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# Assessing the welfare impacts of Shared Mobility and Mobility as a Service (MaaS)

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A B S T R A C T

*Mobility as a Service* (MaaS) is an attempt to overcome market segmentation by offering transport services tailored to the individual traveler's needs. An alternative to prior investment into single mobility tools, it may allow less biased mode choice decisions. Such a setting favors shared modes, where fixed costs can be apportioned among a large number of users. In turn, car-sharing, bike-sharing or ride-hailing may themselves become efficient alternatives to public transport. Although early field studies confirm the expected changes away from private car use and towards public or shared modes, impacts are yet to be studied for larger transport systems. This research conducts a first joint simulation of car-sharing, bike-sharing and ride-hailing for a city-scale transport system using MATSim. Results show that in Zurich, through less biased mode choice decisions alone, transport-related energy consumption can be reduced by 25%. In addition, introduction of car-sharing and bike-sharing schemes may increase transport system energy efficiency by up to 7%, whereas the impact of ride-hailing appears less positive. Efficiency gains may be higher if shared modes were used as a substitute for public transport in lower-density areas. In summary, a MaaS scheme with shared mobility may allow to slightly increase system efficiency (travel times & cost), while substantially reducing energy consumption.

## 1. Introduction

In current transport systems, short-term travel behaviour is to a large extent governed by long-term choices of mobility tool ownership. Such mobility tools usually require a substantial investment up-front and subsequently allow to travel with the specific modes at low (or zero) marginal cost. Eventually, distinct mobility portfolios arise dividing a population into car drivers and transit riders (Becker et al., 2017c).

The concept of *Mobility as a Service* (MaaS) aims to break the determining role of car ownership. Instead, travelers are presented a variety of travel options tailored to their respective needs, either as a subscription package or in a pay-per-use approach, by an integrated mobility provider (Kamargianni et al., 2016; Jittrapirom et al., 2017; Mulley, 2017). Consequently, short-term mode choice decisions are driven by the actual cost of use (instead of fixed/sunk costs biasing decisions to a certain mode), which allows for a more time- and cost-aware travel behaviour - an observation already made for early car-sharing customers (Cervero and Tsai, 2004) More recently launched shared mobility services already point into this direction: Uber, Bridj, car2go as well as many others do not charge membership fees, but follow a pay-per-use approach. However, it is unknown if they currently charge their average cost per km (including overheads and profit margins).

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In the past years, there were first attempts to transfer this concept to private cars and public transport, and thus turn travellers into mobility consumers. For example, Sochor et al. (2015, 2016) conducted a six-month field test in the city of Gothenburg, Sweden, in which participants could purchase a monthly credit for the use of individual cars, car-sharing and public transport. Using one-week travel diaries, they show that participants generally over-estimated their actual travel demand and that as MaaS users, they would substantially reduce their use of individual cars and increase their use of public transport instead.

However, it is still unclear how to re-design a whole transport system to reap these benefits of MaaS shown in small-scale field tests. In particular, this will require changes in the supply side of the system, i.e. restructuring public transport services (Hensher, 2017) and integrating them with novel systems of shared mobility (Cervero, 2017). On the demand side, the first insights from field tests have to be generalized to learn more about the preferences of travellers in such integrated mobility systems (Matyas and Kamargianni, 2017). Indeed, differences observed between Uber riders and taxi customers or users of different car-sharing schemes indicate that even small changes in the service types may attract different customer segments (Rayle et al., 2016; Becker et al., 2017a)

Following the approach suggested by Ciari and Becker (2017), a framework to assess the impact of supply side characteristics of a potential MaaS scheme on the transport network is developed in this research. Variables include type and fleet sizes of shared modes, their integration with public transport and additional taxes on car travel. Target indicators are generalized cost (welfare) measures, total network travel times and total energy consumption. The framework is applied to the city of Zurich, Switzerland. The aim of this research is to provide some first simulation-based evidence on possible system-level impacts of large-scale MaaS schemes and the role shared mobility can play in such an integrated service. The results may help to generate additional research to provide more detailed analyses of relevant aspects.

## 2. Background

For almost a century, private cars have dominated transport systems in industrialzied countries around the globe, by far outnumbering any form of collective transportation. A main reason for this (among various others) is that accessibility levels by public transport are usually substantially lower than those by car - even in Switzerland, which arguably has one of the best public transport offerings worldwide, there is a 35% difference (Axhausen et al., 2011). Whilst in dense cities, bundling passengers in buses or trains allows to increase system capacity (Loder et al., 2017), such bundling is not feasible in low-density neighborhoods or countrysides and usually results in long headways and/or stop-spacing. In such situations, demand-responsive transit services (Mulley and Nelson, 2009) may help to extend public transport networks, although no large-scale implementations have been tested yet.

In recent years, numerous new mobility services have emerged, such as bike-sharing (Fishman et al., 2016), car-sharing (Shaheen and Cohen, 2013) or ride-hailing services like Uber. They mostly operate in urban areas and often attract public transport users, thus also having a potential of extending public transport networks by offering last-mile connections (Fishman et al., 2014) or fast tangential trips (Becker et al., 2017b). However, currently, most such schemes are operated independently from each other and from collective transportation, so that reaping such benefits cannot be guaranteed.

MaaS aims to combine existing modes of collective transportation with such emerging services to establish a more attractive alternative to the private car (Kamargianni et al., 2016; Jittrapirom et al., 2017; Mulley, 2017). A twofold integration will be required to achieve this goal

- integrated strategic and operational planning across all mobility services (i.e. network/service areas, fleet sizes, fare integration),
- integrated user interface, through which all services can be accessed and booked.

While the first part is obviously required to offer a seamless mobility solution, the second part allows travelers to make informed (and therefore better) decisions.

Sochor et al. (2015, 2016) conducted a first field test of a MaaS scheme with an emphasis on the second part (integrated user interface). In their study, participants purchased credit for the use of different mobility services, which they could then book through a unified service center. The results indicate that participants typically over-estimated their need for private car use. This is in line with an observation made for car-sharing customers, who often switched to a public transport lifestyle and use car-sharing vehicles for far less trips than they previously used their car for (Cervero and Tsai, 2004). Such observations point at one key behavioral implication of MaaS: Current transport modes are typically dominated by fixed costs (Becker et al., 2017c; Bösch et al., 2018), so that acquisition of a mobility tool often predetermines later mode choice (because of the low marginal costs). MaaS overcomes the separation of fixed (sunk) and marginal costs by a pay-per-use approach. This way, it enables travelers to take unbiased and hence, more suitable mode choice decisions.

Yet, user interface and cost transparency are only two ways, through which MaaS contributes to a more efficient transport system. A third way lies in a supply-side integration. Various forms of organizational and contractual frameworks have been proposed to accomplish this integration whilst maintaining certain levels of autonomy for the individual operators (Ambrosino et al., 2016; Hensher, 2017; Smith et al., 2018). However, the question of which particular systems to include in an effective MaaS offering has not been addressed yet.[1] Moreover, it is still unclear, to what extent they could even substitute current line-based public transport services (Hensher, 2017).

Various new mobility services have emerged in the past years, ranging from dynamic ride-pooling services like *Via*[2] in New York

[1] Aiming for maximum attractiveness, Mulley (2017) suggests to include all available modes.
[2] https://ridewithvia.com/.

City to electric bike-sharing like *Smide*[3] in Zurich. Given the novelty and variety of such schemes, there is only limited knowledge about their overall impacts on the transport system. Moreover, insights gained about one scheme cannot necessarily be transferred to others. For example, it has been established that station-based (round-trip) car-sharing schemes leverage a reduction in their members' vehicle ownership and vehicle miles traveled (Cervero and Tsai, 2004). For free-floating car-sharing, such impacts were found to be substantially weaker, because this structually different service attracts other user groups and usage patterns (Becker et al., 2017a). Also for ride-hailing, Rayle et al. (2016) found the user types and demand patterns to be different from taxi riders. Moreover, differences do not only appear between schemes, but also between cities. For example, Fishman et al. (2014) suggest that the ecological impact of bike-sharing strongly depends on city characteristics. They found that while bike-sharing may help to reduce $CO_2$ emissions in car-centered cities, they may even trigger an increase in transit-oriented cities. Also, such schemes will likely be used differently when integrated with public transportation: As shown by Wang and Ross (2017) for the case of New York City, taxi trips made in connection with a public transport trip are typically shorter and are done by lower income users than point-to-point taxi trips. However, there have hardly been any empirical results on the interrelations between the different emerging mobility services yet.

Instead, simulation-based and game-theory approaches have mostly been used to study interactions of emerging modes. For example, Djavadian and Chow (2017) modeled a MaaS scheme offering first/last mile services. Their results reveal the existence of stable local optima for fleet sizes and fares. Those findings extend earlier research by Li and Quadrifoglio (2010), who define critical demand levels below which demand-responsive services serve demand more efficiently. Generalizing these insights to maximizing social welfare instead of minimizing operational costs, Kim and Schonfeld (2015) presented an approach to define a welfare threshold between conventional and flexible services in systems with multiple dissimilar regions. The welfare-centric approach was also supported by Qiu et al. (2018), who suggest that minima of monetary cost may not correspond to a transport system-level optimum given that also MaaS fleets contribute to road congestion. For the case of ride-sourcing schemes, Zha et al. (2016) even found that a welfare-optimum state could only be reached if competitors were forced to merge and subsequently be regulated.

For the case of shared mobility, optimization has mostly been performed with respect to profit. Jorge and Correia (2013) and Li et al. (2018) provide an overview of such approaches, which mostly addressed fleet sizes, station locations, service areas, reservation policies or relocation strategies for car-sharing services. Similar approaches have been developed for bike-sharing (Raviv et al., 2013). However, most of such optimization approaches have substantial limitations, such as a small study area, no load-dependent travel times or fixed demand. Moreover, the individual emerging modes have usually been studied in an isolated manner. To address those limitations, Ciari et al. (2015) simulated free-floating car-sharing as part of the transport system using the agent- and activity-based transport simulation tool MATSim (Horni et al., 2016). In particular, this allows to study substitution effects with other modes (private car, schedule-based public transport, bike and walk). Although this approach does not allow mathematical optimization of a target function, it allows to perform a scenario-based analysis to identify plausible, near-optimal solutions. Also, MATSim has recently been extended to model automated taxi services (Hörl, 2017) or competing operators of shared mobility (Balac et al., 2019).

In this research, MATSim is further extended to allow a first joint simulation of large scale car-sharing, electric bike-sharing and ride-sourcing schemes to study their interactions with each other as well as with the existing transport system. Also, a potential integration with line-based public transportation including a subsidy framework is tested. The various scenarios are then used to understand, how large fleets of shared modes could contribute to welfare and resource efficiency of the transport system. This way, the potential efficiency gains of the strategic and operational integration aspect of MaaS (step 1) are studied, assuming that the integrated user interface (step 2) is already in place.

The approach is applied to the greater Zurich area. Zurich presents a special case, because it not only has a highly-developed public transport network reaching a 32% mode share[4]. In addition, a number of conventional and electric bike-sharing schemes as well as an electric scooter-sharing scheme have been launched in the recent years, complementing the already existing station-based car-sharing scheme called Mobility[5]. Also Uber is already present in the market with its UberX, UberBlack and UberGREEN services. Hence, Zurich already is a test-lab for diverse emerging mobility services, none of which, however, is integrated with the public transport providers.

## 3. Methodology

In this research, the agent-based microsimulation tool MATSim (Horni et al., 2016) is used to simulate use of MaaS services in the city of Zurich. In MATSim, a synthetic population of agents aims to pursue their desired daily activities whilst trying to minimize their generalized cost of travel. Agents' choice dimensions include the transport mode and route for each trip. A key advantage of MATSim is that it offers a dynamic demand response towards changes in service attributes such as travel times or costs. Agents have predefined (fixed) levels of mobility tool ownership (cars, season tickets and car-sharing membership), which reflect the current distribution in the local population.[6] In the standard model, cars, public transport (timetable-based and routed), bike and walk are available modes. For this research, car-sharing services are added using earlier work of Balac et al. (2015, 2017, 2019) and a plugin for autonomous taxis (Hörl, 2017) is used to simulate ride-hailing services. In addition, a framework to simulate free-floating electric

[3] https://www.smide.ch/.

[4] For trips within the city of Zurich, according to Planungsbüro Jud (2012) Städtevergleich Mobilität https://skm-cvm.ch/cmsfiles/130124_stadtevergleich_mobilitat.pdf.

[5] https://www.mobility.ch/en/.

[6] Note that current MATSim does not allow agents to change their portfolio of mobility tools, nor their home or work locations. In this research, a fixed level of car-ownership means that the actual VMT reduction impact of shared modes may be higher than reported in the results.

bike-sharing services was implemented for this research (see Appendix A). To the authors' best knowledge, this is the first time that these different modes of shared mobility are jointly simulated not only in MATSim, but in any agent-based model.

### 3.1. Implementation of shared modes

All shared services are simulated on a microscopic level. Hence, the number of available vehicles (supply) is both limited and time- and space-dependent. For bike-sharing and car-sharing trips, agents identify the closest available vehicle, which they subsequently access by walk. The trip is routed on the congested network (car-sharing only). At the end of the trip, the shared bike or car is parked at the agent's destination. Availability of vehicles at the trip start time is recorded to inform re-planning decisions in the following iterations (see below for details). A detailed presentation of the car-sharing framework is provided by Balac et al. (2019). The implementation of the bike-sharing framework is described in Appendix A. Agents using the ride-hailing service wait at their origin to be picked up by the closest available ride-hailing vehicle. The actual waiting time is stored and used in the later iterations to estimate the expected waiting time at the specific location. After being picked up, the agent is driven on the congested network to its destination, where it is dropped off. The vehicle remains at the drop-off location until it is dispatched to serve a new customer. Details are provided by Hörl (2017).

Although MATSim's shared-mobility extensions allow to assign membership to specific subgroups of agents for shared modes, in this research it is assumed that all agents have access to all (shared) modes, irrespective of any memberships.[7] Following general practise, car-sharing and electric bike-sharing are only considered available for agents holding a driver's license. Shared modes are available for all trips within a pre-defined service area. In this research, the service area covers the city of Zurich as well as a small belt around it (including the airport). It is shown in Fig. 1. The area has around 380 000 residents of which about 280 000 hold a drivers license. Initial positions of bike-sharing, car-sharing and ride-hailing vehicles were drawn randomly from the population density distribution within the service area.

Fares are based on current implementations of free-floating car-sharing, free-floating e-bike-sharing and ride-hailing in Switzerland and are calculated as follows:

- *Car-sharing:* $0.38\ \text{CHF/min}\cdot t$
- *Bike-sharing:* $0.25\ \text{CHF/min}\cdot t$
- *Ride-hailing:* $\max\{6.0\ \text{CHF};\ 3.0\ \text{CHF} + 1.8\ \text{CHF/km}\cdot d + 0.3\ \text{CHF/min}\cdot t\}$

where $t$ is the travel time in minutes and $d$ is the in-vehicle distance in kilometers. Of course, larger fleet sizes and integration with other (shared) modes may result in different fares. However, to limit complexity, fares were assumed fixed in this research.

As a comparison: public transport fares in MATSim are 0.36 CHF/km, with season tickets reducing this fare by 50% or 100%.[8] For car trips, a perceived (marginal) cost of 0.27 CHF/km is assumed following Hörl et al. (2018b). This value does not include any fixed cost (not considered in MATSim), but only the perceived cost of car travel relevant in mode choice.

### 3.2. Mode choice

The MATSim simulation follows an iterative process, in which after each iteration, a certain number of agents are allowed to change their mode and/or route to reduce their generalized cost of travel (re-planning). At this stage, a discrete mode choice extension for MATSim is used in the re-planning phase to allow for mode-choice decisions.[9] Agents chosen for re-planning are allowed to change their modes of travel on a tour level by using an MNL mode-choice model (introduced below). The discrete mode choice extension makes sure that only feasible mode chains are possible (e.g. car-transit-car mode chain is not feasible as an automobile needs to be available for the second car trip). Benefits of using an estimated mode-choice model and how it was integrated in the re-planning phase of the MATSim loop can be found in Hörl et al. (2018a, 2019).

To the authors' best knowledge, no mode choice models exist yet, which cover all seven modes simulated in this research. Therefore, mode choice parameters are based on a recent stated-preference experiment on automated vehicles (Hörl et al., 2018b). The general form of the utility for mode $m$ is:

$$U_m = \alpha + \beta_{tt,m}\cdot tt_m + \delta_{m=cycling}\cdot\beta_{age}\cdot(\text{age} - 18) + \beta_{access,m}\cdot tacc_m + \delta_{m=PT}\cdot\beta_{transfers}\cdot\#transfers_m + \beta_{cost,m}\cdot\left(\frac{dist}{40\ \text{km}}\right)^{\lambda}\cdot cost_m \tag{1}$$

Since the mode choice model described in (Hörl et al., 2018b) does not include services like bike-sharing, car-sharing and ride-hailing, the respective mode choice parameters were defined as follows: For the valuation of travel time of bike-sharing and car-sharing, the respective parameters for bike and car were used. This is motivated by earlier research of Li and Kamargianni (2018) who show this equivalence using survey data for a Chinese context. For ride-hailing, half of the value for public transport was used to account for the increased level of comfort and privacy.[10] For all shared modes, access walk parameters were assumed to be equal to

[7] For most free-floating schemes, this is already the case given that they only charge a small registration fee. For ride-hailing services users can usually sign up for free.

[8] The simulation does not exactly model the zone-based fare system, which actually is in place. Instead, fares are broken down into marginal cost while roughly maintaining the same level of average fares.

[9] www.eqasim.org.

[10] To the authors' best knowledge, no earlier research is available which would allow a more accurate assumption. Anyway, implications on the

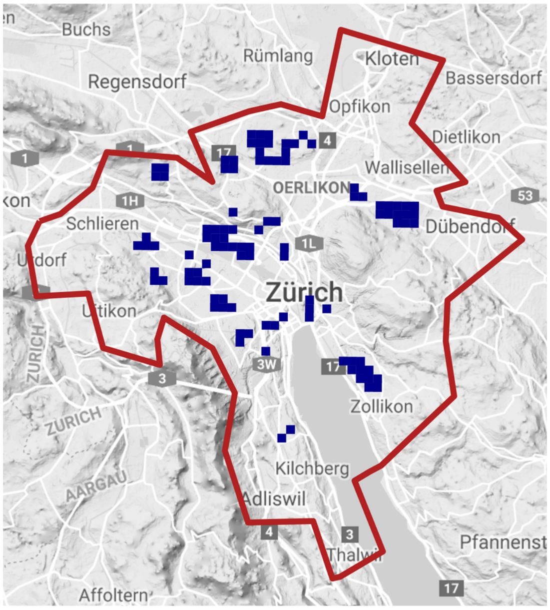



**Fig. 1.** Service area for shared modes. Blue zones denote areas eligible for subsidies (see Section 4 for details). Background map by Google Maps (maps.google.com). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

public transport access walk parameters. This also corresponds to results of earlier research (compare Li and Kamargianni (2018) and Miguel Martinez et al. (2017)). Waiting time for ride-hailing was assumed 50% of the corresponding parameter for public transport (motivated by Frei et al. (2017)).

Alternative-specific constants were used to calibrate the number of daily rentals per vehicle in the base case. For free-floating car-sharing around 5 rentals per vehicle are assumed for small fleet sizes (compare Habibi et al. (2017)). For bike-sharing 6–8 rentals per bike were assumed realistic for Zurich.[11] Finally, based on taxi data from New York City, up to 35–40 daily rentals per vehicle were assumed realistic for a highly utilized ride-hailing scheme.[12] All resulting mode choice parameters used in this research are summarized in Table 1.

It should be noted that such a combination of partial mode choice models may only have limited validity. Hence estimating a dedicated choice model based on empirical data capturing all those modes simultaneously would be a superior approach. In both cases, a sensitivity-analysis could help to account for potential changes in behavior or errors in the model. However, in this research such a sensitivity analysis had to be omitted due to the high computational burden associated with it.

### 3.3. Cost structures

To allow economic analysis of the schemes, their respective cost structures were estimated using the framework of Bösch et al. (2018). The values are presented in Table 2. Fixed and variable vehicle cost for car-sharing and ride-hailing are derived from Bösch et al. (2018) for the case of conventional midsize vehicles operated as a shared fleet. For ride-hailing, the variable vehicle cost is increased by 15% compared to car-sharing to account for empty rides (Bösch et al., 2018). For bike-sharing, fixed cost were assumed to equal the retail price of the cheapest Stromer e-bike, minus 25% discount, written off over 5 years with 200 business days per year. This roughly corresponds to the current system characteristics of the local e-bike sharing scheme Smide in Zurich. For the variable costs, a product test revealed maintenance cost of 0.135 CHF/km for private customers, off which 25% discount was subtracted for larger fleets (economies of scale).[13] Overhead and management cost were used from Bösch et al. (2018), but reduced by 50% for e-bikes.[14] For ride-hailing services, it is assumed that each vehicle is driven for 14 h[15] with a gross salary of 20 CHF/h.[16]

(*footnote continued*)
results are minor since the utility function of ride-hailing is dominated by the fare component.

[11] https://edition.cnn.com/travel/article/bike-share-boom-global-report/index.html.

[12] http://toddwschneider.com/posts/taxi-uber-lyft-usage-new-york-city/.

[13] https://www.ktipp.ch/artikel/d/e-bikes-pannen-trueben-den-fahrspass/.

[14] Bike-sharing schemes usually supply more bikes per member, so that user administration cost per bike is lower (compare Zhao et al. (2014)). In addition, bikes are easier to collect when service is required.

[15] There may actually be more than one driver per vehicle.

[16] This roughly corresponds to the salary of newspaper delivery workers (compare https://www.srf.ch/sendungen/kassensturz-espresso/themen/arbeit/zeitungsvertraeger-so-schlecht-zahlt-die-post).

**Table 1**
Mode choice parameters for conventional modes (left) (Hörl et al., 2018b) and assumptions for shared mobility (right).

| | Walk | Bike | Car | PT | FFCS | FFBS | Ride-hailing |
|---|---|---|---|---|---|---|---|
| Constant | 0.631 | 0.344 | 0.827 | | −0.300 | −0.300 | −0.300 |
| Travel time [min] | −0.141 | −0.080 | −0.067 | −0.019 | −0.067 | −0.080 | −0.010 |
| Age (>17) | | −0.049 | | | | −0.049 | |
| Access walk [min] | | | | −0.080 | −0.080 | −0.080 | |
| Waiting time [min] | | | | −0.038 | | | −0.019 |
| Number of transfers | | | | −0.170 | | | |
| cost [CHF] | | | | −0.126 | | | |
| $\lambda$ | | | | −0.400 | | | |

**Table 2**
Cost structures of shared mobility services.

| | Bike-Sharing | Car-Sharing | Ride-Hailing |
|---|---|---|---|
| Fixed vehicle cost (CHF per veh./day) | 4.1 | 8.5 | 8.5 |
| Variable vehicle cost (CHF per km) | 0.101 | 0.223 | 0.256 |
| Overhead & management cost (CHF per veh./day) | 7 | 14 | 14 |
| Driver's salary (CHF per veh./day) | | | 280 |

### 3.4. System-level analyses

To allow an evaluation of the system-level impacts of the MaaS services, all scenarios are evaluated with respect to three key indicators:

- **total network travel time**: sum of travel times of all trips
- **generalized cost**: sum of the (dis-)utility of all performed trips (c.f. Eq. (1)), to which profits or losses of shared mobility operators as well as subsidies paid for public transport services are added. For private car travel, the full costs are considered in all cases.[17]
- **total energy consumption**: distance of all trips multiplied with an energy consumption factor. For private cars, an average gasoline consumption of 6.5 l/100 km was assumed.[18] Car-sharing vehicles operating in Basel and Geneva are VW up with an official consumption of 4.1 l/100 km. For electric bikes, a consumption of 1 kWh/100 km is assumed.[19]. For public transport, the total energy consumption reported by the local bus and tram provider was used.[20] Fuel consumption was converted into energy at 9.7 kWh/l.

For the system-level analyses, all trips conducted within the service area (compare Fig. 1) are considered, including those made by public transport or private car.

## 4. Scenarios

The main goal of this research is to study how a large-scale MaaS system could help to increase efficiency of the transport system. To this end, walk, bike, private car, public transport, electric bike-sharing, car-sharing and ride-hailing are all available to agents at their marginal cost. This way, mode choice is assumed unbiased from fixed / sunk costs, theoretically yielding more optimal results.

Hence, no subscriptions are considered for any of the shared modes. Only for public transport, season tickets are still in place. For the private car, only marginal costs are considered. Here, two cost levels were analyzed: First, the marginal cost of car travel was set to the currently perceived costs (0.27 CHF/km), while in a second step, the full costs according to Bösch et al. (2018) are assumed relevant for the agents' mode choice decisions (0.64 CHF/km)[21].

Since the impact of shared mobility schemes may depend on their respective fleet sizes, different scenarios have been defined covering all combinations of the set fleet sizes:

- *Car-sharing:* 0, 250, 1000, 4000, 8000
- *Bike-sharing:* 0, 250, 1000, 4000, 8000

[17] For *Scenario 1*, the hidden cost was added to the disutility.
[18] For fuel consumption data of new car registrations compare http://www.verbrauchskatalog.ch/de/informationen/verbrauch.
[19] Compare https://www.stromerbike.com/en_INT/e-bikes/st5.html.
[20] VBZ business report for 2017: https://www.stadt-zuerich.ch/vbz/de/index/die_vbz/geschaeftsbericht.html.
[21] In this context, the full cost include acquisition cost, fuel, vehicle maintenance, insurance, taxes, administration and any other expense related to private car ownership and use.

- *Ride-hailing:* 0, 250, 500, 1000, 5000

The fleet sizes were chosen to cover all possible implementations from small fleets towards multiples of today's number of vehicles. For example, Uber claims to have 2500 drivers at their service across all of Switzerland as of July 2018.[22] Moreover, about 1800 shared bikes were available in the city of Zurich in early 2018.[23] Free-floating car-sharing is currently not available in Zurich, however, in other Swiss cities schemes operate with up to 150 vehicles.[24] Fleets smaller than 250 vehicles were not simulated for computational reasons.[25] Simulations included a baseline case with zero fleet size for all three shared modes.

In the first part of the analysis, impacts on transport system performance are studied for all combinations of fleet sizes using the perceived costs for private cars (*Scenario 1*). Second, the analysis is repeated for the full cost of private cars (*Scenario 2*). Each of the scenarios is then evaluated with respect to total generalized cost, total network travel times and total energy consumption.

Yet, shared modes may not only increase system performance by complementing existing modes, but in certain situations, they may also represent an efficient substitute. To test this hypothesis, the 25 bus and tram lines operating in the city of Zurich with a fare recovery rate of less than 75% were removed.[26] This would amount to (hypothetical) savings of more than 200 000 CHF per day. In those areas, for which the distance to the next served public transport stop is increased by more than 50 m through this measure, use of shared mobility is subsidized as follows:

- subsidies are paid for any trip starting or ending in an eligible zone,
- ride-hailing trips are subsidized with 50% of the fare,
- those portions of bike-sharing or car-sharing fares, which exceed the corresponding public transport fare are subsidized by 100%, i.e. travelers only pay rental charges up to the fare of the alternative (removed) public transport service.

To identify zones eligible for subsidies, the city was divided into 250 m grid cells. Fig. 1 highlights the cells eligible for subsidies.

Of course, such a rough approach can only provide very first insights. In particular, it is well possible that removing a public transport line will affect the productivity of various remaining lines. As a result, an optimal public transport network subject to the budget contraint stated above may likely look different.

## 5. Results

More than 150 single scenarios were simulated in MATSim. For brevity, only a selection showing the key insights from the analyses is presented in this paper. The full set of results is available from the authors upon request.

In the following, *Scenario 1* denotes all simulations, where the cost for private car travel was set to 0.27 CHF/km, i.e. the perceived cost level. In *Scenario 2*, this value was set to 0.64 CHF/km, which corresponds to the full costs.

### 5.1. Competition of shared modes

The first part of the analysis allows insights on the interactions and competition between the shared modes. To this end, Fig. 2 shows their number of rentals.

The results indicate that for each shared mode in Scenario 1, there is a saturation effect for larger fleet sizes. Hence, despite increasing availability of the respective service, utilization of the vehicles drops after a certain point. The simulation results suggest optimal fleet sizes of around 1000 vehicles for car-sharing and bike-sharing, and at most 250 vehicles for ride-hailing. Yet, given the limited number of scenarios, the true optimal values may likely be slightly higher or lower than indicated here.

The figure also provides insights into the competition between the shared modes. For example, it shows that demand for car-sharing and bike-sharing is affected by the fleet sizes of the other schemes. However, with a relative difference of up to 10%, the demand impacts through competition are not substantial. Still, a certain pattern can be observed: presence of small car-sharing and ride-hailing fleets increases demand for bike-sharing, whereas competition by large car-sharing fleets reduces it. In contrast, presence of a small bike-sharing scheme lowers demand for car-sharing, but larger bike fleets increase it. Interestingly, ride-hailing demand seems to be independent from competition of other shared modes.

Yet, presence of other shared modes in the market does not seem to substantially alter the structure of demand. Table 3 presents the access times and network distances. The standard errors are mostly less than 5% of the reported means. Also the trip distances are mostly independent of the fleet sizes of the different services. Only the access times are lower for larger fleets, with the strongest effect observable for ride-hailing with a 60% reduction in wait times when the fleet increases from 250 to 1000 vehicles.

Although trip distances are fairly constant throughout all scenarios, the spatial distribution of start locations varies substantially,

[22] https://www.nzz.ch/schweiz/chef-von-uber-schweiz-haelt-fest-fahrer-wollen-nicht-angestellt-sein-ld.1403722

[23] https://www.nzz.ch/zuerich/publibike-lanciert-den-heissen-zuercher-mietvelo-sommer-ld.1374926

[24] https://www.catch-a-car.ch/en/home/

[25] To limit computation time to a feasible level, only a 10% sample of the population was simulated in the model. While network capacities could be scaled down proportionally, this was not possible for shared mobility fleets. Here, only 10% of the fleet were simulated. While this approach has been widely used for medium to large fleets (compare Balac et al. (2015, 2017)), it may yield unreliable results for very small fleets.

[26] Compare https://www. kantonsrat.zh.ch/Dokumente/Df49fc539-2ea1-4654-98df-68d694fec079/R15301.pdf.

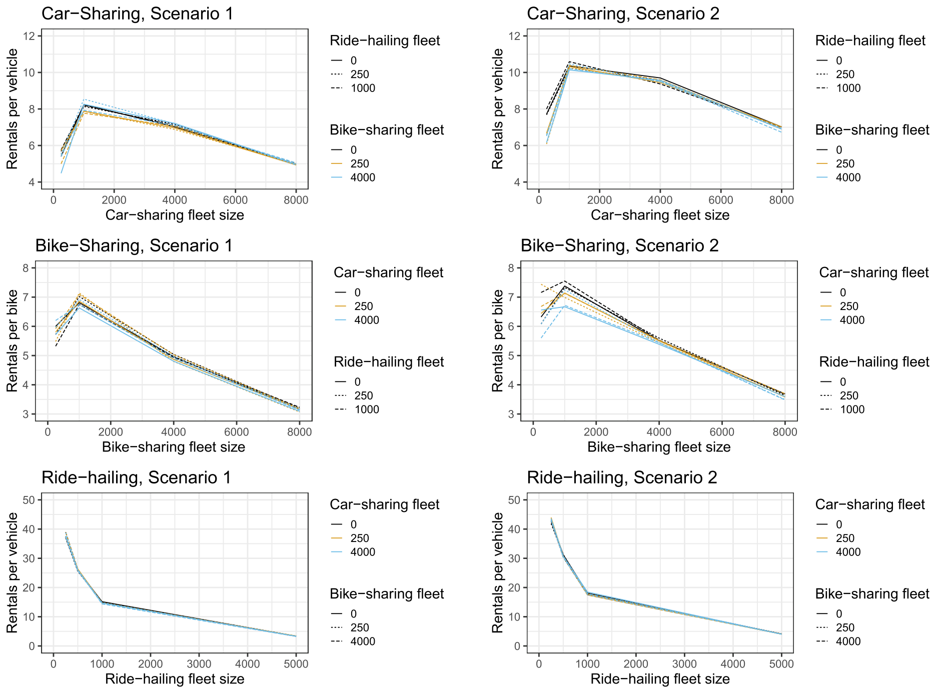


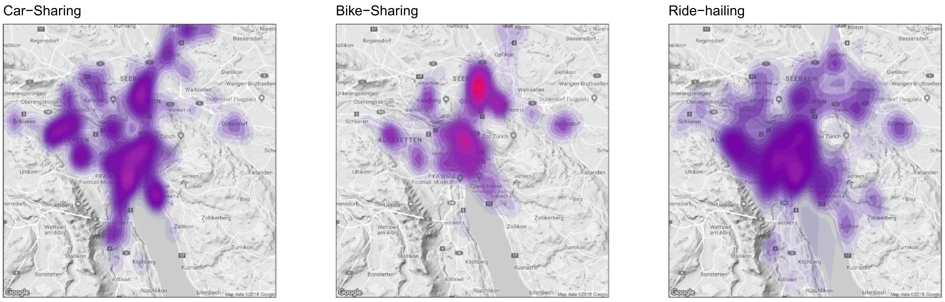

**Fig. 2.** Number of rentals for shared modes. Line color and shape denote composition of shared fleet.

as shown in Fig. 3. For example with a small fleet size, bike-sharing start locations are quite concentrated to certain spots in the city center and the northern sub-center Oerlikon. When car-sharing and ride-hailing enter the market, the concentration is even more focused to the North, where the other services are less strong. Only at very large fleet sizes the distribution becomes more continuous and centered towards the city center. Also for car-sharing, demand is more disperse without competition. For small fleets and with competition, it is focused on the city center, while larger fleet sizes lead demand to spread more into outer parts of the city. Interestingly, for case (b), car-sharing demand and bike-sharing demand appear to complement each other with demand peaks in different parts of the city. In contrast to bike- and car-sharing, ride-hailing demand follows a similar demand distribution throughout all scenarios. A reason for this may be that ride-hailing vehicles can move towards their clients at higher speeds, increasing local availability of the service. For the same reason, car-sharing demand distribution approaches the one of ride-hailing for very large fleets.

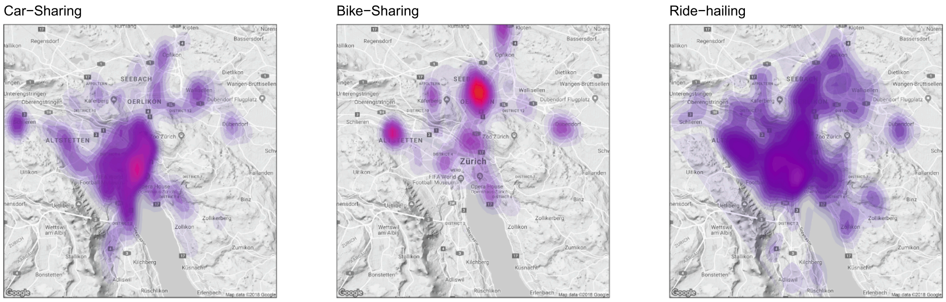
The results suggest that free-floating car-sharing and electric bike-sharing compete over similar demand hot spots, whereas ride-hailing serves a different demand segment. The key drivers of this segmentation are the conveniece of access as well as fares (also compare Table 1). Moreover, the speed difference of cars and electric bicycles is relatively small, at least during peak hours. Although Fig. 3 even suggests a certain overlap between free-floating car-sharing and electric bike-sharing demand, their trip distances are substantially different. There are also features which the simulation model cannot capture: For example, car-sharing allows users to

**Table 3**
Mean access times [min] and mean network distances [km] of trips. Access times are walk time for car- and bike-sharing and wait time for ride-hailing.

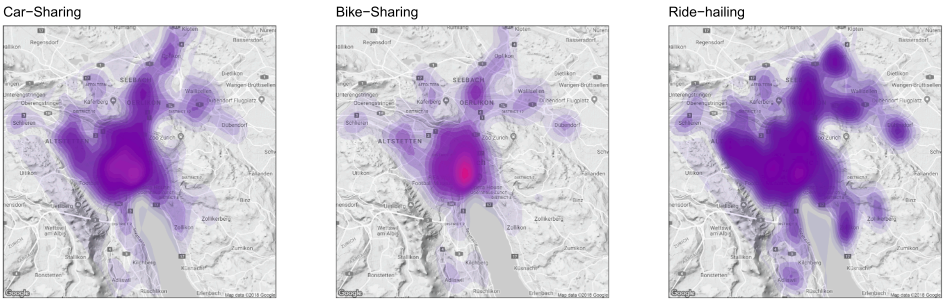
| Service | Fleet | Access time [min] | | Trip distance [km] | |
|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| Car-sharing | 250 | 3.67 | 3.74 | 4.57 | 5.05 |
| | 1000 | 3.47 | 3.49 | 4.52 | 5.07 |
| | 4000 | 2.73 | 2.80 | 4.42 | 5.04 |
| | 8000 | 2.09 | 2.20 | 4.45 | 5.08 |
| Bike-sharing | 250 | 3.70 | 3.64 | 1.83 | 2.31 |
| | 1000 | 3.36 | 3.42 | 1.95 | 2.20 |
| | 4000 | 2.49 | 2.54 | 1.90 | 2.22 |
| | 8000 | 1.87 | 1.91 | 1.88 | 2.19 |
| Ride-hailing | 250 | 9.09 | 9.56 | 3.48 | 3.69 |
| | 500 | 4.04 | 4.26 | 3.44 | 3.67 |
| | 1000 | 3.69 | 3.74 | 3.43 | 3.66 |
| | 4000 | 1.91 | 1.90 | 3.46 | 3.67 |




(a) Only one service operating in the area. Fleet size is 250 in each case.




(b) Each service simultaneously operating with fleet size 250.




(c) Each service simultaneously operating with fleet size 4 000 for car- and bike-sharing and 1 000 for ride-hailing.

**Fig. 3.** Rental start locations for selected cases from Scenario 1.

transport larger items, which is an important factor for a certain number of trips (Becker et al., 2017a).

### 5.2. *Profitability of shared modes*

Using the fares and cost structures outlined in Section 3, the profit of each operator was determined for all scenarios. The results are presented in Fig. 4. They indicate that in *Scenario 1*, bike- or car-sharing services cannot be operated at a profit. However, losses are only a few CHF per vehicle per day and are lowest for fleets of 1000 vehicles each. Interestingly, car-sharing profits are reduced in the presence of a small bike-sharing scheme (fleet size 250), whereas bike-sharing profits are reduced in the presence of a large car-sharing scheme (fleet size 4000).

For ride-hailing, operations are profitable for very small fleets of 250 vehicles. For larger fleets, vehicle utilization would not be sufficient to support the high labor costs.

### 5.3. *Impact of full car cost in mode choice*

The results described above all refer to a case, in which shared modes were introduced into today's transport system. Yet, in the current situation, ownership of mobility tools causes a market segmentation into public transport users and car owners (Becker et al., 2017c), leading to sub-optimal mode choice decisions. For private cars, the bias is most substantial, because agents only consider a part of the full car cost in their mode choice decisions. Therefore, all simulations were repeated in a *Scenario 2*, in which costs for car

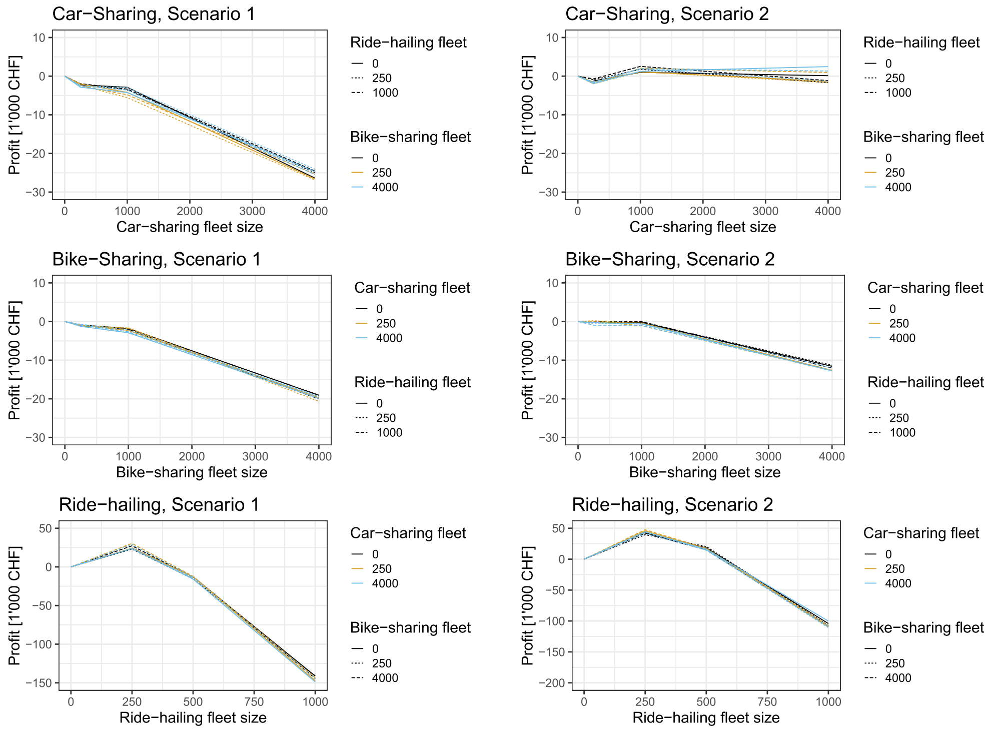



**Fig. 4.** Profit per day for shared modes. Line color and shape denote composition of shared fleet.

travel were increased to 0.64 CHF/km), thus including all costs related to car ownership and use.[27]

As shown in Fig. 2, increased costs for car travel lead to a shift of demand towards shared modes. Car-sharing benefits the most with a 25% surge in the number of rentals. Ride-hailing sees an almost 15% increase, whereas bike-sharing demand only rises by about 7%. Also trip distances are getting longer for all shared modes (especially car-sharing and bike-sharing) to replace certain car trips. But despite the higher utilization, access times are only marginally longer.

The increased utilization has substantial impacts on the profitability of car-sharing and bike-sharing. In particular, daily losses for operating a fleet of 1000 share bikes are reduced to less than 1 CHF per bike. In case of a simultaneous offering of car-sharing and ride-hailing with small fleets, even a profit of up to 0.8 CHF per bike is reached. Yet, most profound impact can be observed for car-sharing. Here, the surge in demand allows for substantial daily profit of up to 3 CHF per vehicle (for fleet size 1000). The strong increase in profitability for car-sharing can be explained by the high fixed costs (compare Table 2) of these services. For ride-hailing, a small fleet of up to 500 vehicles can be operated at a daily profit of up to 50 CHF per vehicle, but for larger fleet sizes, the balance turns into a large loss.

### *5.4. System-level analyses*

Judging from a system's perspective, operator profit is not necessarily the most important target function. Like for public transport, subsidizing such systems might be an interesting option if those schemes contributed to a more efficient transport system or to an increased level of accessibility. To this end, all scenarios were evaluated with respect to their impact on *total travel time*, *total generalized cost* and *total energy consumption*, across all modes.

The results are presented in Fig. 5. The upper plots show the total travel times and provide various key insights: First, introduction of shared modes generally reduces travel times. Hence, despite the slow access walk towards the next available vehicle, they offer a faster alternative than other modes. The effect is especially strong for car-sharing and ride-hailing. Second, transparent car costs (Scenario 2) would increase network travel times, which is the result of a mode shift away from the private car. Indeed, car mode share falls from 49% to 34% in the base case (without shared modes). And while the introduction of shared modes helps to reduce total travel time by up to 2%, increasing perceived car costs drive them up by about 11%.

Yet, given that different modes provide different levels of comfort, travel times may not be the most important indicator of system performance. As described in Section 3, a simple welfare measure has been used for this purpose: It includes the disutility of travel for

[27] In this study, fares and subscriptions for public transport operations remain unchanged, because they are set politically and mostly aim at providing a basic level of accessibility for the respective area. Here, a more promising approach would be to prune the network as studied in Section 5.5.

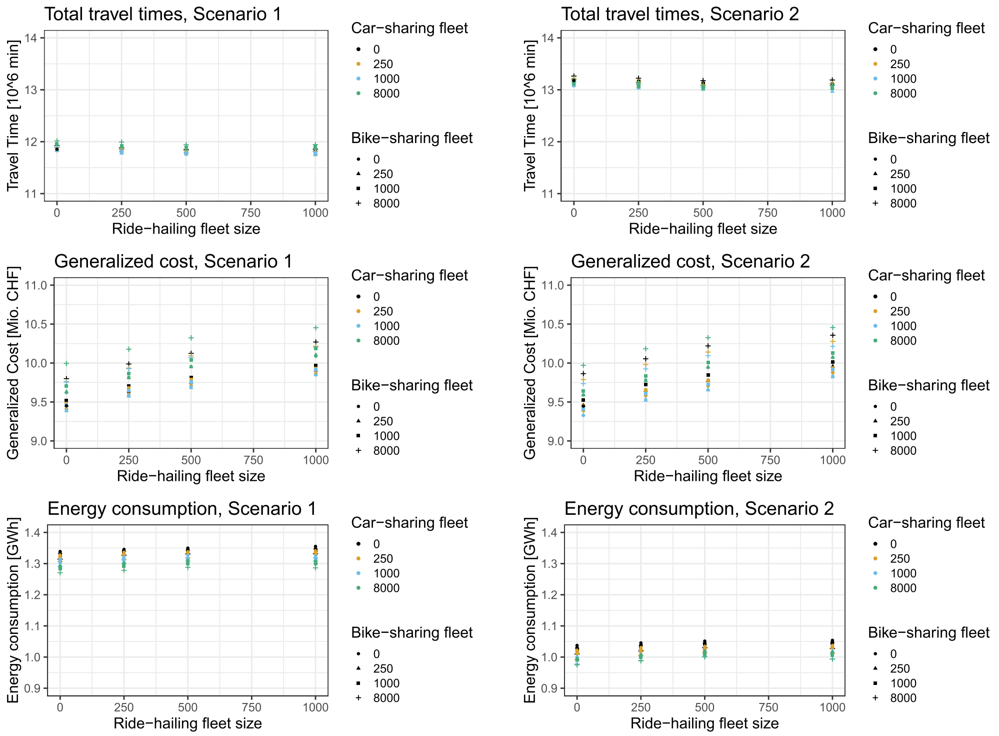



**Fig. 5.** System-level analyses. Color and shape denote composition of shared fleet.

all trips (without fares paid for shared modes) as well as the operating costs of the shared services and subsidies paid for public transport operations. As shown in Fig. 5, the fleet sizes of the three shared modes (and the respective economic losses) are the key drivers of the generalized cost. Interestingly, the base case (zero fleets of shared modes) ranks among the most efficient cases. Hence, the three shared modes do not appear to generate substantial gains in system efficiency. Generalized system cost are slightly lower in *Scenario 2*, which is due to the more efficient mode choice behaviour (hidden car costs are included in the value for *Scneario 1*).

For *Scenario 1*, a fleet of 1000 car-sharing vehicles, 250 shared bikes and zero ride-hailing activity was found to provide lowest generalized system cost. Yet, savings are not substantial: compared to the baseline case, the potential efficiency gain is less than 1%. In turn, a case of 1000 car-sharing vehicles, 1000 shared bikes and 500 ride-hailing vehicles would generate a 3% increase in total system cost. In *Scenario 2* (transparent car costs), system-optimum is shifted towards a fleet of 1000 free-floating car-sharing vehicles (no other shared modes), and although potential efficiency gains due to introduction of shared modes generally appear higher, savings compared to the respective baseline are still minor.

As a third measure, the impact on total energy consumption was analyzed. Here, all trips with car, car-sharing, ride-hailing and electric bicycles were considered. For public transport the total energy consumption reported by the local tram and bus operator was used.[28] As expected, larger car-sharing and bike-sharing fleets reduce overall energy consumption by up to 7%, indicating that they do attract substantial demand from other motorized modes (also compare Appendix B). The most striking difference is between *Scenario 1* and *Scenario 2*: Making agents consider their full car cost would already help to reduce transport-related energy consumption by almost 25% (for trips within the service area). Concerning the different shared modes, it becomes obvious that only ride-hailing has a slightly negative impact on energy consumption. The reason for this is that it also competes with public transport and active modes, which it cannot make up for by a higher fuel efficiency.[29]

It is important to note that this analysis does not consider any grey energy or impacts on car-ownership, which were found to be the key drivers of the environmental impact of shared modes in earlier research (Shaheen and Cohen, 2013).

### 5.5. Public transport integration

In Zurich, operations of various bus and tram lines are subsidized, to provide all parts of the city with a dense network of frequent public transport services. For the city alone, subsidies amount to more than 105 Mio. CHF per year.[30] Since shared modes can also be

[28] 129 GWh in 2017 according to VBZ business report: https://www.stadt-zuerich.ch/vbz/de/index/die_vbz/geschaeftsbericht.html.

[29] For ride-hailing vehicles, the same average fuel consumption as for private cars was assumed.

[30] Values are for 2013 and were published by the city's governing council in 2016: https://www.kantonsrat.zh.ch/Dokumente/Df49fc539-2ea1-4654-98df-68d694fec079/R15301.pdf.

considered as part of public transport services, it is studied to what extent they could substitute highly subsidized bus and tram lines in providing accessibility towards lower-density areas. To this end, all 25 bus and tram lines with a fare recovery rate of less than 75% were dropped in return for subsidized offers of shared mobility (see Section 3 for details). To limit computation time, only a selected number of cases was simulated for this analysis.

Obviously, the subsidies increase attractiveness of shared modes. As a result, the number of ride-hailing trips skyrockets by 55%. Also, there are 22% more rentals of car-sharing vehicles and a 9% increase in bike-sharing use. As a result, ride-hailing becomes highly profitable in all cases (below 1000 vehicles) and car-sharing is profitable for a fleet size of 1000 vehicles. Bike-sharing generates a small profit only in *Scenario 2*. These results reflect the amount of subsidies for the different shared modes as presented in Tables 4 and 5: By far the most subsidies are paid for ride-hailing trips, whereas car-sharing and bike-sharing rides only attract a marginal share. Most importantly, in all cases the total amount of subsidies is lower than the amount currently paid for regular public transport services on the lines that were dropped (218 400 CHF per day).

In most cases, this monetary gain comes at the expense of slightly increased total travel times. However, the net impact appears to be only marginal: As shown in Tables 4 and 5, generalized cost is up to 2% lower compared to the corresponding case with the full public transport network. Compared to the base case (no shared mobility, full PT network), generalized cost can be slightly reduced by a small car-sharing fleet, but would be 3% higher for a fleet of 1000 shared cars, 1000 shared bikes and 500 ride-hailing vehicles.

In contrast, the impact on energy consumption is substantial with a potential reduction of up to 18% when dropping the selected bus and tram lines and replacing them with shared modes.[31] Compared to the base case, up to 36% reduction in total energy consumption is possible through a combination of both the substitution of underused bus lines and the introduction of transparent car costs.

## 6. Discussion

The simulation results provide various first insights on how *Mobility as a Service* (MaaS) and shared modes can help to increase efficiency of the transport system.

The paper presents a first joint simulation of three types of shared mobility: free-floating car-sharing, free-floating electric bike-sharing and ride-hailing. Although such schemes already co-exist in many cities around the globe, their interactions have rarely been studied yet. The simulation results show that for each of the shared modes, a critical fleet size is required to allow efficient operations. However, once a certain fleet size is reached, demand saturates. Hence, extremely large fleets of shared modes do not appear economical (compare Ciari and Becker (2017)). In addition, the results suggest that there is a twofold interaction between car-sharing and bike-sharing (and to a lesser extent ride-hailing): On the one hand, larger fleets of other shared modes result in competition on the level of single trips. However, since agents plan their whole trip chain in advance, availability of, say, bike-sharing may guarantee a return trip, and thus enable a traveler to use car-sharing for the outbound trip. In fact, such behaviour has earlier been observed for car-pooling, where one of the deterrents is passengers' fear of getting stuck at their destination.

Moreover, the distributions of rental start locations suggest that car-sharing and bike-sharing compete in similar demand hot spots: both serve mostly the densest parts of the city, although demand for car-sharing reaches a bit further out (and generally includes longer trips). But also because of specific characteristics not modeled here (e.g. bicycles consume less space, but car-sharing vehicles are weather-prone and allow transport of larger goods (Becker et al., 2017a)), they should be seen as complements as long as barriers to use both schemes are not too large. In contrast, ride-hailing serves a different demand segment by connecting the outskirts of the city. However, some demand for trips starting within the city center is taken away by car-sharing or bike-sharing.

Yet, the results indicate that on a system level, overall travel time savings induced by shared modes are only marginal and often come at a slight increase in total generalized cost. Capturing all monetary cost and disutility of travel, the generalized cost value can be considered a measure of efficiency of the transport system. Introduction of small fleets of free-floating car-sharing can increase system efficiency by about 1%, whereas larger fleets and combinations of shared modes appear slightly detrimental. This means that on a system-level operating cost of such services often outweigh the travel time gains they produce. The picture may, however, look different if agents had non-uniform values of time.

Although their impact on system-wide operational efficiency may be limited, car-sharing and bike-sharing were found to have a major impact on energy consumption. In the light of earlier research on bike-sharing (Fishman et al., 2014), this means that to a substantial degree, both shared modes substitute private car trips. It also supports an earlier study showing that free-floating car-sharing is mostly used for tangential trips and trips for which public transport service is poor (Becker et al., 2017b). Indeed, mode shift findings of this research are compatible with both interpretations. Only for ride-hailing no positive impact on system-wide energy consumption could be found. In fact, energy impacts across all three shared modes should be even higher given that car-ownership reductions (not modelled here) were found earlier to trigger even stronger behavioural change (Shaheen and Cohen, 2013).

Interestingly, in most energy-optimal scenarios, car-sharing and bike-sharing operators operate at substantial losses. In contrast, ride-hailing services may be profitable at limited fleet sizes, but do not generate positive externalities with respect to energy consumption. This raises the political question, whether operators of such systems should be subsidized and/or charged as an incentive to adjust their fleet sizes towards an energy-optimal state.

[31] Disaggregated data on energy consumption per bus line was not available. Therefore, the total energy consumption for public transport was reduced by 51.5%, which corresponds to the share of the operating costs of the dropped lines among the total operating cost of all lines.

**Table 4**
System-level analysis for base case and substitution case, where shared modes are subsidized to replace line-based public transport in certain areas. All numbers are for *Scenario 1*, i.e. mode choice depending on perceived car cost.

| Fleet size | | | Travel time [1000 h] | | Gen. cost [Mio. CHF] | | Energy [GWh] | | Subsidies [kCHF] |
|---|---|---|---|---|---|---|---|---|---|
| CS | BS | RH | base | subst. | base | subst. | base | subst. | CS + BS + RH |
| 0 | 0 | 0 | 198 | 198 | 9.45 | 9.45 | 1.34 | 1.34 | 0.00 |
| 250 | 0 | 0 | 197 | 199 | 9.41 | 9.34 | 1.33 | 1.18 | 0.69 |
| 0 | 250 | 0 | 197 | 199 | 9.46 | 9.40 | 1.34 | 1.19 | 0.23 |
| 0 | 0 | 250 | 197 | 198 | 9.63 | 9.53 | 1.35 | 1.21 | 28.63 |
| 250 | 250 | 250 | 196 | 197 | 9.59 | 9.47 | 1.33 | 1.19 | 29.04 |
| 1000 | 1000 | 500 | 196 | 197 | 9.76 | 9.56 | 1.32 | 1.17 | 45.06 |
| 4000 | 4000 | 1000 | 198 | 199 | 10.22 | 10.01 | 1.29 | 1.15 | 69.13 |

**Table 5**
System-level analysis for base case and substitution case, where shared modes are subsidized to replace line-based public transport in certain areas. All numbers are for *Scenario 2*, i.e. mode choice depending on full car cost.

| Fleet size | | | Travel time [1000 h] | | Gen. cost [Mio. CHF] | | Energy [GWh] | | Subsidies [kCHF] |
|---|---|---|---|---|---|---|---|---|---|
| CS | BS | RH | base | subst. | base | subst. | base | subst. | CS + BS + RH |
| 0 | 0 | 0 | 220 | 220 | 9.45 | 9.45 | 1.04 | 1.04 | 0.00 |
| 250 | 0 | 0 | 219 | 220 | 9.39 | 9.31 | 1.02 | 0.89 | 0.90 |
| 0 | 250 | 0 | 220 | 221 | 9.46 | 9.40 | 1.03 | 0.90 | 0.51 |
| 0 | 0 | 250 | 219 | 220 | 9.65 | 9.54 | 1.05 | 0.92 | 36.95 |
| 250 | 250 | 250 | 218 | 219 | 9.60 | 9.45 | 1.03 | 0.89 | 34.74 |
| 1000 | 1000 | 500 | 217 | 218 | 9.72 | 9.52 | 1.01 | 0.87 | 57.12 |
| 4000 | 4000 | 1000 | 218 | 217 | 10.21 | 9.96 | 0.99 | 0.86 | 81.40 |

Moreover, simulation results indicate that shared modes can be an efficient solution to substitute under-used bus services. Since pruning of the network was done in a very rough manner, the actual efficiency gains of complementing a reduced line-based public transport network with subsidized modes of shared mobility may be higher. This insight will also be highly relevant to design public transport networks in an era of automated taxis, which can be operated at even lower cost (Bösch et al., 2018).

Finally, the simulation results confirm the key expectation of *Mobility as a Service* (MaaS), i.e. that an integrated transport system with cost transparency at the trip level helps to increase system efficiency. To study this effect, all simulations in this paper were conducted twice: In *Scenario 1*, car-owners had a private car available for all trips at the generally perceived marginal cost (0.27 CHF/km). In *Scenario 2*, the cost attribute was increased to 0.64 CHF/km, which captures the true cost of the trip (i.e. fixed/sunk cost were converted into marginal cost): This change alone triggered a 25% reduction in transport-related energy consumption, because many travellers prefered other modes rather than paying the higher price for using a car. Yet, due to longer travel times of the alternative modes, generalized cost are only marginally lower for the case of transparent car prices.

A next step would be to include externalities in the generalized cost, such as grey energy, GHG emissions, noise pollution or space consumption[32]. Moreover, a dedicated mode choice model based on empirical data would be required to obtain even more realistic results. In addition, sensitivity analysis would allow to show how robust the results are for deviations or changes in actual travel behavior. Also, the limited number of cases studied in this research does not allow to identify the optimal combination of different fleet sizes of shared modes, suggesting that the possible impacts may even be higher than reported here. Moreover, the current mode choice approach does not allow inter-modal trips (e.g. using car-sharing as a feeder for public transport). Given the relatively small service area, this limitation will only lead to a small underestimation of demand for shared modes here, but needs to be addressed if larger areas were to be studied.

## 7. Conclusion

A key component of *Mobility as a Service* (MaaS) is to allow travellers unbiased choice of modes for each trip. First field tests of MaaS schemes confirmed that in such a setup, test persons do make better choices, both saving money and reducing carbon emissions (Sochor et al., 2016). The results of this research further support this notion by showing that simply by basing mode choice decisions on the full cost of private car travel, transport-related energy consumption can be reduced by 25%.

Moreover, results show that MaaS impacts are even stronger when fleets of shared modes are introduced into the network. In fact,

[32] Space consumption is only indirectly covered by parking cost included in the cost for car and car-sharing.

integration of shared modes may even allow efficiency gains on the supply side, when used to provide accessibility to areas, in which demand is too low to support line-based public transportation. Combined with unbiased mode choice decisions, system efficiency can be increased by 2%, but total energy consumption reduced by another 18% if shared modes were used to substitute underused bus lines.

It is important to note that in most cases, where shared modes reduce system-level energy consumption, operation of such fleets is unprofitable. Hence, operators may get stuck in a local optimum with small, but potentially profitable fleets. However, only if their operations were subsidized (and simultaneously regulated), their highest system-level impacts could be achieved. In a way, this is similar to the economics of public transportation.

Given the limited number of scenarios this research can only provide first insights into the impacts of large-scale integrated MaaS systems. For example, the large intervals between the studied fleet sizes do not allow to precisely determine the services' actual impacts. Moreover, this study had to rely on partial models for mode choice, which may lead to (minor) bias in agents' behaviour. Hence, the analysis should be validated once comprehensive mode choice models become available. However, already now, the results of this scenario-based analysis may inspire further research to investigate certain aspects in more detail.

Independent of possible uncertainties in the results, it is still unclear how the lessons learned can be put into practise. Difficult issues have to be addressed both at the demand and at the supply side. From a planning perspective, a new definition of public transportation is needed to include certain shared modes. Among other aspects, a measureable minimum level of service will have to be imposed if shared modes were to take over the role of public transportation in certain areas (Hensher, 2017). Finally, more effective measures of taxation (or road pricing) will have to be developed to manage demand towards a more system-optimal state.

## Acknowledgements

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## Appendix A. Bike-sharing module

Free-floating bike-sharing service for this study is implemented in a similar manner as the free-floating car-sharing service (Balac et al., 2019). The fleet of bicycles is available for rental in the service area defined by a shapefile. Upon departure from an activity, agents reserve the closest available bike, which thus becomes unavailable to other customers. The agent is then routed on the shortest path in the road network with a constant speed of 14 km/h.[33] After finishing the bike-sharing trip, the agent leaves the bike at the destination facility, where the bike becomes available to other customers.

An important limitation of the current framework is that it does not consider re-charging of the electric bicycles. In the current bike-sharing scheme in Zurich, this is addressed by both providing customers with bonuses if ending their trip at a charging station and by collecting bicycles with empty batteries to re-charge them. Optimizing this process would require substantial further work, which is out of the scope of this research. For the results presented here, this limitation means that there is a slight underestimation in operating costs and a marginal overestimation in demand.

Information on all rentals is gathered throughout the mobility simulation and stored in the output directory for analyses. Recorded information includes access time, trip duration, bike used, origin coordinate and destination coordinate. Information on bicycle availability and access times is also recorded in 15 min time bins for km$^2$ zones during the simulation. In the subsequent iteration, to inform mode-choice decision in the subsequent iteration.

## Appendix B. Mode share impact

The environmental impact of shared modes depends on the conventional modes it substitutes (among other factors). However, a switch towards shared modes may also induce second-order impacts. Therefore, Table B6 summarizes the global change in distance travelled by conventional modes. For simplicity, only scenarios with a single shared mode with a fleet size of 1000 vehicles are reported. Other fleet sizes or combinations of services are not presented here.

The results clearly indicate that all three shared modes have a strong tendency to replace car trips and even more so in case of transparent car costs (*Scenario 2*). Interestingly, use of public transport increases in select cases for bike-sharing and car-sharing fleets. This indicates that such schemes may have a leverage effect: The shared mode may only substitute one leg in a car tour, with the other legs being shifted towards public tranport.

Note that the distance travelled with the shared modes is mostly lower than its combined impact on other modes. Besides more efficient routes, this is due to the fact that access walk to the vehicle was not included in the totals. Anyway, the results have to be treated with caution given that multiple independent simulation runs would be required for each scenario to determine their statistical significance.

[33] This corresponds to average speeds observed at the local electric bike-sharing scheme *Smide* in Zurich.

**Table B6**
Changes in total distance travelled by conventional modes induced by appearance of shared modes (example of fleet size of 1 000 vehicles; no mixed occurence of different shared modes is considered).

| | shared mode | bike | car | public transport | walk |
|---|---|---|---|---|---|
| *Scenario 1* | car-sharing (+38 419 km) | −4 037 km (2.3%) | −64 645 km (4.1%) | +2201 km (0.2%) | −460 km (0.2%) |
| | bike-sharing (+14 039 km) | −396 km (0.2%) | −15 819 km (1.0%) | −1 025 km (0.1%) | −1 346 km (0.6%) |
| | ride-hailing (+52 349 km) | −6 236 km (3.5%) | −26 027 km (1.7%) | −6 964 km (0.6%) | −6 659 km (3.2%) |
| *Scenario 2* | car-sharing (+51 574 km) | −5 544 km (2.8%) | −89 883 km (8.3%) | −6 192 km (0.4%) | −1 120 km (0.5%) |
| | bike-sharing (+16 296 km) | −1 077 km (0.5%) | −19 240 km (1.8%) | +1 994 km (0.1%) | −1 463 km (0.6%) |
| | ride-hailing (+66 075 km) | −8 540 km (4.3%) | −40 163 km (3.7%) | −4 149 km (0.2%) | −5 548 km (2.3%) |

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