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Implications of pricing and fleet size on shared bikes and e-scooters.

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Abstract

In many cities, shared micromobility services (SMMS) have become popular. These services contribute to the popularity of car-alternative mobility by promoting the use of micro-vehicles. Bike-sharing and e-scooter-sharing systems are examples of these services. Despite their potential, SMMS are still marginal. To unlock this full potential, there is a need to comprehend the implications of the introduction strategies of SMMS on the adoption, use, and profitability of these services.

This paper investigates the implications of the size of the fleet and pricing of shared bikes and e-scooters. This research relies on an agent-based transport simulation framework of Lyon, France.

The results show that despite their actual marginal share, SMMS have a non negligible growth potential in Lyon. This potential is actually unfulfilled due to sub-optimal pricing and fleet size strategies. More optimal strategies from the point of view of service providers and customers are discussed in the paper.

Keywords: Shared micromobility services, E-scooter, Bike-sharing, Pricing, Fleet size, Agent-based.

1. Introduction

Over the past decade, shared micromobility services (SMMS) have become increasingly available in many cities around the globe. SMMS can be defined as shared mobility solutions that offer short-term access to micro-vehicles whose speed and weight are limited in order to serve short-distance trips (Shaheen et al., 2020). Bike-sharing systems (BSS) and e-scooter sharing systems (SSS) are popular examples of these services. BSS and SSS have seen a remarkable development during the last years and received increased attention from citizens, policymakers, and the transportation industry.

Research has already underlined the potential role SMMS can play in shaping sustainable cities (Abduljabbar et al., 2021). These services can help reduce car-dependency, especially for short-distance trips (Şengül and Mostofi, 2021), complete existing public transport (PT) systems (Oeschger et al., 2020; Martin and Shaheen, 2014), help reduce congestion (Fan and Zheng, 2020), boost active travel (Milakis et al., 2020), improve spatial accessibility, and serve as a first and last mile travel mode for people and goods (Martin and Shaheen, 2014).

The potential benefits of SMMS and their associated economic opportunities have boosted their development, sometimes in a frenzy (The Meddin Bike-sharing World Map team, 2021; Gössling, 2020). The recent experience drawn from the anarchic introduction of shared free-floating bikes and e-scooters in several cities has made policymakers and citizens question the benefits of these services. Consequently, many cities became aware of the need to regulate their negative externalities and to control their implementation (Riggs et al., 2021). In many cities, ad hoc policies were adopted to control SMMS with little regard for the systemic impacts of these regulations (Gössling, 2020). The capping of the number of operators and their fleet size are popular examples of regulations that were massively adopted and that can have unintended consequences on the operation and success of these services (Riggs et al., 2021).

In spite of the rich literature on SMMS, research on the implications of the fleet size and price of SMMS is still scarce (Hu and Creutzig, 2021; Lo et al., 2020). Few studies have addressed the question of how SMMS demand reacts to changes in their supply, specifically in their pricing and fleet size. Yet, the success of these services relies basically on supplying an appropriate number of shared vehicles (fleet size) at an appropriate cost (price). These strategies have far-reaching implications on the use of these services, their spatial and social access, their role in complementing or competing against existing travel modes,

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and the financial viability of their operators (Hu and Creutzig, 2021; Lo et al., 2020). It is therefore
30 important to study the implications of these two strategies in order to ensure successful, efficient, and
socially acceptable introduction and operation of these services.

For SMMS operators, the profitability of their business models is required for the sustained provision
and development of SMMS (Button et al., 2020; Schellong et al., 2019; Team, 2018). The success of
these business models depends on many factors, including the pricing and fleet size strategies. Under-
35 supply and over-supply of these services have direct implications on capital and operating costs, profit
margins, unit economics, and customer satisfaction (Gu et al., 2019). Under-pricing and over-pricing
of these services also impact their profitability, especially in competitive markets. Examples of such
unsuccessful business models were implemented during the first attempts to introduce shared dockless
bikes and e-scooters.

40 From a societal point of view, the supply of the appropriate quantity of SMMS at the appropriate
price is important as well. The over-supply of shared vehicles can induce haphazard parking and un-
desirable public space occupancy (street cluttering) (Gössling, 2020; Riggs et al., 2021). Depending on
their implementation, these services can also compete against existing travel modes like walking or PT.
Moreover, the pricing and spatial deployment of shared vehicles can rise spatial and social equity issues
45 by targeting specific population segments and neighborhoods and neglecting many others (Ursaki et al.,
2015). The study of the implications of SMMS pricing and fleet size strategies is therefore critical to
operators, urban planners, and decision-makers.

In this paper, we investigate the impacts of different pricing and fleet size strategies on the demand
and operation of shared bikes and e-scooters in Lyon, France. This paper builds on existing literature
50 on the elasticity of travel demand for shared micromobility services to evaluate the impacts of different
pricing and fleet size capping strategies on the adoption and operation of shared bikes and e-scooters
in Lyon. Findings from this research can be of interest to policymakers, urban planners, and service
providers.

The rest of the paper is organized as follows. Section 2 reviews existing literature on the impacts of
55 the size of the fleet and the price. The methodology, data, and case study are described in Section 3.
Results are discussed and compared with existing literature in Section 4. Operational implications of our
findings are provided and discussed in Section 5.

2. Background

In economics, the study of how much demand for a product or a service changes when its price changes,
60 is known as price elasticity. Similarly, we can define the elasticity of demand towards the fleet size as
fleet elasticity. In general, the estimation of demand elasticity is challenging. It requires measuring
the percentage change of SMMS demand caused by a one percent change in a specific attribute, like
the price or fleet size, everything else should be held constant. Practically, elasticity estimation often
relies on longitudinal revealed preference (RP) data and statistical analysis to isolate the effect caused
65 by a change of the attribute of interest from other artifacts, like changes in other attributes, seasonality,
trends, confounding factors, market fluctuations, change in competition, etc.

In transportation economics, research on demand elasticity has been mainly concerned with car and
public transit (Litman, 2017; Hanly et al., 2002), and rarely with new mobility services, and even less with
shared micromobility (Shah et al., 2022; Lee et al., 2021). The introduction of these services is relatively
70 recent and their market is constantly evolving. This limits the availability of appropriate longitudinal
data on their use. Consequently, it becomes challenging to isolate the causal effect of one attribute like
price or fleet size, everything else held constant, in a continuously changing micromobility landscape.

2.1. Fleet size implications

Previous research has already underlined the importance of the size of the fleet to the adoption and
75 use of SMMS (Krauss et al., 2022; Lee et al., 2021; Shah et al., 2022; Mclean et al., 2021; Kabra et al.,
2020; de Chardon et al., 2017). The availability and accessibility, in space and time, of these services are
dependent on the size of their fleet. Larger fleets are likely to have more available shared vehicles and
better accessibility, i.e. shorter access/egress walking distances, than smaller fleets, *ceteris paribus*.

Lee et al. (2021) estimate the fleet elasticity of SSS demand by using regression analysis and aggregate
80 trip data from three US cities: Austin, Chicago, and Portland. The authors find an elasticity of 0.78
($Std = 0.3$ and $p\text{-value} < 0.02$), meaning that an increase of 10% in the fleet size will induce an increase
of 7.8% in e-scooter use in the three cities.

By using similar data from Nashville, USA, Shah et al. (2022) find a lower fleet elasticity of 0.55 ($Std = 0.02$ and $p - value < 0.01$). The authors define the size of the fleet as the number of e-scooter-hours deployed per square mile. This research shows that demand elasticity differs between operators according to their fleet size. Operators with larger fleets have a higher elasticity than operators with smaller fleets. Results also show that this elasticity differs between weekdays and weekends and according to the built environment in each zone (Shah et al., 2022).

McClean et al. (2021) estimate the fleet elasticity of SSS demand in Calgary, Canada. The authors find an elasticity of 0.43. In contrast with previous studies that rely on aggregate trip data, McClean et al. (2021) use a discrete-event simulation framework to simulate different fleet size scenarios. This research shows that beyond a fleet size threshold, demand becomes perfectly inelastic, i.e. an increase in the fleet has no effect on demand, meaning market saturation.

Kabra et al. (2020) find that the short-term demand for BSS in Paris is nearly elastic (0.96) to the size of the fleet and that the long-term elasticity is 1.17. This research relies on BSS trip data and statistical modeling.

Shen et al. (2018) show that BSS demand, in Singapore, increases with the availability of shared bikes with a decreasing marginal effect. The higher the number of additional shared bikes the lower the additional number of induced trips. This finding is also highlighted in the case of SSS in Calgary (McClean et al., 2021) and BSS and SSS in Zurich (Reck et al., 2021).

By using data from 75 bike-sharing systems, de Chardon et al. (2017) show that the density of BSS, measured as the number of stations per km^2 , is positively correlated with the performance of the system, measured by the mean number of trips per day and per bike. However, the authors challenge the size and network effect that states that ‘*Big is better*’ for BSS and confirm that BSS systems do not ‘*need to be big to be successful*’. Findings of McClean et al. (2021), Reck et al. (2021), and Shen et al. (2018) on the decreasing marginal effect of the fleet size partly confirm this assertion.

2.2. Price implications

In comparison with fleet elasticity, the price elasticity of SMMS has received less attention. Its estimation requires longitudinal data on changes in prices and corresponding demand over a significant period of time, which are less frequent than changes in the size of the fleet.

As expected, existing literature suggests that higher prices are likely to reduce demand for SMMS (Krauss et al., 2022; Reck et al., 2021), especially among underprivileged communities (Goodman and Cheshire, 2014).

Reck et al. (2021) compare the use of BSS and SSS in Zurich using revealed preferences data and discrete choice modeling. Their model suggests that a 10% increase in the e-scooter cost induces a decrease in their choice probability between 9.4 and 15.5 points. An increase of 10% of the cost of dockless e-bikes induces a decrease of 4.1 points in their choice probability. The authors find that demand for SSS is more sensitive to the price than BSS. It is noteworthy that changes in the choice probability of SMMS cannot be directly translated into demand elasticity.

By using stated-preference data and discrete choice modeling, Krauss et al. (2022) estimate the marginal effects of pricing on shared micromobility services in Germany. The authors find that an increase of 150% in e-scooter costs induces a decrease of 0.8% point of their choice probability and that a decrease of 50% in the cost induces an increase of 0.6% point of the choice probability of shared e-scooters. For shared bikes, increasing their cost by 150% induces a decrease of 1.5% point in their choice probability, and a decrease of 50% of the cost produces an increase of 1% point in the choice probability of shared bikes. Most of the increase or decrease in BSS and SSS choice probability when their cost decreases or increases comes at the expense or to the benefit of the private car and walking. These results indicate a marginal change in the choice probability of SMMS when their prices change. It is noteworthy that these results are significantly different from those of Reck et al. (2021) in terms of magnitude of change.

Previous research confirms that the fleet size and price of SMMS have a significant impact on their use. Findings suggest that demand is inelastic to changes in the fleet size, i.e. $elasticity < 1$. They also suggest that BSS and SSS have different elasticity values and that price elasticity is less studied than fleet elasticity. Also, the implications of the fleet size and price of SMMS have often been studied independently from other travel modes, except the work of Krauss et al. (2022) and Reck et al. (2021). Moreover, these implications are often limited to travel demand and rarely discussed in terms of mode competition and operators’ profitability. We propose to fill this gap by investigating the implications of different pricing and fleet size strategies on the demand and operation of SMMS and in relation to other competing travel modes. This is achieved thanks to a calibrated simulation framework of shared micromobility services in Lyon, France.

140 This research distinguishes itself from previous studies in three respects: **(i)** it relies on a calibrated multimodal simulation framework of the metropolitan area of Lyon where SMMS are in competition with other travel modes: walk, public transit, personal bike, and car; **(ii)** it includes two shared micromobility services: bikes and e-scooters that can compete for similar market segments; **(iii)** it evaluates the implications of pricing and fleet size strategies of SMMS on the profitability of their operators.

145 3. Methodology

MATSim, a multimodal agent-based simulation framework, is used to assess the implications of different pricing and fleet size deployment strategies on SMMS. Three SMMS scenario configurations are tested: reference, base, and elasticity. The reference scenario replicates the multimodal transportation system of Lyon in the presence of shared bikes and e-scooters. This scenario includes the main travel
150 modes: car, walking, PT, individual bike, shared bikes, and e-scooters. The implications of the introduction of SMMS are evaluated by comparing the reference scenario to the base one where SMMS are not included. The elasticity scenario configuration is a variant of the reference one that introduces marginal changes to the price and to the fleet size of BSS and SSS in Lyon. In each elasticity scenario, only one attribute of one shared service is changed and everything else is held constant.

155 3.1. MATSim

MATSim is an agent-based multimodal transportation simulation framework (Horni et al., 2016). Agents in MATSim are utility-maximizers. Each agent seeks to maximize its utility by performing all required daily activities like work, education, leisure, or shopping, and minimize its unproductive travel time, by choosing appropriate travel modes, routes, and departure times. In each simulation/iteration,
160 agents make a series of travel decisions, score the resulting daily plan and decide whether to keep this plan or to marginally change it in the next iteration. Plan mutations follow an evolutionary algorithm. After a sufficient number of iterations/mutations, agents optimize their daily mobility plans given their individual constraints and capabilities, but also choices made by other agents that are in competition for limited mobility resources like shared vehicles.

The simulation of BSS and SSS is performed thanks to the Shared Mobility extension (Balać and Hörl, 2021). This extension provides appropriate tools to simulate the use and operation of various shared mobility services, be they station-based or free-floating of one or multiple operators. Most important operations are simulated: booking, pick-up, use, drop-off, access and egress walk, excess walk in case of pick-up or drop-off conflicts, and pricing strategies. This extension has already been used for the
170 simulation of shared bikes and e-scooters in at least three case studies (Balać and Hörl, 2021; Diallo and Manout, 2022; Arango, 2022).

All MATSim agents can use BSS and SSS. Thanks to plan mutation, shared bikes and e-scooters are introduced in the mobility plans of agents. Once the decision is made to use such vehicles, the agent searches for the nearest available vehicle to book and walks toward it. Before booking the vehicle, agents
175 are assumed to have perfect information on the instant availability of shared vehicles. A maximum walking distance can be set to limit unreasonable access times. If the vehicle is still available at the pick-up location, the agent picks up the vehicle, performs its trip, and drops off the vehicle either at its destination (for free-floating services, like SSS) or at the nearest available station (for station-based services, like BSS).

In its actual version, the extension does not perform dynamic relocation to adapt supply to demand during the simulation. We adopt a static rebalancing strategy that relocates SMMS vehicles to their initial location at the end of each simulation. Furthermore, since road congestion is a minor issue when using BSS and SSS, we assume that these modes are not routed on the network and that they have constant speeds: $11km/h$ for shared bikes and $\approx 15km/h$ for e-scooters. Motorized modes like car and
185 PT are routed. These two assumptions help reduce computation times.

3.2. Data

MATSim is an activity-based simulation framework. For the simulation of the transportation system, MATSim requires information on travel demand and supply. Travel demand relates to data on the activity plans of agents. This data can include various information on agents like age, gender, driving license,
190 their residential location, and daily activity plans. For confidentiality reasons, this information is often unavailable for all individuals, but only for small samples of the population of interest. Consequently, MATSim, like most agent-based models, relies on population synthesis.

In transportation, a synthetic population is a set of agents that replicate in the most relevant aspects (age, gender, household composition, car ownership, for example) the original population of interest. The definition of this population is based on the combination of various data sources. In Lyon, this population is defined thanks to census data (INSEE, 2019a), household travel survey (HTS) (SYTRAL, 2016), housing data (IGN, 2022), and employment (INSEE, 2022). The socio-economic characteristics of agents are extracted from census data. Travel and activity routines are provided by the HTS. The combination of these data is performed via the EQASIM pipeline (Hörl and Balać, 2021). Activity plans are cloned from the HTS and assigned to synthetic agents using a statistical matching algorithm. Activity locations of agents are defined using the methodology of Hörl and Axhausen (2021). This method computes the location of activities by reproducing observed distributions of travel demand and travel distances according to the activity type: primary or secondary.

On the supply side, MATSim is a multimodal simulation framework that simulates various travel modes. For this, it requires information on their characteristics: network, speed, capacity, stops, schedules, etc. MATSim relies as much as possible on open data. For the car network and its characteristics, we use OpenStreetMap¹. For the PT network, GTFS data from Lyon is used (SYTRAL and Métropole de Lyon, 2022).

For the simulation of BSS and SSS, the Shared Mobility extension requires information on their fleet size, the initial location of vehicles, the location of bike stations and their associated capacity, and pricing schemes. BSS and SSS data has been collected from various open and proprietary sources (Métropole de Lyon, 2022; FLUCTUO, 2022; Métropole de Lyon and JCDecaux, 2022). BSS and SSS trip records from the first three weeks of May 2022 are used for the preparation of input data and the calibration of the simulation framework. We also use historical data on BSS use in Lyon between 2018 and 2021 for the calibration of the simulation. Details on the collection and description of these data can be found in Diallo and Manout (2022).

In transportation, the agent-based approach requires various data sources on travel demand and supply. The variety of these data poses several coherence problems: collection methodology, quality, spatial resolution, time resolution, collection dates. In the case of Lyon, the various data were collected at different times. Travel demand relates to 2015. Population census dates back to 2018. Travel supply describes the network in 2022. By using these data, we implicitly assume that travel routines from 2015 are still valid in 2022 and that the population of 2018 is also representative of 2022. This assumption is of course questionable, especially with the advent of COVID-19. With more up-to-date data on travel demand this assumption can be overcome. Such data is nowadays unavailable in the case of Lyon.

3.3. Case study

3.3.1. Reference scenario

The reference scenario replicates the transportation system of the metropolitan area of Lyon. Métropole de Lyon, called hereafter Lyon or ML, is the third most populated in France (Figure 1). ML has a population of 1.4 million inhabitants and 59 municipalities (INSEE, 2019b). Nearly half of this population lives in the cities of Lyon and Villeurbanne. The average density in these cities exceeds 9,000 inhabitants per km^2 .

The PT system of ML has 4 subway lines ($\approx 33km$ and 44 stations), 7 tramway lines ($\approx 77km$ and 128 stations), 8 bus rapid transit lines ($\approx 74km$ and 208 stops), and more than 150 bus lines ($\approx 1,900km$ and $\approx 4,000$ stops). In 2019, this system carried 1.8 million daily trips, which makes it the second-largest PT system in France in terms of ridership.

BSS was first introduced in Lyon in 2005 under the name Vélo’VTM to encourage bike use and active micromobility. The system is station-based and it had more than 4,000 shared bikes and 420 stations in 2019. Most of the stations are located in Lyon and Villeurbanne (Figure 1). The BSS is operated by the private company JCDecaux under the authority of ML. In 2022, Vélo’VTM established a new yearly record with 10.5 million rentals (Lyon, 2023). The 2022 record is 16% higher than the last record set in 2021. Vélo’VTM can be used under different pricing plans²: occasional, regular, e-bike rental, and long-term rental. Within each plan, different pricing schemes are proposed. In terms of membership, Vélo’VTM has, approximately, 84,000 long memberships (annual) and 610,000 short-term memberships (daily) (Lyon, 2023).

In 2017, 2 new free-floating bike-sharing services were introduced in Lyon by private operators. Hundreds of shared bikes were deployed with little or no coordination with local authorities. Shortly after

¹openstreetmap.org

²<https://velov.grandlyon.com/en/offers/groups>

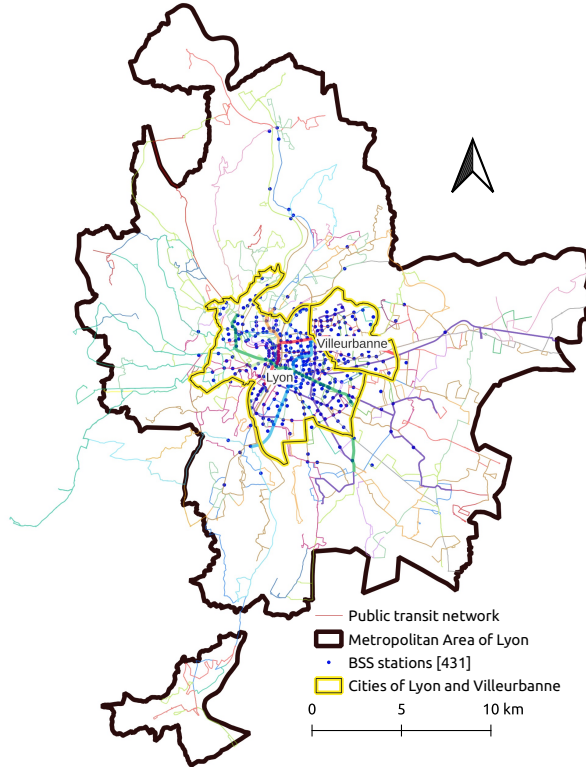


Figure 1: The metropolitan area of Lyon, its PT network and bike-sharing stations. [431] means 431 BSS stations.

their introduction, these services disappeared due to vandalism and unprofitable business models. Only Vélo’V™ was maintained and developed since to include e-bikes and long-term bike rentals.

Free-floating shared e-scooters were gradually introduced in Lyon in 2018. At its climax, 8 operators and thousands of e-scooters were introduced, mostly in a state of anarchy. These new services raised various issues about road safety, vehicle parking, and public-space occupation, and vandalism. Since then, local authorities have introduced legislation to limit these externalities by limiting to two the number of e-scooter operators and to 4,000 their total fleet size. Parking, geo-fencing, and speed limitations were also introduced gradually.

BSS and SSS have different pricing schemes. For SSS, the default pricing scheme is pay-as-you-go, which is based on two components: a flat fare and a time-dependent fare. SSS operators also offer passes and promotions that can be more economical to frequent users than the default pricing strategy. For confidentiality reasons, the average share of SSS users that benefit from promotions or that hold a pass is unknown in Lyon. For SSS, all users are assumed to be billed according to the pay-as-you-go pricing with a flat fare of 1€ to unlock the e-scooter and a variable fare of 0.25€ per minute of use.

For BSS, more than 5 pricing schemes exist: single ticket, membership, 1 or 3 days memberships, special tariffs for youngsters, etc. The pricing scheme of BSS includes a time-dependent fare only billed after 30min of rental: 0.05€/min after 30min, 0.10€/min after 60min, and 0.30€/min after 90min. For simplicity, we assume an average constant price of 1.17€ for all BSS users. This average price is computed using the average use duration of bikes and the rate of annual and daily membership users.

Shared bikes are assigned to stations proportionally to their capacity and given the average occupancy rate of the system (0.45 is the ratio of the number of bikes to stands in Lyon). Thanks to the multi-day data on the use of e-scooters, their initial position is inferred from their most frequent location between 5 AM and 7 AM. More details on data collection and preparation can be found in Diallo and Manout (2022).

3.3.2. Elasticity scenarios

For each SMMS service, 5 new fleet size strategies are simulated. Both an increase and a decrease in SMMS supply are simulated (Table 1). The size of the fleet of the BSS and SSS ranges between 50% (2,000 vehicles) and 300% (12,000 vehicles) of its actual size (4,000 vehicles). The initial location of vehicles is set using the same methodology as for the reference scenario. The capacity of BSS stations is set proportionally to the change in the size of shared bikes.

Scenario	Ref.	1	2	3	4	5
Fleet size	4,000	2,000	6,000	8,000	10,000	12,000

Table 1: Fleet size scenarios of shared bikes and e-scooters. The reference (Ref.) scenario is in **bold**.

Different pricing schemes are also simulated. For the BSS, 4 new pricing scenarios are tested. The rental fee ranges between 0 and 2 times the actual price (Table 2). For the SSS, 6 new pricing schemes are tested (Table 3). These schemes combine different flat and variable fares.

Scenario	1	2	Ref.	3	4
BSS fare (€)	0	0.585	1.17	1.755	2.34

Table 2: Scenarios of the pricing strategy of shared bikes. The reference (Ref.) scenario is in **bold**.

Scenario	1	2	3	4	Ref.	5	6
Flat fare (€)	0	0	0	1	1	1	2
Variable fare (€)	0	0.15	0.25	0.15	0.25	0.30	0.25

Table 3: Scenarios of the pricing strategy of shared e-scooters. The reference (Ref.) scenario is in **bold**.

280 To limit the computational time of these simulations, the price is assumed constant and equal to its reference value (1€ and 0.25€/min) for all fleet scenarios. Similarly, the fleet is assumed constant and equal to its reference value (4,000 vehicles) for all pricing scenarios.

3.3.3. Calibration of MATSim and shared mobility

285 For MATSim to be operational and capable of simulating prospective scenarios, the reference scenario of Lyon is calibrated to replicate observed data on modal shares (SYTRAL, 2016). Parameters of the utility function of MATSim are estimated using the method of Kickhofer et al. (2016) to replicate the observed mode shares of the car, walk, PT, and bike. In general, simulation results (blue line) replicate observed modal shares (black dotted line) (Figure 2).

290 For the calibration of SMMS services, the latest HTS of Lyon does not provide the modal shares of shared bikes or e-scooters. These shares are estimated to be marginal. By using SMMS trip records, this share is estimated to be 0.8%.

Parameters of the utility function of BSS and SSS are calibrated to replicate the distribution of the number of rentals of vehicles in Lyon. Figures 3a and 3b compare simulated and observed numbers of rentals per hour of an average day of May 2022 of the BSS and SSS, respectively. Simulation outcomes on the daily use of shared bikes and e-scooters replicate, to a certain degree, observations from Lyon. As expected, most of the rentals are performed during the morning (6 AM-9 AM) and evening (4 PM-7 PM) peak periods. For SSS, the simulation underestimates the number of rentals. The total simulated daily number of rented e-scooters is 9,520 (± 480 given the stochasticity of the framework) while $\approx 12,000$ rentals were observed. For BSS, the simulation predicts 25,756 (± 1288) bike rentals against $\approx 25,000$ observed rentals. The discrepancy between simulation outcomes and observations is due to calibration issues, but also to the intrinsic variability in the use of SMMS that depends on various factors not considered in this research, like weather conditions.

305 To reduce the computational time of the simulation, all scenarios are down-scaled to 25%. The down-scaling of the framework produces a reduced-scale experimental model of reality that produces outcomes similar to that of the full model while limiting computational times. Reduced-scale models are often used in physics, ecology, biology, engineering, etc. In MATSim, this is achieved by randomly drawing $N\%$ ($N = 25\%$ in our case) of synthetic agents and by reducing correspondingly travel supply (network capacity, PT capacity, number of shared vehicles, etc.). Previous research shows that the impact of down-scaling on the quality of simulation outcomes decreases with N and recommends to choose $N \geq 20\%$ (in our case $N = 25\%$) (Ben-Dor et al., 2021). Thanks to down-scaling, computations in Lyon take 14h on a personal computer with 12 CPUs and 32Go of RAM.

4. Results

4.1. Implications of the introduction of SMMS

In the reference scenario, the modal shares of SMMS are marginal (Figure 4a).

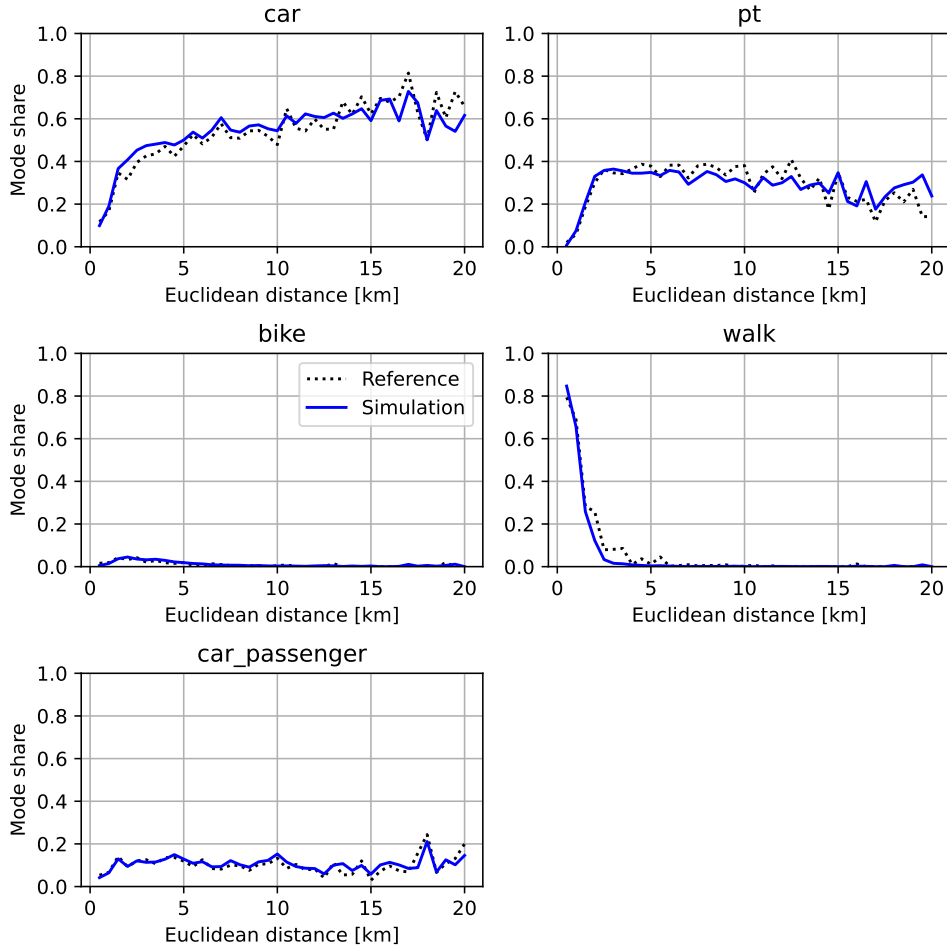
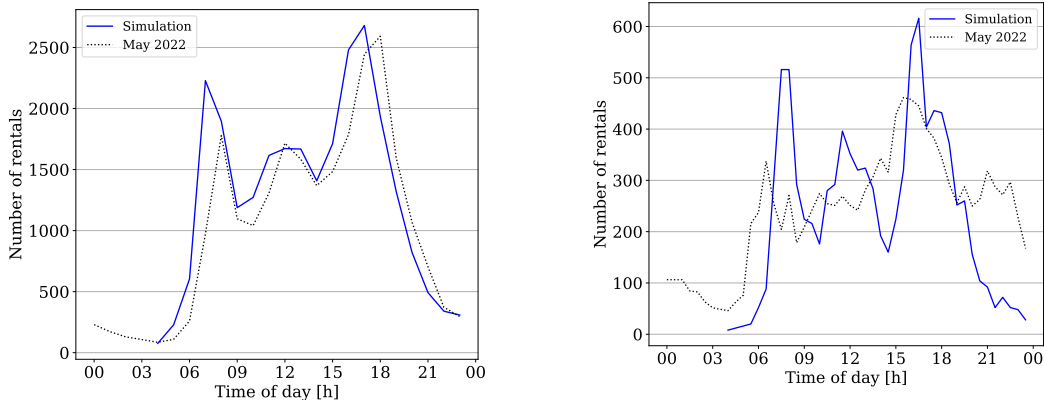


Figure 2: Comparison between estimated and observed modal shares of the reference scenario of Lyon.



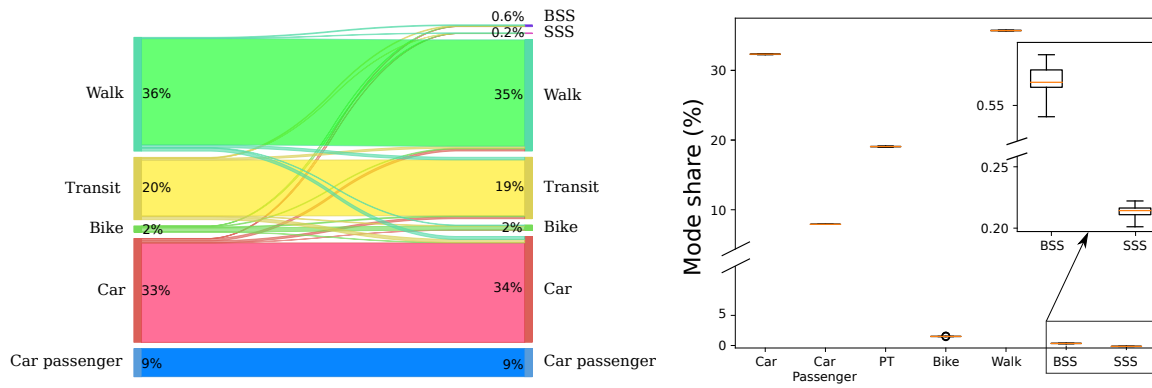
(a) Observed and simulated hourly rentals of shared bikes.

(b) Observed and simulated hourly rentals of shared e-scooters.

Figure 3: Comparison between estimated and observed daily rentals of shared bikes and e-scooters in Lyon.

315 Results show that BSS and SSS have a share of 0.6% and 0.2% of the total trips in Lyon, respectively (Figure 5). Most of this demand is shifted from PT and walking (Figure 4a). 69% and 18% of SSS demand comes from walking and PT, respectively. 43% and 39% of BSS demand is shifted from walking and PT, respectively. Most of the trips that shift to SMMS have a short trip duration, i.e. less than 25min, on average. The modal shift from car to SMMS is limited. Only 6% and 7% of SSS and BSS
 320 demand is shifted from the private car, respectively. Mode shift to SMMS is mainly motivated by savings in the generalized travel cost.

In view of the low modal shares of the SMMS modes and the stochasticity of the simulator, a sensitivity



(a) Simulated modal shares before and after the introduction of BSS and SSS in Lyon. (b) Sensitivity of mode shares in the reference scenario to the random seed.

Figure 4: Mode shares before and after the introduction of SMMS in Lyon and their sensitivity to the stochasticity of the framework.

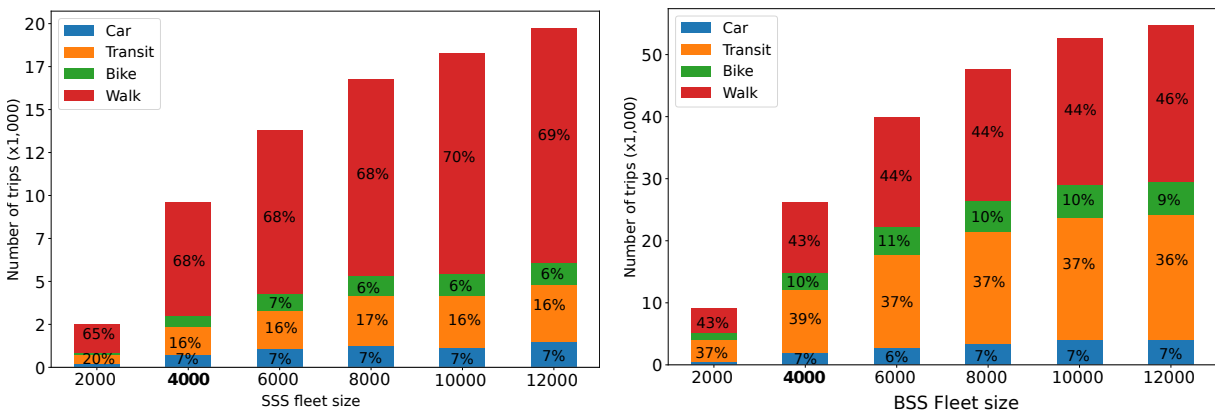
analysis on the stochastic behavior of the simulator is undertaken by changing its random seed, i.e. random state. 16 simulations with different random seeds are tested. The share of SMMS is found to vary within the range of $\pm 5\%$ (Figure 4b). The modal share of BSS, for example, is between $0.006 \times (1 - 0.05)$ and $0.006 \times (1 + 0.05)$.

4.2. Implications of the fleet size

4.2.1. Implications on mode shares

Figure 5 provides an overview of the impact of the fleet size on the demand for BSS and SSS and the competition they introduce. As expected, demand for SMMS increases with their supply. Least expected is that the increase is not equal between BSS and SSS. Demand for SSS increases by nearly 10 times when the fleet of e-scooters increases from 2,000 to 12,000 (Figure 5a), while BSS demand increases by only 6 times (Figure 5b).

In general, the increase in the fleet size of BSS and SSS has a differentiated impact on existing modal shares (Figure 5). For both services, the increase in their fleet size shifts demand mostly from walking and PT. The modal shift from walking is more significant for SSS than BSS (Figure 5a), while the shift from PT is more significant for BSS than SSS (Figure 5b).



(a) Impact of the fleet size on the use of shared e-scooters and mode competition. (b) Impact of the fleet size on the use of shared bikes and mode competition.

Figure 5: Demand and mode competition of SMMS according to the fleet size. The reference scenario is in **bold**.

Simulation results show also that demand shifted to SMMS from other travel modes has a constant distribution regardless of the fleet size (Figure 5). The share of walkers or car users that shift to e-scooters, for example, is constant whatever the size of the fleet. This result is expected since additional vehicles are deployed according to the spatial distribution of the fleet in the reference scenario. If the additional vehicles are deployed differently, the resulting competition brought by additional vehicles might change the existing distribution.

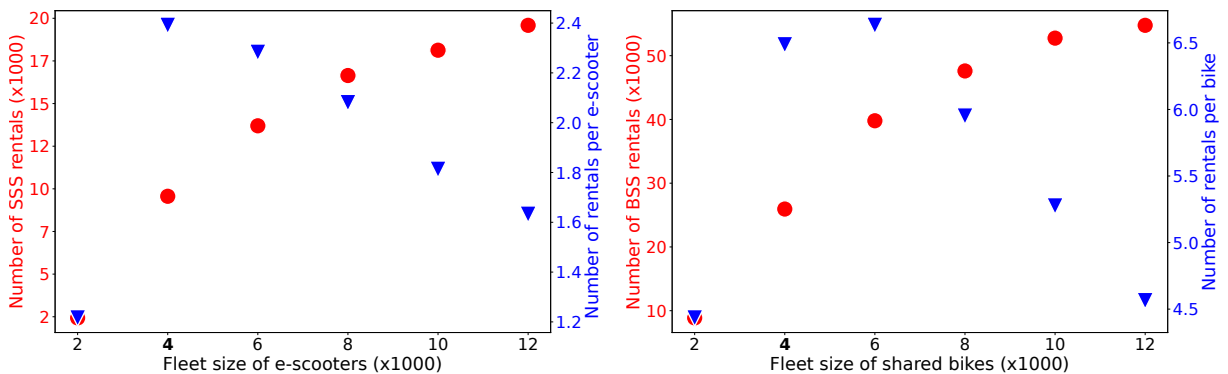
One of the implications of the increase in the fleet size of free-floating e-scooters is the increase in their accessibility, namely the reduction in walking access distances. By increasing the number of e-scooters from 2,000 to 12,000, walking access times decrease from 3.4 min (median 3min) to 2.8min (median 2.5min). Even if the reduction in walking times is marginal, i.e. less than 1 min on average, with a fleet four times larger, the availability of shared vehicles is proportional to the increase.

4.2.2. Fleet elasticity

Previous findings show that the introduction of SMMS attracts travel demand and reshuffles, to a limited extent, existing mode shares. The extent of this impact is, however, dependent on the fleet size of SMMS (Figure 6). For shared e-scooters, the simulated average fleet elasticity is 0.83. An increase of 10% of the fleet size of SSS produces, on average, an increase of 8.3% in the number of rentals. This elasticity is however asymmetric and size-dependent. SSS demand is more sensitive to a decrease in the size of the fleet than to an increase (asymmetric). A decrease of 10% in the number of shared e-scooters induces a drop in demand of 18%, while an increase of 10% produces an average increase of 7%. The fleet elasticity decreases even more when the size of the fleet increases, i.e. size-dependent elasticity. The average fleet elasticity of SSS is 1.34 when the size of the fleet is less than 6,000 and 0.5 when the size is greater than 6,000. This translates into decreasing marginal returns for SSS with respect to supply. When the fleet size increases from 2,000 to 4,000, the number of rentals increases by nearly 300%, while it increases by only 9% when the fleet increases from 8,000 to 10,000. This result indicates a saturation of the market of e-scooters.

Similar findings can be drawn from BSS simulation outcomes (Figure 6b). Total demand for BSS increases with the size of the fleet, while the marginal demand decreases with size. The average fleet elasticity of BSS is 0.8, but demand reacts more to a decrease in the fleet (elasticity of 1.47) than to an increase (elasticity of 0.6).

For both services, the number of rentals per shared vehicle follows a quadratic function (inverted U function) of the fleet size (blue triangles in Figure 6a and 6b). There exists a fleet size for which the number of rentals per vehicle is maximum. In Lyon, this tipping point is around 4,000 for shared e-scooters (Figure 6a), while for BSS, this point is around 6,000 (Figure 6b). The existence and identification of this tipping point are of vital importance to the operation and profitability of SMMS.



(a) Total daily numbers of e-scooter rentals and their utilization rates according to the fleet size. (b) Total daily numbers of bike rentals and their utilization rates according to the fleet size.

Figure 6: Number of rentals of BSS and SSS and their utilization rates according to the fleet size. The reference scenario is in **bold**.

4.2.3. Implications on SMMS earnings

Earnings generated from the operation of SMMS depend on the use of their vehicles. In general, earnings are proportional to the number of rentals. Operators are therefore encouraged to adopt strategies that increase the use of their fleet, like increasing its size. Nevertheless, it is also of critical importance to generate viable unit economics, i.e. positive earnings per unit of production or service. If SMMS operators can be tempted to increase their fleet size to generate more demand and seek higher revenues, this increase is however limited by the decrease in the average use of vehicles and the drop in their unit economics, due to the existence of the decreasing marginal returns with respect to the fleet size (Figure 6).

This means that there exists an optimal fleet size strategy to optimize the operation of SMMS. In the case of Lyon, the maximum revenues per shared e-scooter and bike are achieved with a fleet of 4,000 and 6,000 vehicles, respectively (Figures 7a and 7b). Given appropriate assumptions on the unit cost of SMMS operations, different fleet size strategies can be devised depending on the business model of SMMS operators.

By assuming an average total cost of shared bikes of 6€ per day³ (Courbe et al., 2020), simulation results show that some fleet strategies are more profitable than others (blue triangles and green crosses in Figure 7b). Results indicate that the smallest, i.e. 2,000, and the largest, i.e. 12,000, BSS fleet strategies are economically unprofitable. Their revenues per shared bike do not cover their unit cost.

If the objective of a city or a BSS operator is to maximize its bike ridership and boost bike use and adoption via BSS, while generating positive net income to cover BSS-associated costs, this city/operator can increase the fleet size as much as the unit net income per bike is positive, i.e. the average daily revenue per vehicle is higher than its daily cost. In the case of Lyon, this business model would be achieved by increasing the actual BSS fleet size from 4,000 to 10,000 bikes (Figure 7b). With 10,000 shared bikes, the operator can still generate a positive net income of 0.2€ per bike and per day. In comparison with the reference situation of Lyon with 4,000 bikes, the new fleet strategy can raise BSS ridership by nearly 100%. This strategy is however not optimal from a profit perspective.

If the objective of a city or an operator is to maximize its profit, much attention should be paid to the decreasing marginal returns of the fleet size. In the case of Lyon, for example, the local BSS operator can maximize its total net earnings by increasing the fleet from 4,000 to 6,000 bikes. In this case, BSS net earnings are maximal and increase by 66% in comparison with the reference scenario. The under-supply or over-supply of shared bikes in reference to this optimal fleet size will reduce the profitability of the operator.

Contrary to non-electric station-based BSS services, the daily total cost of shared electric free-floating e-scooters depends more on the utilization rate of vehicles. In the case of SSS, this cost is mainly driven by the relocation and charging operations of e-scooters. By assuming an average e-scooter trip cost of 2€ (Rose et al., 2020), a total purchase cost of 800€ and a lifespan of 15 months, the daily total cost of an e-scooter can range between 4€ and 6.5€ depending on its daily utilization rate (green crosses in Figure 7a). Given these assumptions on the cost structure of SSS, results show that not all fleet strategies are profitable. Similarly to BSS, the smallest (2,000) and largest (12,000) fleets are unprofitable.

Similarly to BSS, different fleet size strategies can be defined for SSS depending on the business model of their operators. In Lyon, the strategy that would maximize total ridership and promote micromobility while preserving a positive net income, requires increasing the size of the fleet from 4,000 to 10,000 (Figure 7a). This fleet strategy can increase SSS ridership and revenues by nearly 90% in comparison with the reference scenario of Lyon. However, this strategy is not the most profitable to SSS operators. If the objective is to maximize SSS profit, the optimal strategy in Lyon would be to set the fleet to 6,000 shared e-scooters. This fleet strategy can yield an increase of 43% in revenues and 21% in net incomes in comparison with the reference scenario.

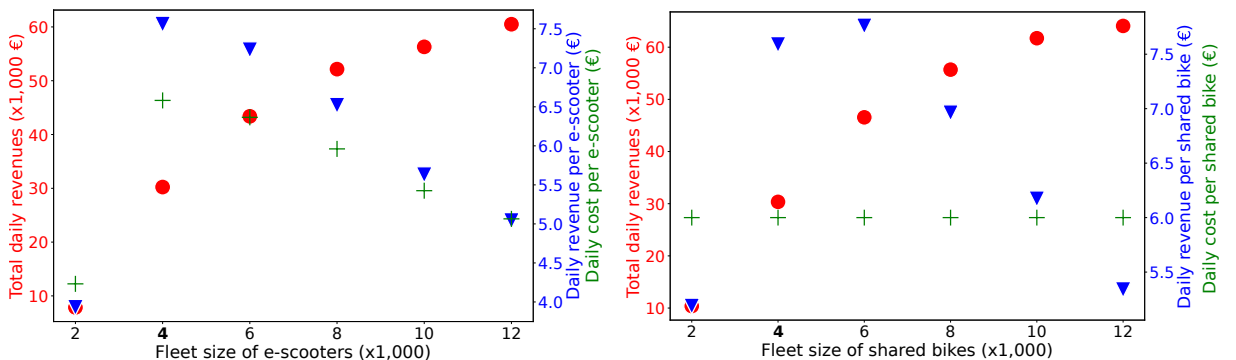


Figure 7: BSS and SSS revenues and earnings according to the fleet size. The reference scenario is in **bold**.

Summary of the implications of the fleet size: The fleet size strategy has a significant impact

³We assume this cost is constant and independent from the size of the fleet.

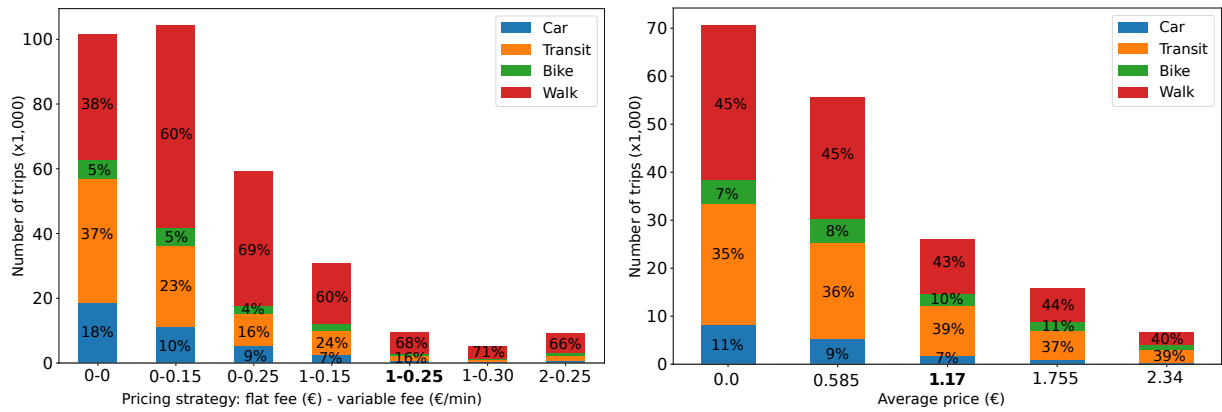
420 on the use and profitability of shared bikes and e-scooters. As expected an increase in the size of the
 fleet induces an increase in the share of SMMS. This increase comes at the expense of alternative travel
 modes, especially walking and PT. The mode distribution of the competition brought by SMMS is found
 to be independent of the size of the fleet.

Simulation outcomes also show that despite having similar fleet sizes, free-floating e-scooters benefit
 425 more from the increase in the size of the fleet than station-based shared bikes. In other words, the
 fleet elasticity of SSS is higher than that of BSS. More importantly, the fleet size is found to have a
 decreasing marginal effect for both services. As the size of the fleet increases, the marginal additional
 demand decreases. This indicates that there exists an optimal fleet size that can maximize the use or
 profit of SMMS. Depending on the business model of SMMS operation, different fleet size strategies can
 430 be devised. In the case of Lyon, the actual fleet size is found to be sub-optimal in terms of use and
 net revenues. In general, these results highlight the critical importance of the fleet size as a strategy to
 support the business model of SMMS and their adoption.

4.3. Price implications

4.3.1. Implications on mode shares

435 Similarly to the effect of the fleet size, the pricing strategy of SMMS has a notable impact on their
 use (Figure 8). When these services are freely available to users, thanks to a public subsidy for example,
 demand surges by nearly 10 times for SSS (Figure 8a) and 3 times for BSS (Figure 8b) in comparison
 with the reference scenario. As the price of these services increases, their demand decreases. The price
 has also a decreasing marginal effect similar to the fleet size (Figure 8).



(a) Impact of the fleet size on the use of shared e-scooters and mode competition. (b) Impact of the fleet size on the use of shared bikes and mode competition..

Figure 8: Demand and mode competition of SMMS according to the pricing strategy. The reference scenario is in **bold**.

440 The distribution of shifted demand from alternative modes, i.e. competition, is influenced by the
 pricing of SMMS services. This is not the case with the fleet size. This change is particularly noticeable
 among car users who are marginally attracted by SMMS unless the price of these services decreases to
 compete against the low marginal cost of car use. When SSS and BSS are free, demand shifted from the
 private car increases from 8% to 18% for SSS, and from 7% to 11% for BSS. The share of the demand
 445 shifted from walking and PT remains almost stable, whatever the pricing of BSS. This is less the case for
 e-scooters which compete more or less against PT and walking depending on their price.

For SSS, we find that the competition against alternative modes is more sensitive to the variable fee
 than to the flat fee. Regardless of the flat fee, when the variable fee of SSS is 0.15€/min, 60% and
 24% of demand for SSS derives from walking and PT, respectively. When the variable fee increases to
 450 0.25€/min, walking and PT contribute to SSS demand by 69% and 16%, respectively. As the variable fee
 decreases, competition against PT increases, while it decreases against walking. This finding is expected
 because a lower variable fee means a higher incentive to use e-scooters for longer trips that are more
 likely to be performed by PT than walking.

4.3.2. Price elasticity

455 For BSS, the average price elasticity is -1.33 (Figure 9b). For a 10% increase in the price, demand
 decreases by 13.3%. Similarly to fleet elasticity, price elasticity is asymmetric and price-dependent. BSS
 demand reacts more to an increase in price than to a decrease. For example, a decrease of 10% of the

price of BSS produces, on average, a 7% increase in demand, while an increase of 10% in the price yields an average decrease of 21% of demand. This asymmetry can be explained by the existence of alternative modes, especially walking and PT, that can be used to satisfy BSS travel demand when their cost increases.

Simulation results show that the flat fee has a significant impact on the demand for SSS (Figure 9a). When the pricing strategy of SSS decreases from 1€-0.25€/min (actual price in Lyon) to 0€-0.25€/min, demand increases by more than 5 times. In comparison, when the price decreases from 0€-0.25€/min to 0€-0.15€/min, demand increases by 75%.

It is noteworthy that when SMMS are freely available, SSS attract more demand than BSS. This is due to the relatively added utility derived from SSS use over BSS use. Shared e-scooters are faster than bikes, which increases their relative utility. E-scooters are also dockless and can be parked near the final destination which engenders no egress walking time, while BSS are station-based and require access and egress walking times. These two factors can explain the higher increase in the demand for SSS over BSS.

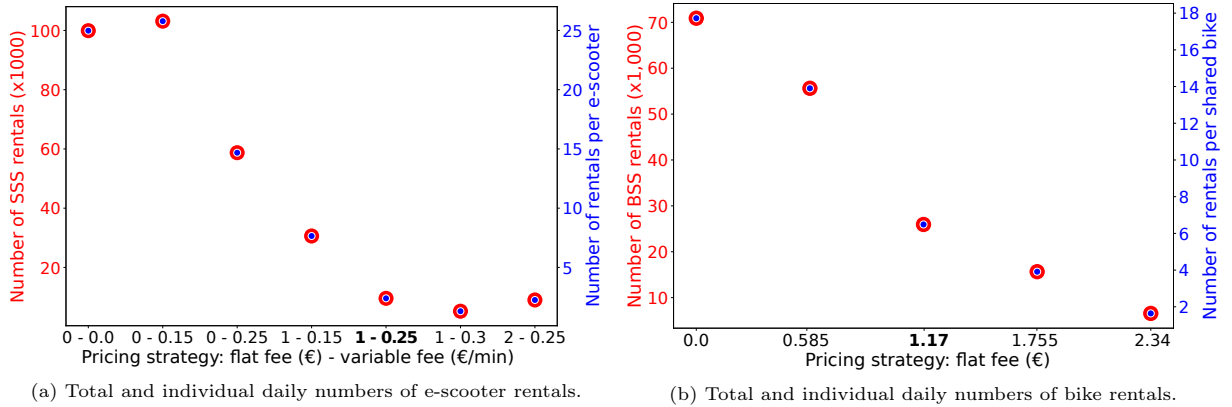


Figure 9: Number of rentals of BSS and SSS according to their pricing strategy. The reference scenario is in bold.

4.3.3. Implications on earnings

The pricing strategy of SMMS has direct implications on the profitability of their operators. Both the demand for SMMS and corresponding revenues depend on the pricing strategy. Simulation outcomes show that the total revenues and revenues per shared vehicle follow an inverted U-shaped function (Figure 10). This means that some pricing strategies are more profitable than others. Depending on the business model of the operators of SMMS, different pricing strategies can be adopted for these services.

For SSS, if the objective is to maximize the social welfare by increasing the adoption and use of shared e-scooters while covering their associated costs, their price can be reduced as much as the net income per e-scooter is positive. In this case, the optimal pricing strategy in Lyon would be 0€-0.25€/min (Figure 10a). The increase in demand following the reduction in the price compensates for the decrease in the price of e-scooter use. In comparison with the reference scenario of Lyon where e-scooters are charged a flat fee of 1€ and 0.25€ for each minute of use, the new pricing strategy can help local operators increase their revenues by $\approx 350\%$ and their net earnings by $\approx 260\%$. From a net earning perspective, this pricing strategy is also optimal. Net earnings of SSS are maximal with the new pricing strategy.

Simulation outcomes suggest that operators can maximize BSS ridership while earning a positive net income, by reducing the actual price of BSS by 50% (Figure 10b). This strategy can yield a 7% increase in BSS demand and 34% in net earnings compared with the reference scenario of Lyon. Similar to e-scooters, the optimal strategy from the perspective of ridership maximization is also optimal from the net earning perspective.

If Lyon seeks to maximize the adoption and use of shared e-scooters by providing this service for free, SSS can acquire a share of more than 2% of total trips, of which 18% is shifted from the private car (Figure 8a). The free provision of e-scooters will require, however, an important subsidy from public authorities to cover their costs. This subsidy is estimated to be more than 200,000€ per day. This cost is mainly driven by the high utilization rate of e-scooters, i.e. 25 rentals per day, which entails higher operational costs (charging and relocation). This subsidy is, however, likely to be overestimated due to the existence of economies of scale in SSS operation that can be achieved when demand for e-scooters is as high as with the free-cost scenario. But, even with a scale economy of 50%, the public subsidy to e-scooter operators would still be considerable (104,324€/day).

For BSS, the free provision of this service can increase the use of shared bikes by nearly 3 times and bring the use of bikes (private and shared) to nearly 4% of the total mode share in Lyon. This comes however at the cost of a public subsidy to cover the cost of BSS operation of nearly 24,000€ per day.

If SMMS operators seek to increase their revenues by increasing their prices beyond the optimal price, demand for these services sharply decreases, and so do their revenues and profitability (Figure 10). An increase of 2 times the current BSS price, for example, will induce a drop in demand and unit revenues below the average unit cost of 6€ per day and bike.

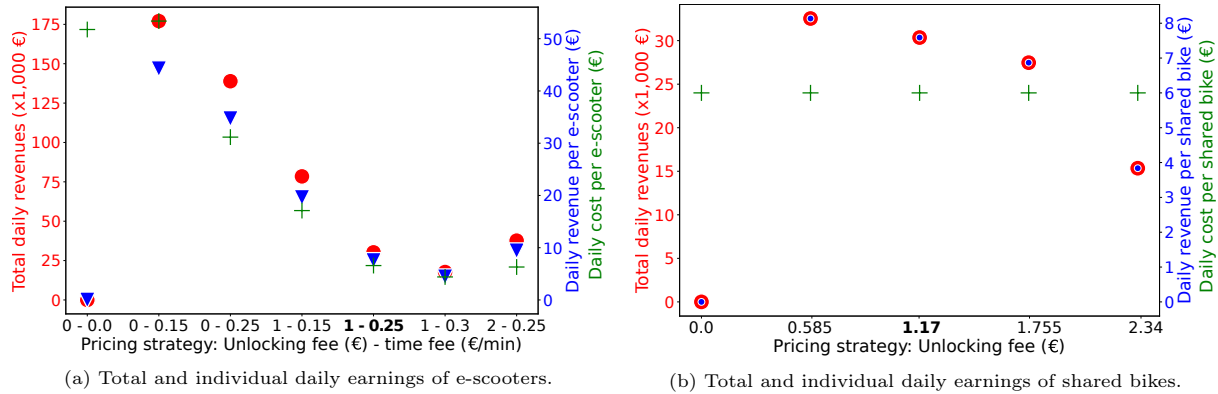


Figure 10: BSS and SSS revenues and rentals according to their pricing strategy. The reference scenario is in **bold**.

Summary of the implications of the pricing strategy:

The pricing strategy has a substantial impact on the adoption, use, and earnings of SMMS. As expected, a decrease in the price of BSS and SSS induces an increase in their use. When these services are freely available, they can take a non-negligible share of travel demand, i.e. $\approx 3.5\%$ in total.

Findings emphasize the important role the pricing strategy can play in the profitability of SMMS operators. In the case of Lyon, the actual pricing strategies of BSS and SSS are found to be sub-optimal. Net earnings and ridership of these services can be increased above their actual levels by adopting appropriate pricing strategies.

For SSS, results indicate that the competition brought by e-scooters depends on their variable cost (€-per-min). When this cost decreases, users are more likely to ride e-scooters for longer trips that used to be performed by PT or the private car. In this case, more travel demand is shifted from these motorized modes than from active modes. When this rate increases, e-scooters are more likely to be used for shorter trips that can be performed by foot. In this case, e-scooters compete more against walking than motorized modes. In comparison with the variable fee, the flat fee has a marginal impact on the relative competition between modes. A decrease in this fee produces an increase in total SSS demand with no impact on the relative mode shift.

Finally, findings indicate that the price elasticity of SMMS is higher than the fleet elasticity. For BSS, for example, the number of rentals increases by 2 times when the price is halved, while the increase in the use is relatively lower when the BSS fleet doubles. Similar results have been found for SSS.

5. Discussion

This research investigates the implications of two important strategies in shared micromobility services: the size of the fleet and pricing. Findings from the case of Lyon confirm that the supply of appropriate quantities at the appropriate price is a vital ingredient to their adoption and profitability. These findings can be generalized to other cities and other shared micromobility services.

SSS and BSS are found to compete more against walking and PT than the private car in Lyon. This competition pattern has already been discussed in the literature in different contexts (Wang et al., 2022; Laa and Leth, 2020; Krier et al., 2019; Kong et al., 2020; Fitt and Curl, 2019; Weschke et al., 2022; Nikiforiadis et al., 2021; Fishman et al., 2014). By surveying more than 4,000 e-scooter users in France, Krier et al. (2019) find that in the absence of e-scooters, 47% of their users would have walked and 29% would have used PT. The same study shows that e-scooters can also substitute for shared and private bikes (Krier et al., 2019). Similar findings have been found for bike-sharing. The competition of BSS and SSS against the private car is limited, especially in European cities where short-distance trips are likely

to be performed by active modes or PT (Wang et al., 2022). These results are in line with our findings from Lyon.

540 In contrast with the literature on SMMS competition, other studies point to the potential of complementarity between SMMS and existing urban mobility services (Nikitas, 2019; Böcker et al., 2020; Zuniga-Garcia et al., 2022). SMMS have the potential to satisfy mobility needs that are currently not or ill-fulfilled. The complementary role of SMMS requires careful design for these services (station location, capacity, parking restriction, geofencing, price integration, etc.). This has not been investigated in this
545 research. Available simulation outcomes can be useful, though, to explore the patterns of SMMS use and the necessary design and deployment conditions to maximize the complementary potential.

The findings show that the competition brought by SMMS, and especially SSS, can be modulated by the pricing strategy. A low variable cost (€-per-min) of use of these services fuels the competition against motorized modes (car and PT), while a high variable cost encourages the competition against
550 active modes (walking). This partly explains why e-scooters in Lyon are found to compete more against walking than bike-sharing, and why bikes compete more against PT than e-scooters. In fact, the cost of a trip by public transport is $\approx 1.9\text{€}$ in Lyon which is higher than the cost of BSS and lower than the average 10 min trip by the e-scooter.

The findings show that demand for SMMS depends on their fleet size and price. As expected, SMMS
555 demand increases with the size of the fleet and decreases with the price. For shared e-scooters, for example, we find an average fleet elasticity of 0.83, meaning that demand is inelastic to the fleet size. The inelasticity of SSS and BSS demand has already been underlined in the literature (Lee et al., 2021; Shah et al., 2022; Mclean et al., 2021; Shen et al., 2018). Our short literature review reveals, however, that different studies find different fleet elasticities. These differences can be attributable to different contexts
560 or research methodologies, but also to the intrinsic variability of the elasticity. Our findings show that the elasticity of SMMS demand is not constant. Results indicate that this elasticity is size-dependent and asymmetric. The intrinsic variability of the price and fleet elasticities can explain part of the differences reported in the literature.

In relation to the variability of the elasticity, our findings show that the impact of the fleet size
565 and price is not linear. As the price and size increase their marginal effect on demand decreases. This finding has already been highlighted in different spatial contexts by Reck et al. (2021), Shen et al. (2018), Mclean et al. (2021), and de Chardon et al. (2017). These authors find that the marginal benefit derived from increasing the size of the fleet of SSS and BSS decreases with the size of the fleet. This finding is noteworthy.

570 The decreasing marginal returns of SMMS has far-reaching consequences on their operation and profitability. We show that the daily use and revenues per vehicle follow an inverted U function with an optimal point at which the use and revenues are maximal. This result points to a notable finding: there exists an optimal strategy for the operation of SMMS. The optimum can be from the perspective of total revenues, net earnings, total ridership, or a combination of these. Depending on the business model
575 behind the operation of SMMS, different pricing and fleet size strategies can be adopted. In the case of Lyon, we find that local operators have sub-optimal strategies in terms of net revenues and ridership. Local operators can increase their profit or ridership by increasing their fleet or reducing their prices.

580 These findings are likely to be generalized to other contexts and other SMMS services. In many cities, ad hoc regulations were introduced to control the development of SMMS and to limit their negative externalities. Among these regulations, fleet size capping is popular (Riggs et al., 2021). Nevertheless, the choice of the appropriate cap is not straightforward and requires appropriate simulation tools to set it. In the absence of these tools, fleet caps are likely to be arbitrarily set. In this case, cities are more likely to operate SMMS under sub-optimal conditions that might undermine the adoption and development of these services as well as the profitability of their operators.

585 Another finding is the significant impact of the flat fee on e-scooter use. We show that a decrease in the flat fee from 1 to 0 € can yield a significant increase in demand in comparison with a decrease in the time fee. This result has been found by Arango (2022) in another spatial context. These authors find that demand for e-scooters increases by nearly 100% when the flat fee is not charged. They also show that an increase of 100% of this fee reduces demand by nearly 50% (asymmetric effect). The implications
590 of this finding seem to be already understood by SSS operators who offer free and unlimited e-scooter unlocking to customers with memberships or passes (Dott, 2022; Lime, 2022).

595 Results also show that the variable fee has a higher effect on the competition brought by e-scooters than the flat fee. With a low variable fee, the competition of e-scooters against long-distance modes, like PT or car, increases. An increase in this fee boosts the competition against short-distance trip modes and especially walking. This finding is noteworthy to cities that seek to steer the development of SMMS

to compete against the private car while limiting the competition against more sustainable travel modes like PT or walking.

In Lyon, shared bikes and e-scooters have similar fleet sizes, but different operating strategies. Shared bikes are station-based and do not require battery charging, whereas e-scooters are free-floating and require frequent battery charging operations. Consequently, these services have different cost structures and revenues. These differences are worth considering by operators that combine e-scooters and bikes in their shared micromobility fleets. With combined fleets, the mixing ratio of these services, i.e. relative shares of bikes and e-scooters, is also a parameter that should be considered in the search for optimal strategies. The optimization of this ratio is, however, more challenging since these services, i.e. shared e-scooters and bikes of the same operator, can be in competition for similar market segments.

Our findings on the profitability of BSS and SSS operators are sensitive to the assumptions on cost structures. The SMMS industry is putting considerable effort into the reduction of these costs. The extension of the lifespan of vehicles is one of their targets. If the lifespan of e-scooters increases, for example from 15 months to 24 or 36 months, the profitability of SSS can substantially change. In the case of Lyon, smaller (2,000 e-scooters) and larger fleets (12,000) will also become profitable even if their utilization rates per e-scooter are low, i.e. less than 2 rentals per day. Most likely, the decrease in the unit cost per vehicle will incentivize operators to increase the size of their fleets to achieve economies of scale, dominate the market, and improve even more their profitability. The advent of this scenario will certainly depend on local regulations that should limit the negative externalities of large fleets.

This research shows that policymakers have two powerful levers to steer the development and supply of shared micromobility services, especially when operated by the private sector. Theoretically, policymakers can control the fleet size of SMMS operators or cap their prices when authorizing the operation of these services. The combination of these regulations can help reap the benefits of SMMS while controlling their externalities. In practice, public intervention in this regard is often limited to the regulation of the maximal fleet size, as is the case in Lyon and many other cities (Riggs et al., 2021). Fleet capping regulation has often been introduced to limit parking and curb-management issues, with little regard for their wider implications on demand and service profitability, as shown in this research. Public intervention in the pricing strategy of these services is hardly seen or even discussed. Yet, our results show that the price-regulation has a higher impact (elasticity) on SMMS demand and profitability than fleet size regulation. In this case, price regulation does not necessarily mean public control of the pricing strategies of private SMMS operators, but it can consist of a partial service subsidy or other incentives that can help optimize their provision and integration with existing modes. For this, policymakers and SMMS operators are still in need of appropriate simulation tools to evaluate the impacts of their decisions. In this regard, the framework used in this research can be of help.

6. Limitations

Despite our efforts, this research still has several limitations. The most noteworthy limitation is due to the mode choice model used by synthetic agents to choose between several travel alternatives. For this, we use a generic utility function that includes the effect of the price and travel time, including access and egress times. Research has already highlighted the important role of other explanatory variables like age, gender, income, safety concerns, social interaction, or weather as determinants of the use of BSS and SSS (Manca et al., 2019). The specification of a new utility function in MATSim requires conducting a stated-preferences survey to collect data on BSS and SSS preferences. Such survey data is not available in Lyon, but future work will address this limitation by including new explanatory variables from other surveys conducted in other French and European cities.

In relation to mode choice, this research relies on pre-pandemic household travel survey data. The impact of COVID-19 on activity and mobility behaviors is not considered.

For the optimization of SMMS earnings, we use a simple unit cost function that is constant for BSS and trip-based for SSS. This function was defined based on reports from the SMMS industry. Nowadays, efforts are put into the reduction of SMMS costs, by introducing swappable batteries or by increasing the lifespan of vehicles, for example. Some of the results, especially those related to SMMS earnings, are likely to be impacted by these new developments. In this case, even larger fleet sizes can become profitable since the unit cost becomes lower, especially in the presence of economies of scale.

We assume that BSS and SSS operators perform static rebalancing at the end of the day to limit their associated costs. We do not simulate within-day dynamic rebalancing that aims to adapt supply to demand in space and time. This strategy is often adopted by operators, but it bears high operating costs.

Future work will explore the impact of dynamic rebalancing on the demand, operation, and earnings of SMMS.

For BSS, we assume a constant cost of use of 1.17€. In fact, the pricing scheme of BSS in Lyon is more complex. This assumption can be overcome by using appropriate data on BSS membership and cost modulation according to individual characteristics. In this regard, the agent-based approach is convenient. This is also true for SSS which offers short term-memberships and passes to users to limit their cost of use.

Lyon, like other cities, has introduced e-scooter parking restrictions. Within the limits of some areas, like the historic district, e-scooters should be parked in reserved places. This regulation can impact the operation, access, and use of SSS. This research does not consider parking limitations. This should be addressed in future work. For this, the simulation framework needs to be updated to include parking limitations in the operation of free-floating services.

In this paper, we also assume that e-scooter batteries are instantly swapped each time they are depleted. In this case, the state-of-charge of the battery is assumed irrelevant to the choice probability and use of this mode. In fact, battery swapping and recharging is time and cost-consuming. The impact of the charging strategy on SSS operation and demand in Lyon needs to be addressed in future work.

7. Conclusion

This research evaluates the implications of the fleet size and pricing strategies on the demand, operation, and earnings of shared micromobility services. These implications are investigated in the case of Lyon via an agent-based simulation framework. Simulation results indicate that SMMS compete against existing travel modes, especially public transit and walking. The extent of this competition is minimal due to the marginal share of SMMS. Nevertheless, the potential of shared micromobility is not negligible.

Results from the simulation of the transportation system in Lyon show that this potential is unfulfilled and that it can be realized by appropriate strategies regarding the fleet size and pricing of these services. In the case of Lyon, we show that the current fleet and price strategies are sub-optimal. Demand for SMMS is not fully met. The full potential of SMMS can be reached by either increasing their fleet size or decreasing their prices. The optimal fleet size and price depend on the business models of SMMS operators. We show that different objectives (maximization of ridership or net earnings) require different strategies.

These findings can be of interest to SMMS operators and mobility planners in the design and operation of efficient SMMS services. The findings of this research and its methodology can support SMMS operators in the supply of optimal services. They can also help policymakers regulate these services and bring the best out of them while offering viable economic conditions for their operation.

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Authors' contributions

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