_{j \in J_r} y_{hj} \leq 1, \quad h \in N, \ h \neq i \tag{7}$$

$$\sum_{\substack{h \in N \\ h \neq i}} \sum_{k \in \mathcal{T}_{hj}} y_{hk} \leq c, \quad j \in J_r \tag{8}$$

$$y_{hj} \in \{0, 1\}, \quad h \in N, \ j \in J_r \tag{9}$$

where, as before, $\mathcal{T}_{hj} \subseteq J_r$ and $h \in N$, with $j \in J_r$, such that $\mathcal{T}_{hj} = \{k \in J_r | t_k \geq 0, t_k < t_j, t_k > t_j - s_h\}$. Note that the pricing problem is the same as the assignment problem but excluding driver $i \in N$. In other words, the pricing problem provides the maximum social welfare reservation assignment when driver i does not participate. Thus, it computes the price for each driver based on the externalities that driver imposes on the system. As a result, if a driver does not create any alteration to the whole assignment of reservations, its reservation fee will be zero. On the contrary, if the driver alters the resulting assignment, the price will be determined based on this alteration. Also, it can be demonstrated, that the prices are the lowest that guarantee the good properties of the auction [45]. For the sake of brevity all the details are omitted here, interested readers are referred to [40].

B. OPERATOR'S PERSPECTIVE

The operator can use the proposed reservation to increase the profits. The operator needs to carefully implement the reservation scheme, adjust the rental fares for drivers participating in the reservation auction, and assign the number of vehicles at each station.

The operator's decision will affect the revenues and costs. On the one hand, the costs of the system can be reduced with an adjusted number of vehicles at the stations. On the other hand the revenues will depend on the number of rentals, the rental fare, and the reservation fees. Thanks to the flexibility motivated by the reservation scheme, less vehicles might be able to serve the same number of rentals. In this context the operator can reduce fleet costs, and additional revenues can be obtained with the reservation fees. However, if the reduction of vehicles at the station is too high, revenues could be negatively affected if not all potential rentals are served.

To analyze the potential improvement of the proposed scheme each operator needs to analyze its system. In particular, how much would be saved for each vehicle at a given station, and which is their drivers' price elasticity. For a general analysis in this work, three main indicators will be used to evaluate the quality of a certain solution: the number of vehicles at each station, the rental revenues, and the reservation revenues. These variables can be used to quantify the overall profit of the operators.

The aim of this manuscript is to demonstrate that with a combination of a reservation scheme and exploiting the flexibility expressed by the drivers, operators can decrease their costs and maintain or increase their revenues.

C. USER'S PERSPECTIVE

Users are passive actors of the system, however they are still free to make the choice that better suits their preferences, and obtain benefits. On the one hand, they can decide not to participate in the system, and proceed with the reservations as before, only with available vehicles at the station. On the other hand, they can decide to participate in the auction, providing in advanced information and flexibility in exchange for a decrease in the rental fares. In this case, they can benefit from a discount, and from securing in advance a vehicle at their desired reservation starting time.

D. SOLVING ALGORITHM

As discussed in [40] there might not be a polynomial time algorithm for the allocation problem in general cases, except when the duration of all rentals is uniform. For that reason, different modifications of the general solution algorithm for the mixed integer linear program based on Branch and Bound (B&B) were studied in [40]. In general, the B&B implementation with the use of initial solutions and the implementation of capacity constraints as lazy constraints performs the best. That is why the same methodology has been used in this paper. Later in Subection IV, the quality of the solutions and the computational times are discussed.

IV. DISCUSSION

This section evaluates the potential benefits of the combination of a reservation scheme with driver's flexibility in car sharing systems. Inspired by real data collected from the car sharing system in Zürich, Switzerland [17], two sets of test instances are created. The formulations have been implemented in the Optimization Programming Language `OPL`, and solved with a tailored branch-and-cut algorithm described in Section III-D based on the commercial software `CPLEX` 12.1. All experiments have been run on a PC limited to 1 thread running at 2.6 gigahertz and 60 gigabytes of RAM, and in all instances optimal solutions were obtained. Computational times are in average below 10 min. Due to the efficiency of the used solving methodology, no alternatives have been considered.

In the first subsection, the instance sets are described. In the second subsection, the scenarios are described. In the third subsection, the results are presented and discussed.

A. INSTANCE SETS

Test instances are designed inspired on the data obtained in Zürich from Mobility for the year 2010. The original data contained the rental information for 3 months including, reservation time, rental start and end time. Data contained 107 stations from the Canton of Zürich with a total of 234 vehicles, and 24,908 rentals. The average duration of the rental is 6.62 hours and 43% of the reservations were made the previous day or earlier. Two different instance sets will be build. In the first set, we analyze a subset of 11 stations with four to twelve vehicles each, and a subset of days with between 15-26 rentals. Every instance was built based on a single day at one station. This resulted in a set of 50 instances (set 1). Each instance represents a day where multiple drivers used the vehicles from one station. We assume that all the drivers participate in the reservation auction. Each original rental corresponds to a driver's planned trip, with the starting rental time and duration. Therefore, we assume they participate in the auction placing a bid for the original starting time and showing different levels of flexibility and bidding behaviors. From the original stations, we also use the maximum number of simultaneously used vehicles ($\hat{c}$) as the number of vehicles at each station. Notice, however, that this is a conservative assumption. In reality, operators tend to hold more vehicles than the strictly operating minimum, because vehicle usage has been found to be higher with a higher number of vehicles in a station [14].

A second set of instances (set 2) is built considering simultaneously all the reservations across all stations (107) of a given day. Although being currently unrealistic, this set intends to represent an upper bound of the reservation benefits and at the same time a potential reservation scheme for a car sharing with relocation according to reservations. One instance contains all reservations from all stations of a single day. In this case, the days selected have between 240 and 470 rentals, and a maximum number of simultaneously used vehicles between 95 and 189.

B. SCENARIOS

Multiple scenarios are considered according to different assumptions, both on driver's behavior and in operator's strategies. The scenarios aim to study the properties of the system. For example, in the operator strategy, the fleet reduction is one of the key design variable of such a system. In each scenario, an assumption on such reduction will be made. In the drivers' behavior, one of the key assumptions is their flexibility. Again, in each scenario different levels of driver's flexibility will be assumed. The results of the scenarios will provide insights on the potential benefits of such a system. Additionally, the scenarios can also be used to reveal how the different assumptions influence the benefits.

As a **reference scenario** we will use the current situation, where drivers pick a single reservation time, and the operator has enough vehicles at the station. In other words, the number of vehicles at the station is $\hat{c}$, corresponding to the number of simultaneous reservations in the original data. The rental revenues are calculated according to the original fares and there are no reservation fees. The demand of the drivers is exactly the demand from the original data, i.e. the number of reservations is maintained. To present the results we will compare the original rental revenues from this reference scenario, with the potential overall revenues obtained under each new scenario. In particular, we will use as indicator a factor of what we call the kept revenues, which is obtained dividing the potential overall revenues by the original rental revenues from the reference scenario. Thus, when the indicator is below (above) 1, it means that the new scenario would obtain less (more) revenues than the reference scenario. Obtaining less revenues is not necessarily undesirable, if these are obtained with less resources, in this case, less vehicles at the station.

Scenario 1 will analyze simultaneously the different levels of driver's flexibility, and levels of fleet reduction. On the one hand, we assume that drivers will be willing to advance or delay the rental starting time. In particular, we consider three levels of flexibility, depending on their willingness to move forward or backwards their original rental start time. Low flexibility (L) for when they are willing to start the reservation either 15min earlier or 15 min later, medium flexibility (M) when that timing is $\pm$30min, and high flexibility (H) with $\pm$60min. This flexibility is then translated into their bids: they will place a positive bid for the original rental starting time, but also for the previous and following intervals. On the other hand, on the operator's side we explore different levels of fleet reduction. The number of vehicles at the station (stations' capacity) is reduced according to three levels, based on the original number of vehicles assumed at the station ($\hat{c}$). The first level reduces 1 vehicle, and the subsequent levels reduce 2 and 3 vehicles respectively.

In the first scenario, we assume that the demand and the rental fare are not modified. That is, we assume that the operator implements a reservation scheme, but does not modify rental fares. We further assume that drivers maintain their original trips in the reservation scheme (inelastic demand), and bid in the reservation auction a small portion of their rental price (e.g. 10%). We assume that all drivers will show the same level of flexibility at each scenario (either all L, M or H). Each driver will bid the same fixed portion of their rental price, which means they would place a uniform bid for the original time of the rental, but also the same bid to advanced or delayed time intervals. This way we can analyze the benefits of flexibility with respect to the number of vehicles per station (i.e. stations' capacity). These assumptions will be relaxed in the following scenarios.

TABLE 1. Scenario summary.

Assumptions		Scenarios					
		Ref	1	2	3	4	FCFS
Drivers behavior	Flexibility	No	Yes (L, M, H)	Yes (M)	Yes (M)	Yes (L,M,H)	No
		No	Hom	Hom	Hom	NH	No
	Demand	Inelastic	Inelastic	Elastic (L,M,H) & NonHom	Inelastic	Inelastic	Inelastic
	Bidding behavior	No	Hom (10)	Hom (10)	Hom (5,10,15) & Peak (15,5)	Hom (10)	No
	Rental duration	All	All	All	All	Only <12h & <6h	All
Operators strategy	Rental reduction	No	No	Yes (10%)	No	No	No
	Fleet reduction	No	$\hat{c}-1, \hat{c}-2, \hat{c}-3$	$\hat{c}-2$	$\hat{c}-2$	$\hat{c}-2$	$\hat{c}-1, \hat{c}-2, \hat{c}-3$

Note that without increased demand, Scenario 1 can not obtain higher rental revenues, as the demand served is fixed. However, we will analyze how this might be compensated with reservation fees and a reduced vehicle fleet. This is also a conservative approach, as it is possible that the existing demand would actually be higher than that used here. In other words, the demand used here is the satisfied demand. In case the demand was higher and not satisfied because of capacity constraints, that additional demand would not have been captured.

Scenario 2 is going to consider different levels of demand elasticity due to a rental fare reduction. According to a case study about variable-pricing strategies in car sharing, the rental rates discount produced a very high price elasticity estimate of -1.59 [46], [47]. In this scenario, we assume that the rental fares will be decreased by 10%, and as a consequence there will be an increase in the number of rentals. According to this estimation, three levels of homogeneous demand elasticity have been evaluated: low (L) with -0.75, medium (M) with -1.59, and high (H) with -2.41, and another alternative with medium (M) demand elasticity (1.59), but with a nonhomogeneous (NonHom) increase of rentals at periods when there are available vehicles at the station. The first set of instances is modified with an increase of the rentals, adding rentals from nearby stations until reaching the desired demand increase. This increase in rentals allows the operator to potentially obtain higher total revenues. Note than in this and the next scenarios, the vehicle reduction will be fixed at $\hat{c}-2$, and drivers' flexibility will be assumed as medium to simplify the presentation of the results.

Scenario 3 analyses different bidding behaviors from the drivers. We first assume that drivers will place a homogeneous (*Hom*) bid of 10% of their rental price. This will be compared with 5% and 15% homogeneous bid, and a peak bidding strategy (*P*). In the peak bidding strategy, drivers will place a bid of 15% of their rental price for their original rental starting time, but only a 5% bid of their rental price for an advanced or a delayed starting time.

In **Scenario 4** two different features of the scheme are analyzed simultaneously. The rental duration of the drivers participating in the auction, and the nonhomogeneous drivers' flexibility. In particular, only rentals shorter than 12h and 6h are considered. Nonhomogeneous drivers' flexibility (NH) is analyzed assuming drivers with shorter rentals show less flexibility than drivers with longer rentals.

An additional scenario will be used to compare the proposed system with a system without reservations. In this scenario, we will analyze the effects of reducing the vehicles at a station, but maintaining the criteria of First-Come First-Served (FCFS) for the assignment. In this case, we analyze what would happen if the operator would reduce the number of available vehicles at a given station but without providing any reservation scheme.

Table 1 presents a summary of the assumptions for each of the scenarios. Shaded cells indicate the relevant features analyzed.

C. RESULTS

The results regarding the potential kept revenues in Scenario 1 using the first set of instances are summarized in Fig. 3, results are grouped by the reduction of vehicles, and each group presents the different levels of drivers' reservation flexibility (No, L, M, and H). Each bar represents the kept rental revenues with light grey, and the reservation fees revenues are added on the top (dark grey). Notice that all graphs in Figures 3–7 have a truncated y-axis to highlight the differences between the bars.

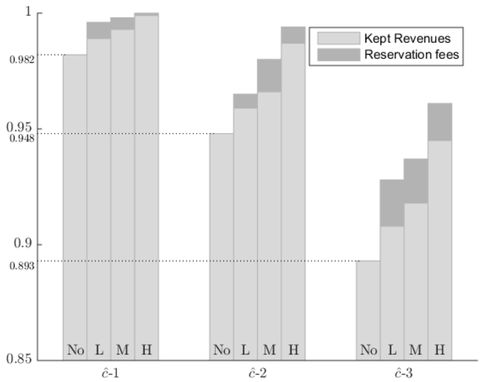


FIGURE 3. Potential kept revenues from rental fare and additional revenues from reservation fees according to the different levels of flexibility and station's capacity reduction for Scenario 1 (same rental fares and inelastic demand) using the first instance set.

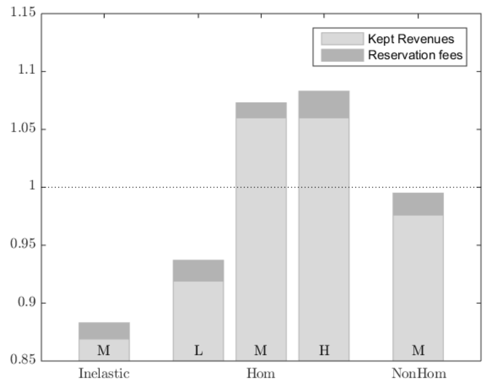


FIGURE 5. Potential kept revenues from rental fare and additional revenues from reservation fees with different demand elasticities Scenario 2 (reduced rental fares and elastic demand) using the first instance set.

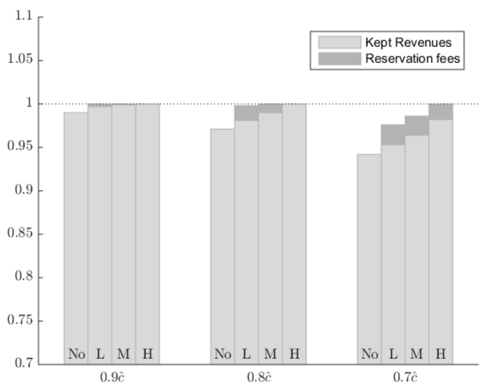


FIGURE 4. Potential kept revenues from rental fare and additional revenues from reservation fees according to the different levels of flexibility and station's capacity reduction for Scenario 1 (same rental fares and inelastic demand) using the second instance set.

First we will only analyze the kept rental revenues. Compared to the reference scenario, with one less vehicle the kept revenues would be 0.982 if drivers showed no flexibility to adapt their starting rental times. As it can be seen, with the higher flexibility of the drivers, this loss could nearly disappear. The reduction of two vehicles results in 0.948 kept revenues when drivers show no flexibility at all. However, as drivers become more flexible, this loss can be significantly reduced and kept revenues rise up to 0.987. If the capacity is reduced by three vehicles, the kept revenues decrease to 0.893. Thanks to the flexibility, the kept revenues can be increased. Additionally, reservation fees can increase the final overall revenues. As expected, the higher the reduction in the fleet capacity, the higher the gain from the reservation fees.

The results regarding the potential kept revenues of Scenario 1 using the second set of instances are summarized in Fig. 4. This set considers the pooling of all drivers together, independently of the station. In this case, the vehicles reduction is a portion of the maximum simultaneously used vehicles (10%, 20% and 30%). It can be seen that, even when reducing 30% the vehicles fleet, the potential kept revenues are 0.942 and in the case that drivers show flexibility, these could be recovered up to 0.982. If the incomes from the reservation fees are included, the revenues are all kept.

Fig. 5 presents the results of Scenario 2, where reduced rental fares are offered to drivers participating in the auction, and demand is assumed to have different levels and types of elasticity. The results of demand elasticity are compared with a reference scenario with inelastic demand but with reduced rental fares. When demand elasticity is assumed low, the kept revenues are below 1. However, with medium or high elasticity, the operators are able to increase their revenues compared to their reference scenario. In the case that demand elasticity is assumed nonhomogeneous (only increasing at non peak periods), the total revenues are nearly the same as the reference scenario (0.995). Recall that these revenues are obtained reducing by 2 the number of vehicles at the station, and assuming a middle drivers' flexibility. That is, with demand elasticity of the proposed scheme the operator is able to obtain similar or higher revenues despite a reduction of 2 vehicles at the station.

Fig. 6 presents the results of Scenario 3, where different bidding behaviors are considered. The kept revenues for the homogeneous bidding strategy are constant at 0.966, as the kept rental revenues are not affected by the amount of bid of the drivers. However, the potential revenues including the reservation fees grow proportionally, from 0.973 when the bid is only 5% of the original rental fare, up to 0.986 when the bid is 15% of the original rental fare. The results of the peak bidding strategy are presented in the last column. The decrease of flexibility from the drivers, bidding a lower portion of their rental fare, show how the overall benefits are reduced. Again, recall that these values are obtained assuming a reduction of two vehicles at the station, and assuming a middle driver's flexibility.

Fig. 7 analyzes the potential kept revenues for shorter rentals and both, homogeneous and inhomogeneous drivers' flexibility. Two different levels of shorter durations

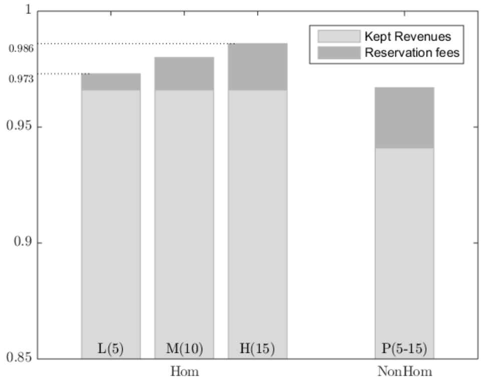


FIGURE 6. Potential kept revenues from rental fare and additional revenues from reservation fees with different demand elasticities Scenario 3 (reduced rental fares and elastic demand) using the first instance set.

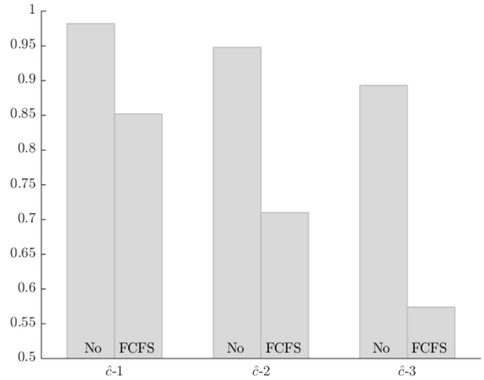
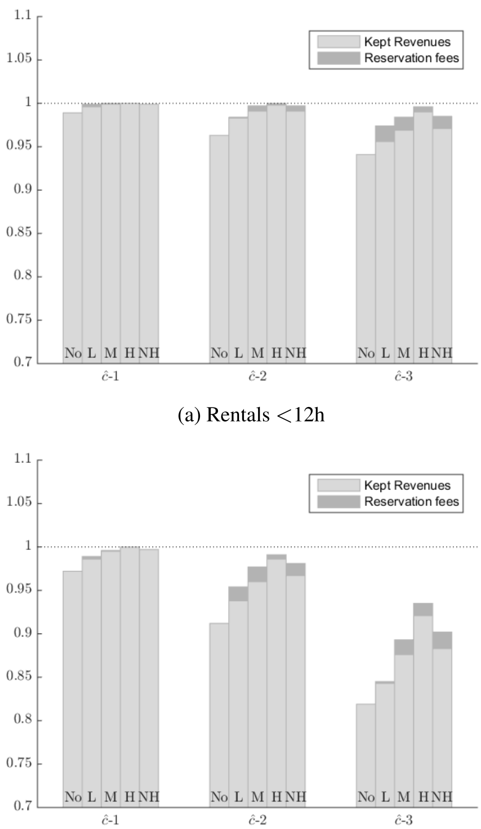


FIGURE 8. Potential kept revenues from rental fare with the FCFS Scenario compared to the No Flexibility using the first instance set.



(a) Rentals <12h

(b) Rentals <6h

FIGURE 7. Potential kept revenues from rental fare and additional revenues from reservation fees for Scenario 4 (shorter rentals and inhomogeneous drivers' flexibility) using the first instance set.

are analyzed: rentals shorter than 12h (on the upper side of the figure) and rentals shorter than 6h (on the lower side of the figure). An extra bar is added to analyze the case for nonhomogeneous flexibility (NH). The results show that when considering rentals shorter than 12h the percentage of kept revenues is slightly higher than when considering only rentals shorter than 6h. In other words, with shorter rentals, higher flexibility increases the kept revenues more drastically than with longer rentals. Therefore, shorter rentals have a higher potential when using this reservation scheme, because in absolute terms the recovery thanks to the flexibility is higher. This is intuitive, as vehicle turnover increases and flexibility becomes more important. For the scenario with inhomogeneous drivers' flexibility, the solutions found are equivalent to the medium level of drivers' flexibility. This means that some drivers' lower flexibility can be compensated by other drivers being more flexible.

Fig. 8 compares the FCFS criteria with the reservation but No Flexibility scenario. Compared to the reference scenario, with one less vehicle the kept revenues would be 0.985 instead of 0.982 if drivers would be assigned in a FCFS criteria instead of prioritizing with a reservation scheme. The reduction of two vehicles results in 0.71 kept revenues when drivers are assigned in a FCFS criteria. If the capacity is reduced by three vehicles, the kept revenues decrease to 0.57. We can see that when capacity is tight, a reservation system can make the best use of the existing resources, by optimizing their assignment, while the FCFS criteria lowers the revenues.

The interdependency of the assumptions of the scenarios proposed has not been specifically analyzed. For example, the value of the rental reduction impacts the demand elasticity, and probably also the bidding behavior. However, this is out of the scope of this first approach where all assumptions have been evaluated independently. This study would also benefit from a detailed sensitivity analysis [48] taking into account the dependency between different inputs [49].

Table 2 presents a qualitative summary of the impacts of each of the assumptions of the presented scenarios. Cross comparing the benefits of each individual assumption, they have been classified with a low (+), medium (++) or high (+ + +) impact according to how they ranked in an overall comparison on how much revenues they kept. At a high impact, we have the levels of flexibility and the combination of the rental price reduction with the elasticity of the demand. It is clear that showing enough flexibility is essential

TABLE 2. Assumptions and their qualitative impact.

Assumptions			Impact
Drivers behavior	Flexibility	Levels (L, M, H)	+++
		Hom vs NH	+
	Demand	Elastic (L,M,H)	+++
		NonHom	+
	Bidding behavior	Hom(5,10,15)	+
		Peak (15,5)	++
	Rental duration	All, Only <12h & Only <6	++
Operators strategy	Rental reduction	Yes (10%)	+++
	Fleet reduction	$\hat{c}-1$, $\hat{c}-2$, $\hat{c}-3$	++

to exploit the benefits of the scheme, and lower levels of flexibility are in some cases insufficient. At the same time, the reduction of the price and demand elasticity are the key features to obtain the best results. On the other hand, the driver's bidding amount has the least impact, only affecting slightly the reservation fees. The non-homogeneity of the assumptions has also low impact. In two of the cases where nonhomogeneous assumptions have been evaluated (nonhomogeneous flexibility from the drivers and nonhomogeneous demand elasticity), the results are not significantly different from the homogeneous respective cases. In the medium level, we have the rental duration, the fleet reduction, and the nonhomogeneous bidding behavior. The benefits are higher when only considering rentals with durations shorter than 6h. At the same time, the fleet reduction has also an important role, where drastic reductions on the fleet, offer also higher potential benefits. In turn, nonhomogeneous bidding behavior represents somehow a decrease on user's flexibility, which is why it has a medium impact level.

V. CONCLUSION

In this paper we have introduced a reservation scheme for two-way station-based car sharing systems that allows to exploit drivers' temporal flexibility. The scheme, combining both reservations and flexibility can provide benefits for both, the car sharing operator and the drivers, thanks to a better management of the reservation information.

Currently, car sharing systems operate using no specific reservation priority, i.e. the first to reserve a vehicle gets to use it, until no vehicles are available for a given period and station. To guarantee customer satisfaction, and vehicle availability, car sharing operators might need to provide an oversized fleet at multiple stations, with the associated high costs.

The reservation scheme proposed is easily implementable and can help car sharing operators to better plan the vehicles needed, and increase the number of trips per vehicle. At the same time, drivers are given the option to show flexibility in the reservation time, in exchange for a reduced fare.

The reservation scheme offers a reduced rental fare for drivers participating in the reservation auctions. Drivers can place their bids for multiple starting rental times. Then the reservation problem is solved assigning drivers to vehicles, and setting the reservation fee.

Results show that operators are able to decrease their fleet with low impacts to the overall rental revenues, especially if drivers show flexibility in their start rental times. Reservation fees are shown to provide an alternative revenue to compensate for the reduced rental fares. Sensitivity analysis shows multiple aspects of different drivers bidding behavior, or operator's strategy. Most importantly, considering drivers elasticity to rental fares, with the implementation of the reservation scheme, the operator can obtain higher or equivalent revenues using two vehicles less at each station. Also, sensitivity analysis shows that potential benefits are higher in systems with shorter rentals, and that inhomogeneous flexibility drivers' behavior still produces savings.

Even though the results show interesting benefits, the implementation of such a system might encounter some resistance. For example, on the operator's side, they need to implement a digital platform to allow the auction to happen. On the drivers' side, any system change might encounter resistance, moreover user's need to provide much more information. That is, not only the rental information but also their flexibility in the form of bids.

Multiple future research directions arise from this proposal. It would be interesting to implement the reservation scheme in a network of stations, so the overall network effect could be considered. In that case, a vehicle relocation strategy for two-way station-based car sharing system could also be explored, to better adjust the resources to the given stations according to the reservation information.

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