How much parking space can carsharing save?

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ABSTRACT

Providing minimum parking requirements for new developments is an important part of urban design, taking away valuable space from people in the process and giving it to cars which are used for only small portions of the day. Free-floating carsharing is a service that provides fast point-to-point connections with an increased flexibility over more traditional carsharing services, with the promise of positive impacts on the environment, travel behavior and potential car ownership. However, the impact of free-floating carsharing services on overall city parking requirements is not yet fully understood.

We therefore explore the potential savings in parking space with different levels of free-floating carsharing service and different penetration rates using travel behavior patterns for Zurich, Switzerland as an example. In the best-case scenario where all eligible agents switch to free-floating carsharing, a reduction in parking requirements of 22% is estimated compared to the baseline scenario. These results indicate that we can indeed better utilize our parking infrastructure by switching from ownership to sharing concepts.

INTRODUCTION

Carsharing is a service that aims to provide an alternative to car ownership. First implementations of the service resembled a traditional rental service, but with some substantial differences: (a) cars were available for short-term rentals (rentals were charged per minute) (b) the fleet was distributed among the unstaffed stations in the service area and (c) users needed to pay a membership fee on a monthly or yearly level or (d) share in the capital costs of the cars.

Technological advances have allowed for new versions of carsharing, namely one-way station-based and free-floating carsharing. As a result of their higher flexibility in comparison to traditional round-trip carsharing services, these new service types have attracted more users and free-floating carsharing has consequently become the most popular carsharing option around the globe. However, higher flexibility meant new difficulties for the operator. One of the well known and well researched problems is the need for vehicle rebalancing. The asymmetric demand patterns in space and time lead to vehicle imbalances which need to be occasionally corrected to prevent vehicles from standing idle for longer periods of time.

Various research has shown the impacts of these three types of carsharing services on the environment, travel behavior and car ownership. A decrease in car ownership has been one of the leading arguments for the sustainability of carsharing services. However, one of the less researched and more difficult topics to tackle is the impacts of carsharing on parking requirements. Providing minimum parking requirements for new developments has been considered and in many places still is an important part of urban design. Increasing parking supply is taking away valuable space from people and giving it to cars which are used for only small portions of the day. Arguably, carsharing can reduce these requirements and can even be used as a parking management strategy (Millard-Ball et al. *(1)*). A decrease in car ownership naturally leads to a decrease in parking spaces needed at home; however, how carsharing impacts publicly available parking space throughout the service area is still unknown. Furthermore, as the era of automated vehicles approaches, where most of the vehicles might be shared, it is of growing importance to lay the groundwork for the estimation of the parking space needed in these future scenarios by investigating current ones.

The purpose of this paper is therefore to fill this research gap. In order to do so, the authors, using Zurich, Switzerland as an example, explore the potential savings in parking space with different levels of free-floating carsharing service and different penetration rates.

BACKGROUND

Free-floating services have increased the flexibility of carsharing, which in turn has further lead to an increase in their membership levels (Shaheen and Cohen *(2)*, Shaheen and Cohen *(3)*). However, it is still a niche product that is rarely able to capture a substantial mode share.

Previous research on carsharing has mostly focused on understanding its impacts on the environment, car ownership, user groups and usage patterns.

Most of the studies on user groups of carsharing services show that members are young and well educated males (Becker et al. *(4)*, Becker et al. *(5)*). Becker et al. *(4)* show that in a free-floating carsharing service in Basel, Switzerland, 70% of users are male and 70% hold a university degree compared to 37% in the control group.

Studies on usage patterns can be split into two groups: those based on the available empirical data and those based on transport simulation frameworks. Using empirical data, researchers have shown that members of free-floating carsharing services are prone to have larger trip frequencies and more intermodal travel behavior than non-members (Kopp et al. *(6)*). Becker et al. *(4)* also find that free-floating carsharing is used frequently when it saves time compared to other modes. Simulation tools were also used to investigate impacts and usage patterns of carsharing (Martínez et al. *(7)*, Martínez et al. *(8)*, Martínez et al. *(9)*). All studies show that there is an untapped potential of free-floating carsharing in the researched cities. *(9)* also show that carsharing has a potential to utilize parking space much better than privately-owned vehicles, not only on a temporal level but also on a spatial level, by increasing the turnaround of parking spaces across the city, thus reducing the potential search times for parking.

Cervero and Tsai *(10)*, Cervero and Tsai *(11)*, Cervero and Tsai *(12)* have shown that carsharing reduces the vehicle kilometers traveled (VKT) and negative emissions. Shaheen and Cohen *(2)* have shown that carsharing has a tendency to promote a car-free lifestyle, thus reducing car ownership. This arguably reduces parking requirements (Millard-Ball et al. *(1)*, Millard-Ball et al. *(11)*). However, to the best knowledge of the authors, there are no studies that attempt to quantify in more detail the potential of carsharing in reducing parking requirements.

Parking has a very specific relationship with traffic in downtown areas for different reasons and if not managed properly can have harmful effects on travel behavior. It is still widely considered an important part of urban design to provide minimum parking requirements for new developments. Increasing unpriced parking supply to meet future demand, however, takes away valuable space from people and gives it to cars. These vehicles are used for only small portions of the day and, therefore, end up standing on these parking lots for long periods of time. The increase of parking supply also attracts more car users (McCahill et al. *(13)*), thus increasing VKT and causing negative environmental effects. Increasing parking supply in downtown areas has negative effects on the urban environment, discourages the use of slow-modes and reduces the economic success of business districts (Manville and Shoup *(14)*, Manville and Shoup *(15)*, Manville and Shoup *(16)*). The land that is taken by parking could be otherwise used to increase the quality of life in urban areas by providing green spaces or higher concentrations of amenities. This would, as a consequence, encourage walking, cycling and public transit.

Searching for parking in downtown areas is yet another negative consequence of poorly managed parking supply. Shoup *(17)* cites other authors who claim that parking search traffic in various cities across the mainland United States varies between 8% and 74% of the total traffic in downtown areas. Shoup points out that the main reason for a heavy parking search traffic are large quantities of free-of-charge on-street parking spaces and mispriced garage spaces.

Having this in mind, it is important to investigate how carsharing could reduce parking requirements and mitigate some of the negative effects parking has on our cities. This will be done by exploring how parking requirements change with different levels of free-floating carsharing penetration and different levels of service.

METHODOLOGY

The main objective of this work is to provide an estimate for the maximum number of parking spaces that can be removed from a city due to the availability of a free-floating carsharing service. To achieve this, different adoption rates where all adopters give up their private vehicle to become customers of the carsharing service are examined. For each one, a minimum carsharing fleet size is determined to insure a desired level of service. Then, given this new vehicle fleet composition, the resulting parking requirements are computed.

The analysis is conducted using the travel demand patterns and parking supply data within the limits of the city of Zurich. The following sections provide an overview of the steps taken to estimate the parking requirement reductions given a free-floating carsharing service, meeting the defined service level requirements for different levels of free-floating carsharing adoption.

Travel demand

The analysis of parking requirements in the presence of free-floating carsharing services inevitably starts with an understanding of where, when and how people travel around a city. This study examines these parking requirements in the case of Zurich, Switzerland by making use of the output of a multi-agent transport simulation (MATSim, *(18)*). For the purpose of this study, we used a 10% sample scenario of the city of Zurich that consists of the population performing at least one of their activities within the Zurich agglomeration, geographically consisting of an area with a 30km radius centered around the Bellevue tram station situated just outside the Old Town by Lake Zurich. The study area considered is shown in Figure 1 with the city of Zurich outlined, which also serves as the free-floating carsharing service area.

The simulated population consists of individual agents, each with preferred daily travel plans and social-demographic characteristics obtained from census data. As the simulation iterates, the agents are scored based on the actual execution of the intended plans and are then allowed to modify these in order to improve their score in the next iteration. The simulation is terminated once equilibrium is reached, that is to say when the overall score can no longer be improved and the behavior of agents matches the reference behavior (in this case statistics from the national travel diary), ultimately providing departure and arrival times and locations, as well as the transport mode used, for all agents in the simulated population on a typical workday. These equilibrium events then serve as the basic input for further parking requirement analysis.

This study area contains a 10% sample of a total population of 1,576,860 agents, of which 816,880 drive a car and where 198,400 vehicles enter within the Zurich city limits during a typical day. The scenario only considers passenger transport and therefore excludes freight transportation, service vehicles, business vehicles and tourists, all of which have an additional impact on the required amount of parking within the city.

Parking infrastructure

The parking infrastructure considered in this study consist of all parking spaces located solely within the limits of the city of Zurich, as shown in Figure 2. These include over 200,000 private parking spaces, 50,000 on-street parking spaces and over 16,000 spaces located inside parking garages, summing up to a total of 47,938 different parking facilities totaling 274,944 parking spaces.

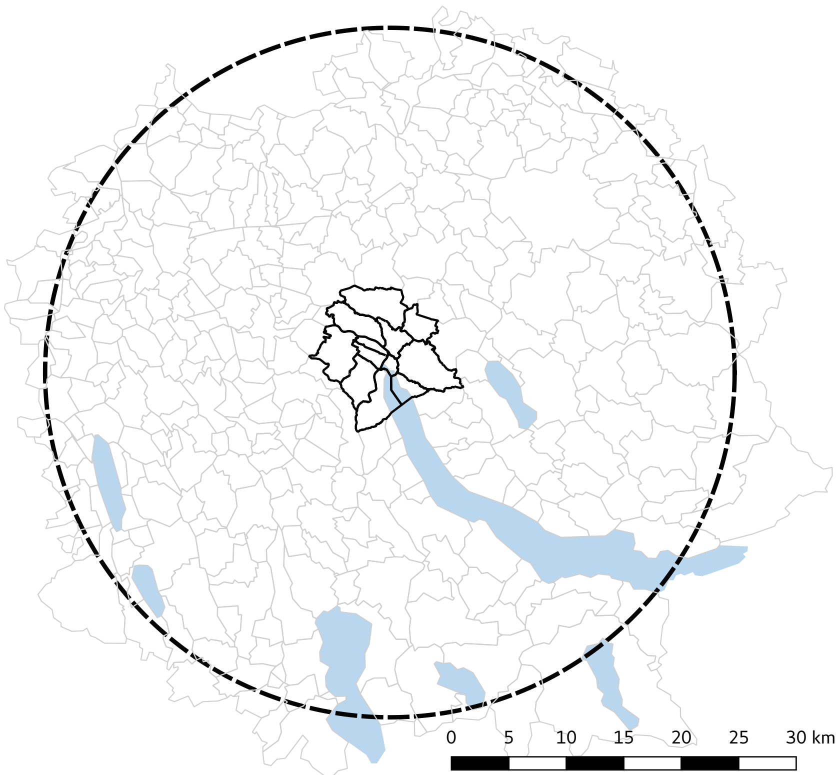


FIGURE 1 Study area

Despite these differences in parking facility types, no difference is made for the purpose of this study, meaning agents can simply park at the free parking space nearest to their destination, irrespective of cost, duration or whether it is private or public. The justification for this is two-fold. First, it allows for a fair comparison, since carsharing vehicles are allowed to park everywhere without any time limit or cost, which is not the case for private vehicles. Second, it allows us to push the analysis to the extreme in terms of how much better we could use the parking infrastructure, even in the current case. For the simulated agents operating in the study area, a total of 770,510 parking/unparking actions occur within the limits of the city of Zurich alone.

Parking simulation

The standard MATSim simulation does not take into account the parking infrastructure, meaning that agents park their vehicles directly at the destination facility without considering any parking constraints. Therefore, an additional step is needed in order to obtain the parking locations of vehicles when parking constraints are taken into account.

The output of the MATSim simulation is a log of all the actions performed by each agent. It enables the tracking of which agent traveled from which to which facility at what time using which mode of transport and additionally allows the determination of which parking facility was being used in the process. Figure 3 shows a flow diagram of the process of how cars are parked, whether they be private or shared, based on the MATSim events associated with the departure from a facility. In the case of unparking a car, an agent is assigned its own vehicle or the nearest available shared

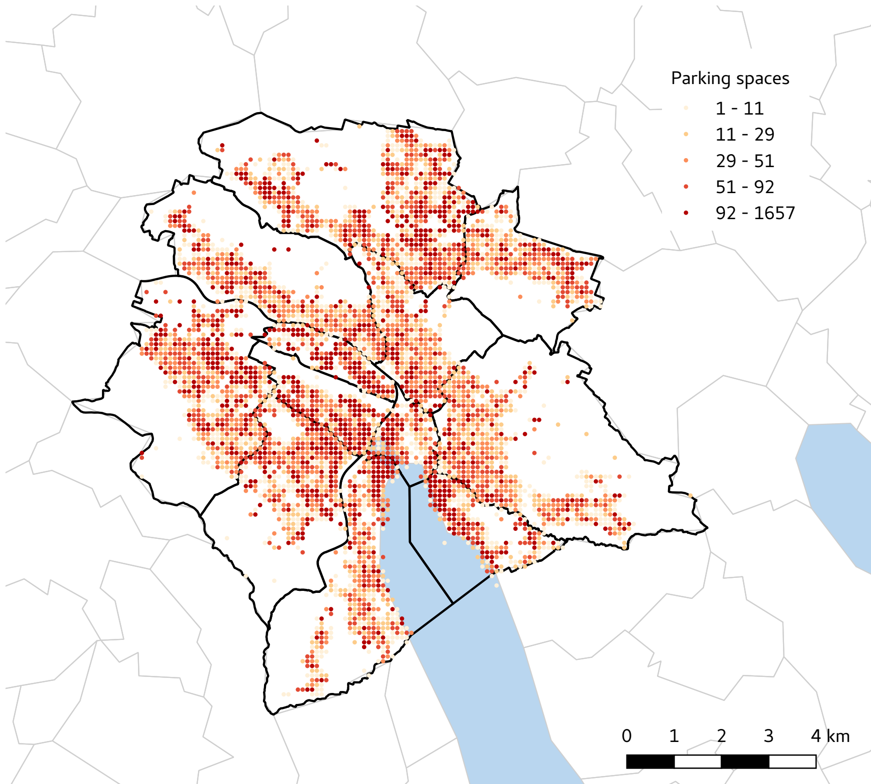


FIGURE 2 Location and capacity of parking facilities in Zurich grouped on a hectare level.

vehicle, depending if it drives a private or shared vehicle respectively.

As the MATSim simulation contains only 10% of the total population, 10 parking and unparking events are sequentially generated for each agent in the model in order to scale up the parking requirements to the 100% case.

Initial parking locations of private vehicle fleet

The MATSim equilibrium events are first processed to determine the facilities at which each car-driving agent first uses its vehicle and the corresponding nearest available parking location to that facility, resulting in a mapping of private vehicles to initial parked locations.

Eligible carsharing customers and change in car ownership

While determining the initial parking locations of private vehicles, a list of all agents eligible to become carsharing customers is simultaneously constructed. An agent is considered eligible for carsharing if :

- a car is used by the agent at least once during the day
- all the agent's performed car trips start and end within the carsharing service area

Figure 4 illustrates examples of different cases of eligible and non-eligible agents, where the dotted line represents the carsharing service area. From this set of eligible agents, a random subset

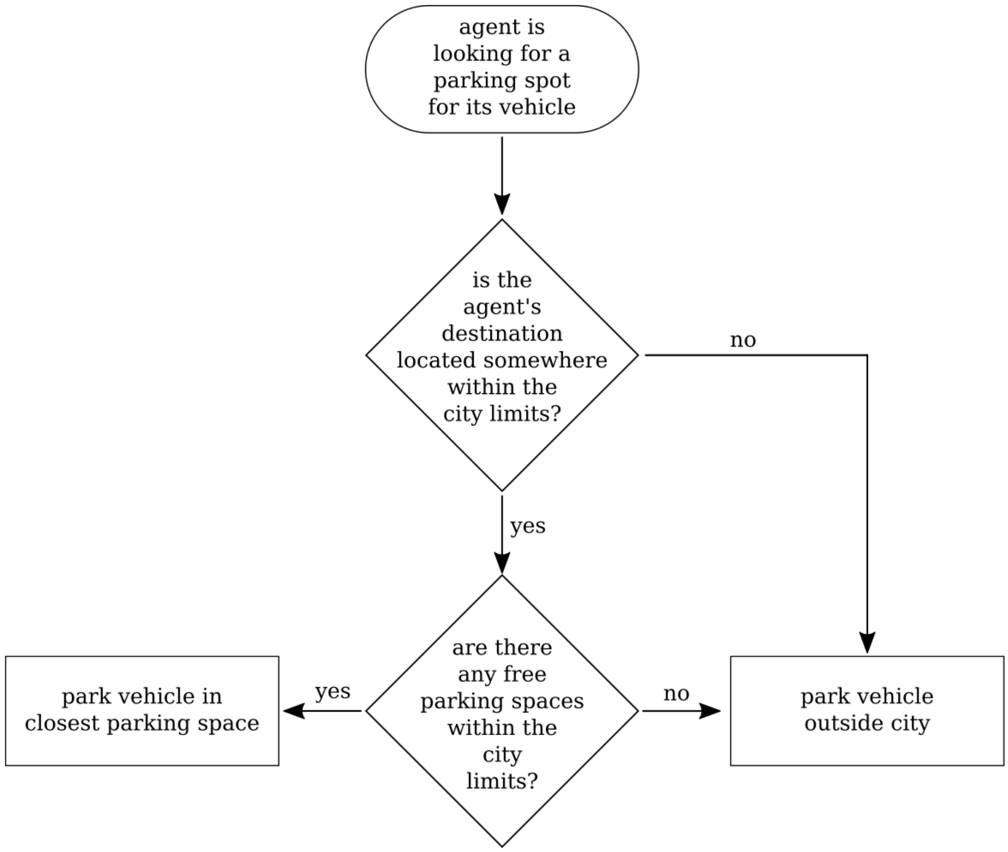
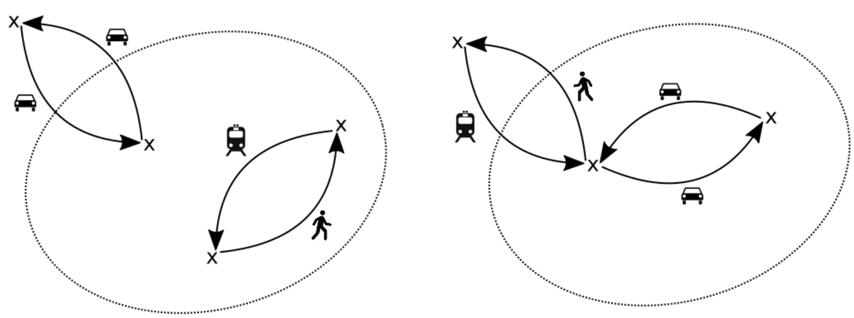


FIGURE 3 Vehicle parking process



(a) Non-eligible agents (b) Eligible agent

FIGURE 4 Example cases of agents non-eligible and eligible to using carsharing

corresponding to the fraction of carsharing adopters is selected. Then, another random sample of these adopters is chosen to give up their private vehicles, which are then removed from the parking infrastructure.

Generating the carsharing fleet

We define the carsharing service as sufficient to meet the demand if it is always able to provide an available vehicle within a threshold walking distance of the departure facility. Figure 5 illustrates

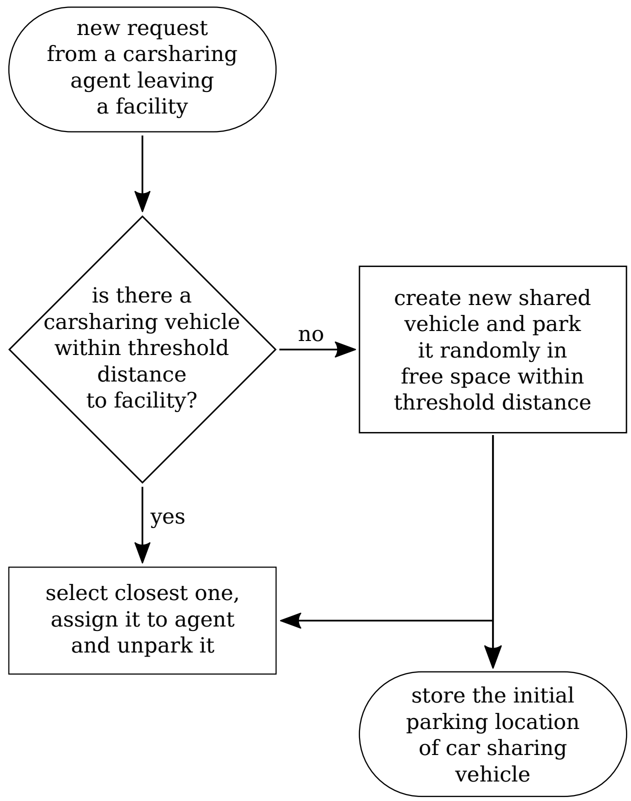


FIGURE 5 Carsharing generation algorithm

the process of generating the minimum required carsharing fleet and initial parked locations based on the requests from carsharing customers in order to provide this desired level of service.

Each time a carsharing customer requests a vehicle, the parking infrastructure is queried to check whether a vehicle is available within the threshold walking distance. If such a shared vehicle is available, the agent is assigned the closest one, unparks it, drives it to its destination and parks it at the closest available parking spot. If no such vehicle is available, a new shared vehicle is created and parked at random in one of the available parking spots within the threshold walking distance. Now that there is a vehicle available that meets the minimum service requirements, the agent can unpark it and drive off to its destination.

Through this process, a minimum fleet size and initial parked locations of the carsharing vehicles are determined. However, given that these shared vehicles are only first parked when needed and not from the beginning of the day, it is possible that these initial locations would have been occupied earlier and therefore not available. This needs to be corrected for before any estimations on parking requirements can be made.

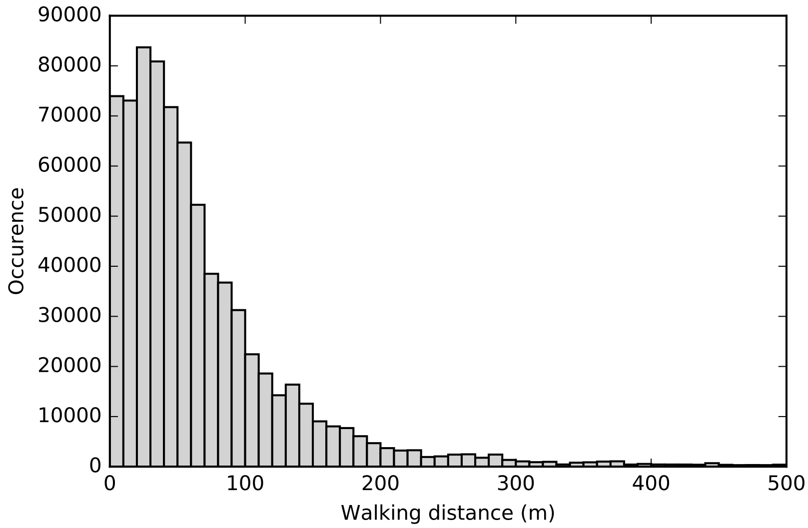


FIGURE 6 Distribution of crowfly walking distances between parking and facility locations for drivers in the base scenario without carsharing

Parking requirement estimate

In order to finally estimate potential parking requirement reductions, the MATSim events are processed a final time. The private vehicles are added to the parking infrastructure at their previously determined initial locations, to which the minimum carsharing fleet can now be added. The carsharing vehicles are parked in the free locations closest to the initial guesses provided from the minimum fleet generation process. The MATSim events are then processed and the agents thus move their vehicles from one parking location to another. A log is kept of each parking and unparking event and of all changes in occupancy levels of each parking facility for further analysis.

RESULTS

By examining the current parking requirements in Zurich without any carsharing, but where car drivers are nevertheless allowed to park their vehicles at any parking space closest to their destination, baseline values are determined to which further cases including carsharing are then compared.

The distribution of walking distances, taken as the crowfly distance between parking and facility locations and shown in Figure 6, provides a feeling of the baseline level of service enjoyed by these car drivers under these conditions. Indeed, 90% of the total number of walking trips between parking spot and facility locations are less than 153 m.

Next, the time evolution of the overall parking capacity usage in Zurich is plotted in Figure 7 to view when most of the vehicles circulating in the city are parked and how much of the overall capacity they use. As one would expect, two different plateau regimes can be observed: one corresponding to the late night/early morning when most vehicles are parked away as the agents are at home, and one corresponding to the midday period when most agents are at work. The latter is higher due to the influx of agents from outside the city limits. Two local minima are observed

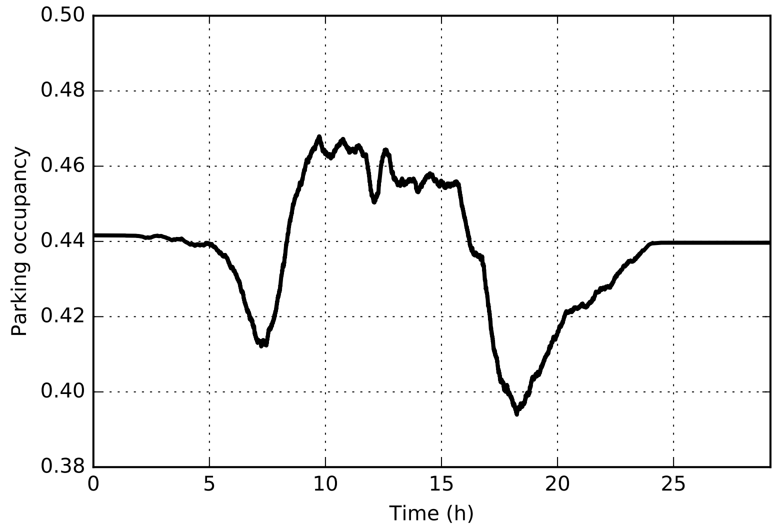


FIGURE 7 Overall parking capacity usage over a typical day for the base scenario without carsharing

corresponding to the rush-hour period when most agents are traveling from home to work. It can also be noticed that the usage of the parking capacity never exceeds 50% of the available spaces, suggesting potential reductions in parking requirements.

However, to properly compute the number of parking spaces we can remove, we need to analyze the maximum parking occupancy not only temporally, but also spatially. Figure 8 shows the maximum registered parking occupancy at a hectare level over the course of a typical day: red indicates high occupancy, whereas blue indicates low occupancy. From these maximum hectare occupancy levels, we compute that, when allowing car drivers to park as close as possible to their destinations without restrictions, only 152,623 of the total available 274,944 parkings spaces are ever used by car-driving agents, representing 55.5% of the total parking spaces in the city.

Next, we explore how much we can further reduce this estimated number of required parking spaces in the presence of free-floating carsharing. Ten different carsharing adoption rates, ranging from 10% to 100% adoption, were tested and in each case, the best-case scenario where the adopting agents gave up their previously-owned private vehicle was used. The agents execute exactly the same plans as in the baseline scenario without carsharing, only the vehicle they use changes. For each adoption rate, the critical fleet necessary to meet the demand was generated such that all carsharing requests are served within a maximum crowfly distance of 300 m between the parking space and facility. This was repeated each time using 20 different random seeds for selecting the carsharing customers and initial locations of the carsharing vehicles.

The average values over all random seeds for each carsharing adoption rate are analyzed. The results are reported as mean values along with their standard deviations, rounded to one or two significant figures. Table 1 shows the number of carsharing users for each adoption rate, the number of carsharing vehicles required to satisfy the demand of those users with a reasonable level of service as well as the number of privately-owned vehicles these shared vehicles replace. The private vehicle

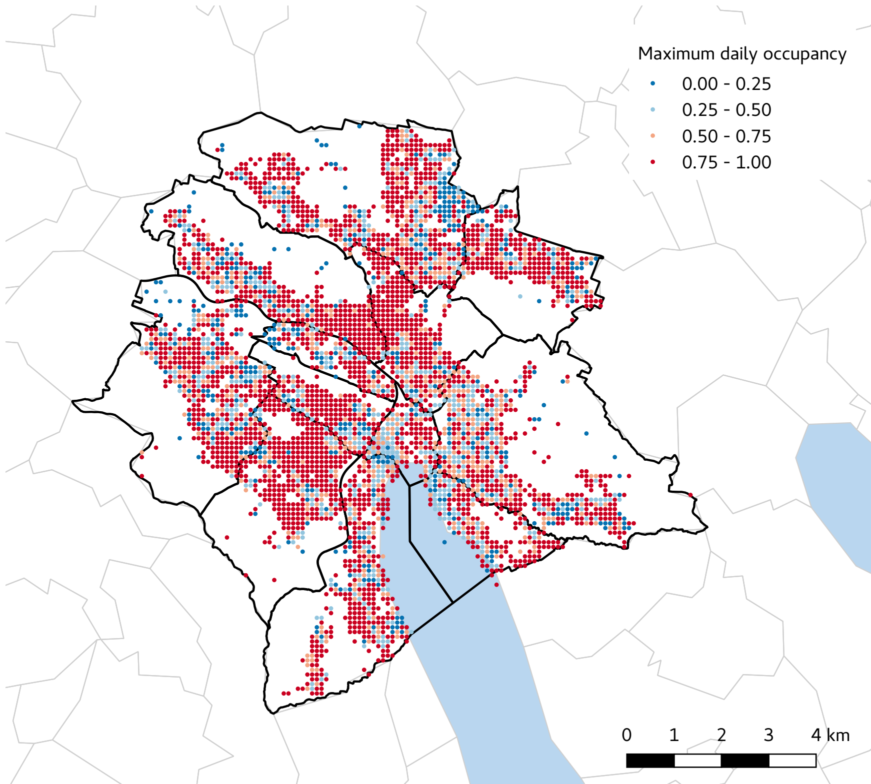


FIGURE 8 Maximum parking space usage over a typical day for the base scenario without carsharing at hectare level

TABLE 1 Vehicle replacement statistics for different rates of carsharing adoption

Adoption rate	Users	Fleet size	Vehicles replaced	Replacement rate
0.1	5190 ± 220	3510 ± 150	5190 ± 220	1.48 ± 0.04
0.2	10300 ± 290	5820 ± 190	10300 ± 290	1.77 ± 0.04
0.3	15420 ± 320	7820 ± 180	15420 ± 320	1.97 ± 0.04
0.4	20630 ± 390	9700 ± 220	20630 ± 390	2.13 ± 0.04
0.5	25760 ± 390	11440 ± 250	25760 ± 390	2.25 ± 0.04
0.6	30850 ± 400	13080 ± 250	30850 ± 400	2.36 ± 0.03
0.7	36100 ± 370	14730 ± 200	36100 ± 370	2.45 ± 0.02
0.8	41280 ± 250	16300 ± 80	41280 ± 250	2.53 ± 0.02
0.9	46510 ± 240	17900 ± 160	46510 ± 250	2.60 ± 0.02
1.0	51590 ± 0	19370 ± 5	51590 ± 0	2.6639 ± 0.0007

replacement rate nearly doubles between the lowest and highest adoption levels, going from nearly 1.5 up to slightly under 2.7 private vehicles for each shared vehicle for a total required fleet of about 19,370 vehicles.

TABLE 2 Trips per user and vehicle by carsharing adopters

Adoption rate	Trips per carsharing user	Trips per carsharing vehicle
0.1	2.86 ± 0.04	4.2 ± 0.1
0.2	2.86 ± 0.04	5.1 ± 0.1
0.3	2.85 ± 0.03	5.6 ± 0.1
0.4	2.85 ± 0.02	6.1 ± 0.1
0.5	2.85 ± 0.02	6.4 ± 0.1
0.6	2.85 ± 0.02	6.72 ± 0.09
0.7	2.85 ± 0.01	6.99 ± 0.07
0.8	2.851 ± 0.008	7.22 ± 0.05
0.9	2.850 ± 0.006	7.40 ± 0.05
1.0	2.848808 ± 0	7.589 ± 0.002

As there are fewer shared vehicles than there previously were private vehicles for the carsharing users, these vehicles perform more trips. Table 2 shows the number of trips per carsharing user and per carsharing vehicle for each adoption rate. Since each carsharing agent previously owned its own car, the trips per user is synonymous to the trips per previously-owned private vehicle. It is therefore obvious that the carsharing vehicles are more efficient, each making up to nearly 2.6 times as many trips than their previous privately-owned counterpart.

Carsharing vehicles reduce the number of vehicles within the city and are more efficient in terms of trips per vehicle. However, their users do need to walk longer to access them, as can clearly be seen in Table 3 which shows the 90th percentile walking distances of carsharing users before and after joining the carsharing service. However, walking distances do decrease with increased adoption of carsharing, since the number of available vehicles increases.

Finally, carsharing allows for substantial reductions in the number of parking spaces used by private vehicles with growing adoption rate, as shown in Table 4. Indeed, in the best-case scenario where all eligible users trade in their private cars to become carsharing customers, a total of just under 28,000 parkings spaces can be removed from the city, representing over 18% of all previously used parking space. It is clear to see that the efficiency of carsharing vehicles in reducing parking requirements also increases with adoption, growing from 0.43 removed spaces per shared vehicle for 10% adoption up to nearly 1.43 for 100% adoption.

If we increase the carsharing threshold crowfly walking distance to 500 m, we estimate that nearly 22% of used parking space could be removed, which is just over 33,000 parking spaces representing 2.35 spaces per shared vehicle. This would require a smaller fleet of just over 14,000 vehicles, each replacing 3.67 private cars and performing nearly 10.5 trips.

Finally, we explore the best scenario in terms of additional reduction in parking requirements for the 500 m walking distance threshold with a 100% adoption rate. Figure 9 shows the effect on the crowfly walking distance distribution under these conditions.

As visualized in Figure 9(a), walking distances from facilities to parking locations tend to

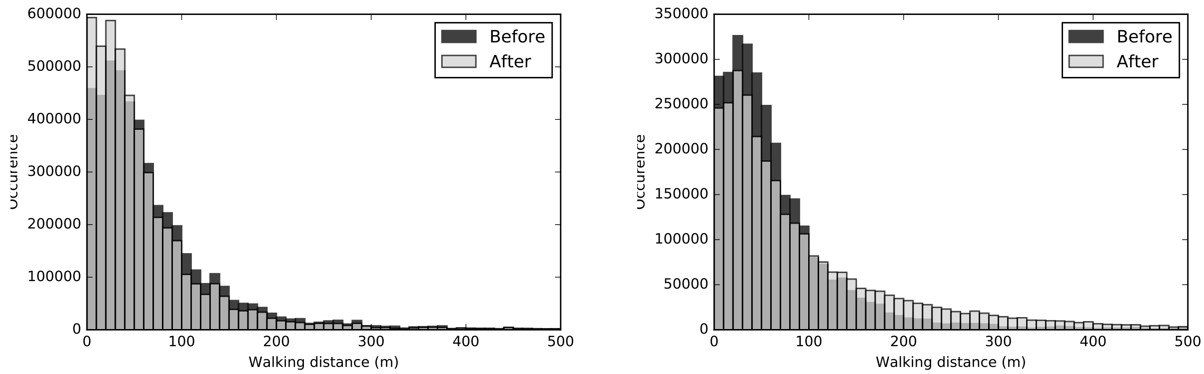
TABLE 3 90th percentile walking distance of carsharing users

Adoption rate	90th percentile walking distance (m) before	after	Increase (m)
0.1	146 ± 4	212 ± 4	67 ± 5
0.2	145 ± 3	202 ± 3	58 ± 3
0.3	145 ± 2	197 ± 3	53 ± 2
0.4	145 ± 2	192 ± 3	47 ± 2
0.5	145 ± 1	188 ± 2	43 ± 1
0.6	145 ± 1	185 ± 2	40 ± 1
0.7	145 ± 1	183 ± 2	38 ± 1
0.8	144.6 ± 0.6	181 ± 1	36 ± 1
0.9	144.7 ± 0.6	179.2 ± 0.8	34.5 ± 0.9
1.0	144.844744 ± 0	178.3 ± 0.1	33.4 ± 0.1

TABLE 4 Parking space reduction due to carsharing

Adoption rate	Removable spaces	Share of used spaces (%)	Removable spaces per shared vehicle
0.1	1520 ± 180	1.0 ± 0.1	0.43 ± 0.05
0.2	4090 ± 220	2.7 ± 0.1	0.70 ± 0.04
0.3	6800 ± 230	4.5 ± 0.1	0.87 ± 0.04
0.4	9780 ± 310	6.4 ± 0.2	1.01 ± 0.04
0.5	12680 ± 300	8.3 ± 0.2	1.11 ± 0.03
0.6	15660 ± 300	10.3 ± 0.2	1.20 ± 0.03
0.7	18650 ± 290	12.2 ± 0.2	1.27 ± 0.03
0.8	21690 ± 230	14.2 ± 0.1	1.33 ± 0.02
0.9	24670 ± 230	16.2 ± 0.1	1.38 ± 0.02
1.0	27650 ± 120	18.12 ± 0.08	1.428 ± 0.006

decrease for those agents who previously and still use their private vehicle. This is rather intuitive, since there are fewer vehicles parked in the city and therefore more available space for private vehicle drivers to park closer to their destinations. In contrast, walking distances tend to increase for agents who previously drove a private vehicle and now have switched to carsharing, as can be clearly seen in Figure 9(b). Due to the constantly changing distribution of the carsharing fleet, carsharing customers will sometimes need to walk further to a parking location to unpark an available vehicle than they initially needed to walk from the location where they parked their previously used vehicle. Indeed, 90% of walking trips made between parking and facility locations were achieved in less than 138 m after the introduction of carsharing as opposed to in under 158 m before carsharing by those who had not adopted carsharing, whereas this number increased from 145 m to 248 m for



(a) Trips previously performed using a private car still performed by private car

(b) Trips previously performed using a private car now performed using carsharing

FIGURE 9 Impact on crowfly walking distance distributions due to the introduction of carsharing

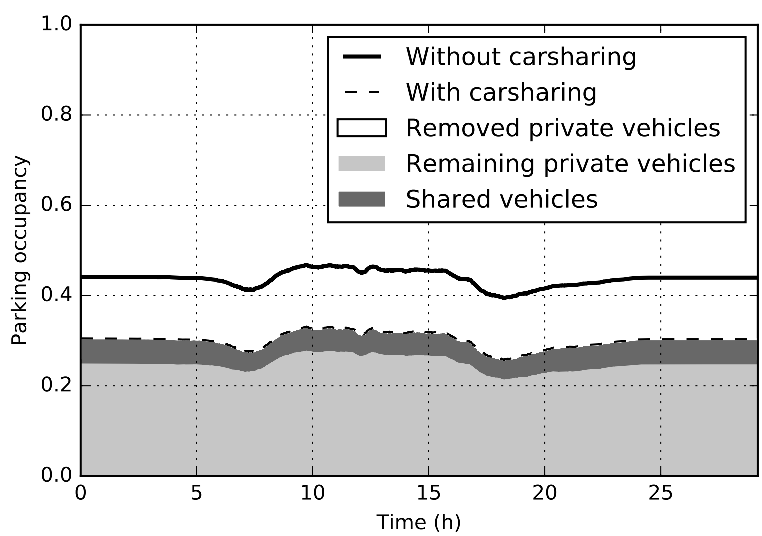


FIGURE 10 Overall parking capacity usage over a typical day in the best-case carsharing scenario

those who made the switch.

Figure 10 shows the parking occupancy levels over the course of a typical day after the full adoption of carsharing by all eligible customers in comparison to the baseline scenario. The solid black line shows the overall parking occupancy levels without carsharing and is the same curve as shown in Figure 7. The dashed black line on the other hand represents the overall parking occupancy levels after 100% of eligible agents for carsharing made the switch. The difference between the solid and dashed line are carsharing customers' previously owned private vehicles that have now been removed from the system, whereas the shaded areas under the dashed line represent the remaining

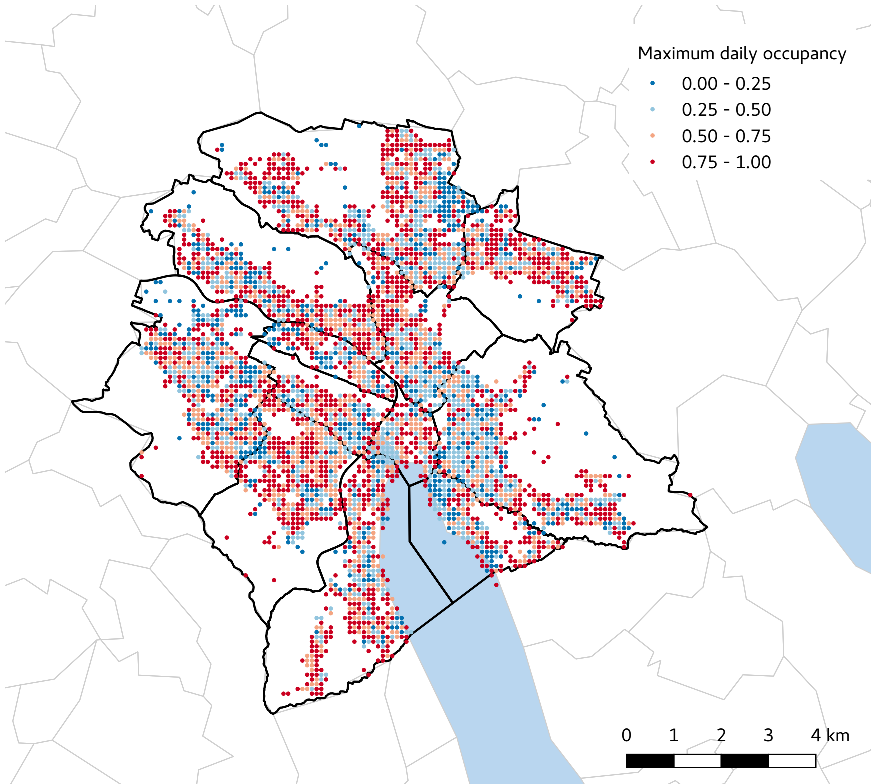


FIGURE 11 Maximum parking space usage over a typical day for the best-case carsharing scenario at hectare level

private vehicles and added carsharing vehicles respectively. We can clearly see that the replacement of all eligible trips by carsharing dramatically reduces the overall parking occupancy levels within the city.

Again, we further analyze parking occupancy spatially and compute the maximum recorded parking occupancy at a hectare level over the course of a typical day, shown in Figure 11. We observe that the overall color shifts toward blue, indicating an overall lowering of the maximum daily parking occupancy levels. Indeed, in this best case where 100% of eligible carsharing agents adopt the service and all car drivers are allowed to park as close as possible to their destinations without restriction, only 119,254 of the previously required 152,623 parkings spaces are now necessary to serve the demand, corresponding to an parking requirement reduction of nearly 22%.

DISCUSSION AND FUTURE WORK

The analyses presented show that free-floating carsharing can help to reduce parking requirements in the city of Zurich by 18% if all trips that were previously made with a private vehicle are now carsharing trips, while ensuring that a carsharing vehicle is always available within a 300 m crowfly distance. Furthermore, for the maximum adoption rate and when every adopter gives up its own vehicle, one carsharing vehicle can replace approximately 1.43 parking spaces. By increasing the distance to 500 m, the parking requirement reduction increases to 22%, replacing approximately 2.35 parking spaces per carsharing vehicle.

At a first glimpse, these estimates represent a sizable fraction of the total space in the city, currently only used to store vehicles, that could be potentially be converted to others uses. However, there are several limitations to the analysis that now need to be discussed.

First, we neither distinguish between the different types of parking facilities, nor do we consider any costs, time limits or any other restrictions associated with parking in a specific location, whether it be in the base scenario or any of the scenarios including carsharing. This simplification allows both for a fair comparison of carsharing and private vehicles when both are equally allowed to park on the same spaces without any restrictions as well as an analysis of how much better we could use the parking infrastructure. It does however present some limitations. These parking policies, amongst others, help regulate the number of car users in the city and control congestion. Completely ignoring them could therefore lead to negative impacts such as a higher share of trips performed by car and higher congestion levels, which could completely offset the positive benefits brought on by a reduction of parking requirements. It would therefore be interesting to conduct additional comparisons that actually consider parking types, costs and duration limits in the next step of our work.

We also would like to specify that our estimate of a 44.5% reduction in the baseline case without any carsharing is rather an upper limit, since there indeed needs to be some minimal amount of parking left free, in part to accommodate the vehicles that are excluded in the MATSim scenario (delivery and service vehicles, business vehicles, tourists, etc.) but also to make sure no high parking search times or congestion builds up. Nevertheless, it does provide an indication that there do exist some substantial gains that can already currently be made today in terms of reducing parking requirements.

In addition, some limitations and improvements can also be mentioned when additionally considering the impact of carsharing on the usage of the parking infrastructure. In order to generate the optimal fleet to meet the demand for carsharing while insuring a minimal level of service, we simply add carsharing vehicles as they are needed until all requests are served. This makes it convenient for modeling purposes, but it creates a lot of idling times that have negative impacts on the system. As a result, this would most likely not happen in reality. We are therefore probably overestimating the amount of carsharing vehicles needed and consequently the amount of parking space needed to store these vehicles. More efficient techniques for generating a fleet of carsharing vehicles capable of meeting the demand should therefore be investigated.

With such large fleet-sizes, the relocation of carsharing vehicles might come into play. This in turn might further optimize the service, removing those vehicles that are not so frequently used and even further reduce the parking needs. However, this would raise maintenance and organizational costs for the service providers.

Finally, we do not consider any change of destination, departure time or mode that carsharing might trigger, as the agents' baseline plans are maintained as is and only those eligible for the service switch their modes from car to carsharing. This additional simplification is important to point out as it might affect the impacts on parking. We supposed that in the presence of a highly performant carsharing service, the usage would increase and so would the parking requirements.

CONCLUSION

This work provides a best-case estimate for the minimal parking requirements for the city of Zurich following the introduction of a free-floating carsharing service. By only considering passenger traffic and allowing all agents within our simulations to park in any available parking space closest to their destination locations, it can be shown that up to 22% of all currently used parking spaces within the city could be rendered obsolete after the massive adoption of free-floating carsharing. This of course neglects any parking regulations required to insure sufficient space for delivery, service, business or tourist vehicles and does not account for the potentially higher share of trips performed by car and higher congestion levels induced by such a parking policy. Although these estimates do present some limitations, they also highlight the remarkable fraction of the total space in the city, currently only used to store vehicles, that could potentially be converted to others uses. Evidently, there is still room to better utilize our parking infrastructure and carsharing could help provide further improvements, both today and in the future.

AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows: study conception and design: Christopher Tchervenkov, Milos Balac, Sebastian Hörl, Henrik Becker; implementation: Christopher Tchervenkov; code optimization: Christopher Tchervenkov and Sebastian Hörl; simulations: Christopher Tchervenkov; analysis and interpretation of results: Christopher Tchervenkov, Milos Balac; draft manuscript preparation: Christopher Tchervenkov, Milos Balac, Kay W. Axhausen. All authors reviewed the results and approved the final version of the manuscript.

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