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1 **MATSim Model Vienna: Analyzing the Socioeconomic Impacts for Different Fleet Sizes and**  
2 **Pricing Schemes of Shared Autonomous Electric Vehicles**

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**1 ABSTRACT**

2 Shared Autonomous Electric Vehicles (SAEVs) are expected to enter the transportation market in  
3 the upcoming decades. In this paper, we describe the preparation of a MATSim model for Vienna  
4 in which we add this new service as a new transportation mode. We simulate different pricing  
5 schemes for various SAEV fleet sizes and analyze their impacts. Our focus is on the impacts in  
6 regards of socioeconomic heterogeneity.

7 One main finding of our paper is that the number of SAEV trips does not necessarily decrease for  
8 higher fares. It is instead the average travel time of SAEV rides which decreases if the service gets  
9 more expensive. Our simulation results for higher pricing schemes show that many people switch  
10 from bike or walk mode to SAEV. Public transport is also highly cannibalized by this new service  
11 regardless of the price, whereas SAEVs would always replace no more than 10% of car trips.

12 SAEVs help reduce travel times significantly. People who do not have a car available in their  
13 household experience the greatest savings in travel time. A similar high share of SAEV trips is  
14 done by people older than 35 years. In regards of gender, our results reveal that women tend to use  
15 SAEVs for shorter trips.

16

17 *Keywords:* MATSim; SAEV; demand responsive transportation; subpopulations; socioeconomic  
18 heterogeneity

## 1 INTRODUCTION

2 Shared, autonomous, electric vehicles (SAEVs) are expected to be gradually released to the market  
3 in the upcoming decades. There is a broad consensus that they will play a substantial role in  
4 future transport systems. The typically strong path-dependencies in the transport sector and, as a  
5 consequence, the risk of sub-optimal equilibria render it essential to investigate the potential effects  
6 of different policies related to SAEVs before their market introduction (Adler et al. (1)).

7 It is particularly important to investigate which socioeconomic groups are likely to benefit  
8 from the introduction of SAEVs in terms of accessibility. Just as other transport modes, SAEVs  
9 are likely to have heterogeneous impacts on different population groups, depending on their home  
10 location, trip patterns, as well as their mobility-related preferences (for instance, the extent to  
11 which they value travel time savings). For instance, Meyer et al. (2) show that persons living in  
12 sub-urban areas will have over-proportionally large gains from the arrival of SAEVs. The same is  
13 true for persons who can use their commuting time productively (Malokin et al. (3)).

14 In this paper, we conduct various simulations which have in common that SAEVs, which  
15 are assumed to be fleet ownership, are added to the transport system of the city of Vienna (Austria)  
16 and surrounding areas. We use the well-known MATSim software for the simulations (Axhausen  
17 et al. (4)). The scenarios differ in terms of SAEV fleet size and the pricing of the SAEVs, as  
18 these two factors are expected to have substantial implications on the usage of SAEVs (e.g. Hörl  
19 et al. (5)). In contrast to macroscopic traffic assignment software such as VISUM, the traffic  
20 demand can be traced back to the single agent. This enables us to characterize the potential user  
21 of SAEVs in the future. For each scenario, we show to which extent the availability of SAEVs  
22 leads to mode switches among specific population groups, which are assumed to differ in terms of  
23 their socioeconomic characteristics and, based on these, their time and mode preferences, as well  
24 as their home location and demand for travel on an average day. The results of these scenarios  
25 provide us with an indication of the heterogeneous accessibility impacts of SAEVs. These can  
26 provide guidance to policy makers regarding regulative (e.g. fleet size limitations, SAEVs limited  
27 to specific areas) as well as pricing measures (e.g. road tolls).

28 We contribute to the literature on heterogeneity of SAEV impacts, which so far has been  
29 mostly derived from preference studies at the level of the individual traveler (e.g. Spurlock et al.,  
30 Zhou et al. (6, 7)), and hence approached mostly from the demand side. The supply side of SAEVs  
31 has been captured in various simulation models, the most well-known ones probably being Austin  
32 (e.g. Chen and Kockelman (8)), Berlin (e.g. Bischoff and Maciejewskia (9)), and Zurich (e.g.  
33 Hörl et al. (5)). While these models pay much attention to spatial heterogeneity, little emphasis  
34 is placed on socioeconomic heterogeneity. Our model combines a demand-side component that is  
35 able to represent heterogeneity in various dimensions (not limited to spatial heterogeneity) and a  
36 supply-side component where SAEVs are added to the existent transport network of Vienna and  
37 surrounding regions.

38 The structure of the remainder of the paper is as follows. The section *Methodology* dis-  
39 cusses the methodology, specifically the MATSim model and its parametrization as well as the  
40 simulated scenarios in terms of SAEV fleet size and pricing. In the section *Results*, we present the  
41 simulation outcomes. The section *Discussion* discusses the implications and in the final section  
42 *Conclusion* we summarize the findings.

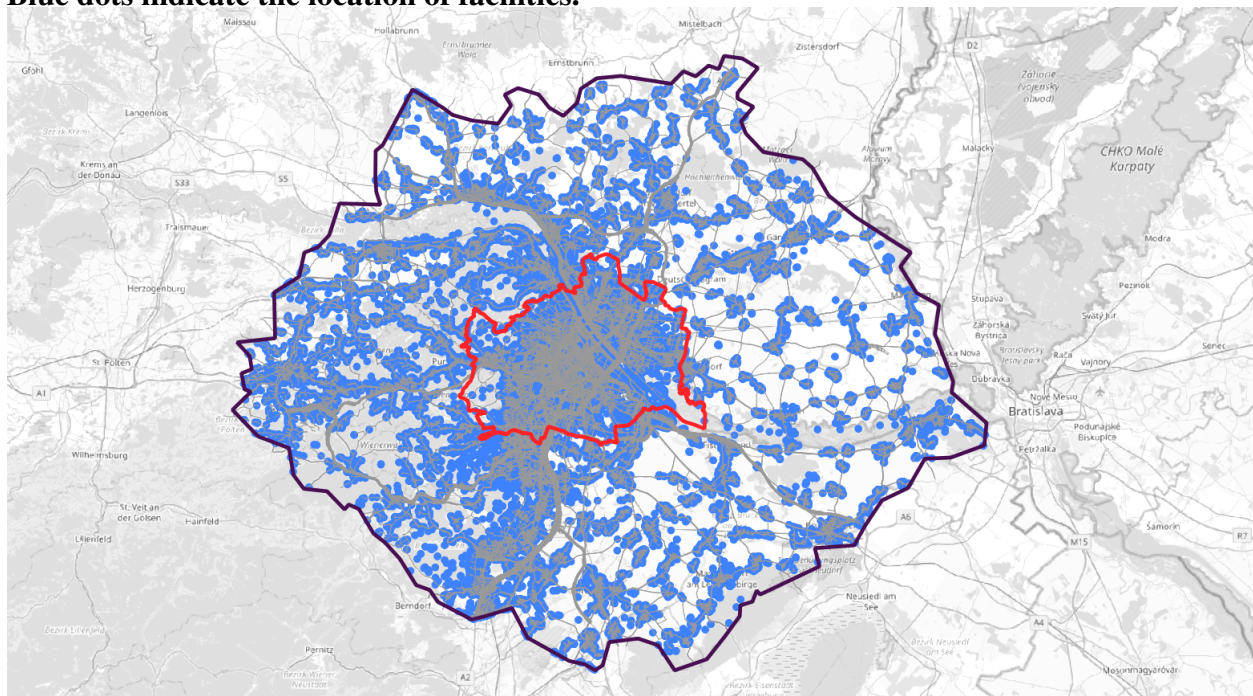
## 1 METHODOLOGY

### 2 Description of the MATSim model for Vienna

#### 3 Area and Network

4 The simulation region of the MATSim model covers the whole city of Vienna as well as the sur-  
 5 rounding area within a radius of roughly 30 km around the city center (Fig. 1a)). The boundary  
 6 is not a perfect circle but was chosen such that infrastructure that is important for traffic in this  
 7 region is included as well. One example is the Danube crossing near Hainburg. It lies outside of  
 8 the radius, but since it is the only possibility to cross the river East of Vienna, it is included as  
 9 well. The population of the city of Vienna and the metropolitan area as of 2019 are 1.91 million  
 10 and 2.85 million (10), respectively. Overall, the simulation area covers  $4170\text{km}^2$ . The car routing  
 11 graph for the simulation region is based on OpenStreetMap (OSM) data and consists of around  
 12 156,000 links and 71,000 nodes.

**FIGURE 1 Maps for the simulation area. The red-framed area marks the city of Vienna. Blue dots indicate the location of facilities.**



#### 13 Simulated population generation

14 Initial daily schedules of the simulated mobility population were created by cleaning, geo-constrai-  
 15 ning and resampling data of the Austrian national mobility-survey “Österreich unterwegs 2013/  
 16 2014” (11), or “ÖU13/14”, for the described region of greater Vienna.

17 Resampling was done to retrieve approximately 12.5% of the total surveyed population  
 18 within the target area, which results in a set of about  $2 \times 10^5$  agents in the simulated scenarios.

19 Computation requirements for the simulation are not high: recent consumer-grade hardware can  
 20 run 100 iterations of the MATSim simulation in less than twelve hours given there is at least 12 GB  
 21 of RAM available.

22 Together with a data set of potential activity locations (home, work, education, shopping,

1 leisure, errand) for the agents, which are based on land use categories and points of interest (both  
2 derived from OSM) as well as open data for population density (12) and workforce (13). An algo-  
3 rithm for spatial dis-aggregation of the survey’s activity location information (given as municipal  
4 code only) was used to assign realistic coordinates for the simulated agent destinations. The im-  
5 plementation of this algorithm relies on the reported trip times and distances as available in the  
6 travel survey data. It finds optimally fitting locations for each agent’s chain of activities within the  
7 sets of possible locations for each activity type.

8 Socioeconomic characteristics as described in 3.1.4 were derived from the data in the  
9 “ÖU13/14” survey and correspondingly added as binary variables to the mobility population data  
10 set. The resulting set of agents and their daily-travel schedules (“plans”) was transformed to a valid  
11 MATSim mobility-agent population description, consecutively.

### 12 *Intermodal routing*

13 For intermodal routing we do not use the MATSim router but instead integrate the AIT intermodal  
14 routing framework *Ariadne* (Prandtstetter et al. (14)) into the simulation cycle. This is done for  
15 two reasons: First, MATSim is currently not capable of intermodal routing, which is not trivial to  
16 implement. Therefore, leveraging our well tested routing framework reduces the required effort.  
17 Second, a tight integration of routing and mode choice while separating this part from the MATSim  
18 iterations provides performance benefits as described in (15).

19 Prior to running the MATSim simulations all candidate plans, i.e. plausible intermodal  
20 plans for the whole day of the agent, are calculated and cached. The agents’ mode availability and  
21 location of personal vehicles is respected, i.e. personal vehicles must be brought back home at the  
22 end of the day and can only be used at a certain location when the agent drove there before.

23 The transportation modes drt, car, public transport, bike and walk are covered by our model,  
24 of which only cars and drt vehicles are simulated on the MATSim network. The other modes are  
25 teleported while retaining the detailed travel time calculated by the intermodal router. Different  
26 cycling speeds due to topography and public transport time tables can thus be taken into account.

### 27 *Subpopulations*

28 To model different behavioral patterns within subpopulations, the synthesized population described  
29 above is split into 10 subpopulations based on socioeconomic characteristics. For each subpopula-  
30 tion, we derive a distinct set of parameters that is used in the scoring function of the MATSim model  
31 (Axhausen et al. (4)) and the model calibration. More specifically, the mode-specific constants, the  
32 value of travel time savings (VTTS), the Value of Leisure (VoL), and the disutility associated with  
33 transfers vary across sub-populations (we present the parameter values in Section 3.1.6, Table 2).  
34 Note that the VTTS equals the VoL (i.e., opportunity costs of time) minus the direct utility (or  
35 disutility) derived from the time spent traveling (which typically depends on travel conditions such  
36 as crowding, comfort, and the possibility to use the travel time productively).

37 The parameters of the subpopulations are derived from the Mobility-Activity-Expenditure  
38 Diary data described in Hössinger et al. (16). This data source contains a weekly mobility and  
39 activity diary as well as expenditures from a representative sample of Austrians. In addition,  
40 stated preference data on hypothetical mode choice situations from the same individuals have been  
41 collected. The detailed data do not only allow for the estimation of the VTTS and other mobility-  
42 related preference parameters, but also for the estimation of the VoL, which is the marginal utility  
43 associated with those activities to which more time than the necessary minimum is assigned (such

1 as leisure activities). The empirical model follows the theoretical framework developed by Jara-  
2 Díaz et al. (17).

3 Estimating of the VoL requires fitting the observed expenditures and time use patterns  
4 against the utility-maximization framework developed by Jara-Diaz and co-authors, using maxi-  
5 mum likelihood estimation. The VTTS and other travel-related preference parameters, in contrast,  
6 can be derived from a (discrete) mode choice model applied to all trips contained in the sample. For  
7 the Austrian data set, these estimations have been performed separately (the VoL estimation can be  
8 found in Hössinger et al. (16) and the VTTS estimation in Schmid et al. (18)), but also jointly in  
9 Jokubauskaitė et al. (19), which has the advantage that correlations between time use, expenditure  
10 and mode choice behavior can be accounted for in a coherent way. The parameters used in this  
11 paper are also derived from a joint estimation, albeit somewhat different from Jokubauskaitė et al.  
12 (19) in order to simplify how socioeconomic characteristics can be combined into subpopulations.  
13 The parameters presented here are derived from a Latent Class Model - a classification model to  
14 assign observable discrete variables to latent classes - (see for instance Greene and Hensher (20)),  
15 in which all model components are connected via a joint likelihood function and an overarching  
16 class membership equation.

17 The mode choice model that is part of the joint estimation is a more parsimonious version  
18 of the model presented in Schmid et al. (18), and uses actual and hypothetical trip data. The  
19 time use and expenditure equations are estimated in a similar way as in Hössinger et al. (16) and  
20 Jokubauskaitė et al. (19). We estimate two classes of coefficients for all parameters, since not  
21 much explanatory power is gained by introducing more classes. The class membership equation  
22 then determines for each individual the class membership probability, i.e. how much weight each  
23 class of coefficients has for a specific person. The class membership probability in turn is a linear  
24 function of several binary socioeconomic variables *sex, age below 35, age above 55, income higher*  
25 *than median, education high-school or above, living in urban area, kids living in the household,*  
26 *single household and full time work with at least 38 hours a week.* These socioeconomic variables  
27 were chosen since they were available both in the estimation data as well as in the synthesised  
28 population. An exception is the high income variable for which the self-reported living standard  
29 was used as a proxy. An overview of the variable distribution among the agents of our population  
30 is shown in Table 1.

31 The subpopulations are then determined as the 10 regularly spaced quantiles of the class  
32 membership probabilities. The characteristics of the different subpopulations can be seen in Fig.  
33 2. Differently pronounced socioeconomic characteristics of the subpopulations become apparent.  
34 As an example, Class 1 is dominated by highly educated males in urban areas and in full time  
35 employment, while Class 7 mostly contains young urban females with kids, without higher educa-  
36 tion and without full-time employment. The VoL and mobility-related preference parameters are  
37 calculated for each of the ten subpopulations by averaging over the personalised parameter values.

### 38 *The SAEV fleet*

39 We implemented SAEV vehicles in the simulation as demand-responsive transportation (drt) ser-  
40 vice by using MATSim's drt module. These vehicles are planned as automated, electric vehicles  
41 with a maximum capacity of 4 passengers. Ridesharing will be executed in case there are ride  
42 requests in the proximity of the vehicle and the the agents' destinations do not differ too much.  
43 The SAEV vehicles have a battery capacity of 20kWh and can be charged at one of the more than  
44 900 charging points (587 in the city of Vienna), each of which have 2 plugs. Existing charging

**TABLE 1 Descriptive statistics by sub-populations**

	Mean	SD
Gender (1=Male)	0.478	0.499
Urban (=1)	0.744	0.436
Single (=1)	0.217	0.412
Kids (=1)	0.356	0.479
Age >= 35 (=1)	0.248	0.432
Car (=1)	0.612	0.487
Education (=1)	0.337	0.473
Employed (=1)	0.509	0.500
Income high (=1)	0.426	0.494
Observations	200,036	

1 stations as well as gas stations and taxi stands, all taken from OSM, were considered as charging  
2 locations.

3 For each of the scenarios that are presented in 3.2 we assume that there is only one fleet  
4 operator with one price scheme operating as door2door service. The actual implementation of such  
5 a SAEV fleet in real life is difficult to predict as fully-automated vehicles (21) will not be available  
6 for city traffic for another 10 years (22). This is the reason why several parameters relevant for  
7 the operation of the fleet (e.g. base fare, minimum fare) could not be chosen based on a business  
8 model of an actual fleet operator but were disregarded instead. We assume that there will be a  
9 rebalancing of the SAEV vehicles every 30 minutes based on the demand which is aggregated over  
10 cells with a size of 500 m. The SAEV vehicles are randomly distributed across the simulation area.  
11 Idle vehicles will return to one of these starting locations as they are regarded as depots. At the  
12 beginning of each simulation iteration, the SAEV vehicles will again start from these predefined,  
13 random locations.

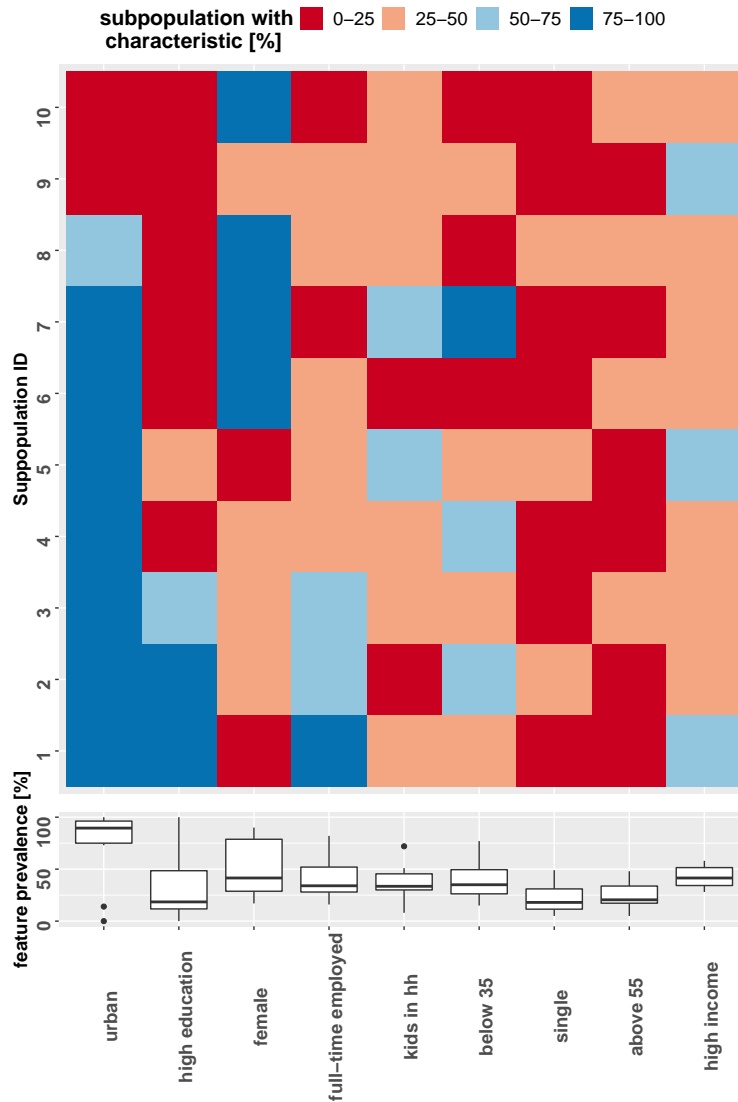
14 The SAEV rides are simulated on MATSim's car network. The maximum waiting time  
15 is set to 10 minutes. If this waiting time is exceeded, the request will be rejected. For boarding  
16 and disembarking the drt vehicle one additional minute of travel time is added. The logic of the  
17 simulation is that an agent only requests a SAEV vehicle as soon as the previous activity has  
18 finished. Then the scheduler of the drt module assigns a vehicle to the agent. This means that  
19 agents always have to wait for the drt pickup.

## 20 *Parametrization of the utility function*

21 Based on the model described in Section 3.1.4, the parameters in Table 2 show the estimated VTTS  
22 for every mode ( $\beta_{mode}$ ) and the according mode-specific constants ( $c_{mode}$ ), whereby the  $c_{walk}$  is set  
23 to 0 for all subpopulations. The values are already standardized by the marginal utility of income  
24 of the mode choice model, such that the `marginalUtilityOfMoney` can be left to 1. The VoL,  
25 which is in MATSim literature often referred to as  $\beta_{dur}$ , and  $\beta_{lineSwitch}$  can be taken directly as  
26 MATSim configuration parameter performing `utilityOfLineSwitch`, respectively. The  
27 parameter `marginalUtilityOfTraveling_util_hr` for the respective modes and subpopula-



**FIGURE 2 Mean prevalence of binary socioeconomic characteristics within the ten subpopulations, determined by application of the class membership model of the latent class model.**



1 tions is however differently implemented (Axhausen et al. (4), p.32) and therefore defined as the  
 2 sum of  $\beta_{mode}$  and  $\beta_{dur}$ .

3 Additionally, the parameters for `lateArrival`, `waiting` and `waitingPt` are set manually. Ac-  
 4 cording to the meta-analysis by Wardman et al. (23), the disutility for arriving 10 minutes too late  
 5 at an activity amounts on average to 1.9 times the disutility associated with a 10-minute increase  
 6 in *in-vehicle time*, whereas waiting for a facility to open is penalized by 1.83 times *pt-in-vehicle*  
 7 *time*, and waiting for public transport by 1.77 times *pt-in-vehicle time*. In accordance to the imple-  
 8 mentation in MATSim (Axhausen et al. (4), p.29), we therefore set

**TABLE 2** Parameters from the choice model to calculate the subpopulations’ parameters for the Charypar-Nagel function.  $c_{mode}$  refers to the not yet calibrated constants,  $\beta_{mode}$  to the value of travel time savings (VTTS), and  $\beta_{dur}$  indicates the value of leisure.

subpop	$c_{bike}$	$c_{car}$	$c_{pt}$	$\beta_{bike}$	$\beta_{car}$	$\beta_{pt}$	$\beta_{walk}$	$\beta_{lineSwitch}$	$\beta_{dur}$
1	2.55	0.85	0.14	-9.38	-12.20	-5.29	-11.06	-0.71	10.71
2	2.72	0.80	0.13	-10.50	-12.29	-5.47	-11.39	-0.75	9.34
3	2.85	0.76	0.12	-11.38	-12.36	-5.61	-11.65	-0.78	6.75
4	2.94	0.74	0.12	-11.99	-12.40	-5.70	-11.83	-0.80	9.11
5	3.04	0.71	0.12	-12.65	-12.45	-5.81	-12.03	-0.83	7.35
6	3.18	0.67	0.11	-13.53	-12.52	-5.95	-12.28	-0.86	9.99
7	3.28	0.64	0.10	-14.20	-12.57	-6.05	-12.48	-0.88	13.02
8	3.42	0.59	0.10	-15.15	-12.64	-6.20	-12.76	-0.92	7.28
9	3.66	0.52	0.09	-16.73	-12.76	-6.45	-13.23	-0.97	6.23
10	4.09	0.39	0.07	-19.58	-12.97	-6.90	-14.07	-1.08	5.92

1  $lateArrival = 1.9 \times (\beta_{car} + \beta_{pt})/2$

2  $waiting = 1.83 \times \beta_{pt} + \beta_{dur}$

3  $waitingPt = 1.77 \times \beta_{pt} + \beta_{dur}$

4  
5 The costs for driving and owning a car follow estimations by (24) for average vehicles and  
6 are considered by setting `dailyMonetaryConstant` to  $-13.521$  and `monetaryDistanceRate` to  
7  $0.00009$  (0.09 EUR/km). Costs for cycling were estimated as 1 EUR/day based on (25). The travel  
8 costs for public transport were manually configured by averaging fares from station to station.  
9 This results in costs of 1.60 EUR/day in Vienna (0.67 EUR/day for trains) and 1.38 EUR/day (and  
10 additional 0.15 EUR/km) outside of Vienna.

11 The costs associated with SAEVs consist of time costs as well as fares (the latter differ  
12 across scenarios and will be specified when introducing the scenario). In line with several studies,  
13 we assume that the VTTS associated with riding a SAEV is similar to the VTTS of car passenger:  
14 whereas Lu et al. (26) found no differences in the VTTS between drivers and passengers of a car,  
15 Fosgerau (27) and Ho et al. (28) come to the conclusion that the VTTS for a passenger can be  
16 regarded as about 75% of the rate for car drivers. We follow in our model these latter findings.

### 17 *Calibration process*

18 The model was calibrated by the modal split per trip that was taken from “ÖU13/14”. By adjusting  
19 the constants along all subpopulations (car:  $-1.25$ , bike:  $-8.75$ , pt:  $-5$ ), we achieved a simulation  
20 equilibrium with a deviation of the modal split by trips of less than 1% for each mode. The modal  
21 split per kilometer also deviates only by a few percentages. This rather good fit was the result of an  
22 a priori selection of activity locations that optimally fit the activity chains and the corresponding  
23 reported travel times and distances from “ÖU13/14”.

24 Cadyts (Flötteröd et al. (29)) was used simultaneously during the search for optimal constant pa-  
25 rameters to align the simulated traffic volumes with the measured traffic counts. From the 180  
26 count stations in our whole network, 95 are placed in Vienna. During the morning and after-  
27 noon rush hour (6am-9am, 3pm-6pm), the sum of the normalized error at the count stations in

1 Vienna is about 0.35, whereas the relative error is below 0.06. We ran the simulations with 500  
2 iterations though an equilibrium was already reached after around 150 iterations. The reason for  
3 this low number of necessary iterations is mainly the intermodal *Ariadne* router which helps re-  
4 ducing the number reasonable alternative routes for the agent. Freight and delivery - which is  
5 estimated to have a share of 8-13% of the traffic in Vienna - is taken into account by reducing the  
6 flowCapacityFactor by 10% and increase the countsScaleFactor to 10.

## 7 **Scenarios for SAEVs**

8 One of our research questions is to assess the acceptance and benefits of SAEVs among different  
9 population groups. As we do not focus on one specific operation model, we analyze different pric-  
10 ing schemes and vary the fleet size. Next to the fix VTTS for the SAEV which is described in 3.1.6  
11 we run simulations with different time-based fares between 0.00 EUR/min and 0.50 EUR/min.  
12 There is no minimum fare or base fare implemented. The different fleet sizes are 100, 250, 500,  
13 1000 and 2500 vehicles. As our model is based on a countsScaleFactor of 10, the real fleet sizes  
14 would be ten times higher. The highest simulated drt fleet represents around 3.5% of the current  
15 fleet of private vehicles in Vienna (2019: 715 000 (30)), but is already more than three times higher  
16 than the current taxi fleet in the city(7500 taxis, (31)).

## 17 **RESULTS**

18 The SAEV rides analyzed in this section always refer to the total number of rides over the day  
19 unless otherwise stated. Though the model fits best for trips with destination or origin in Vienna  
20 during rush hours, we could observe all patterns described in the following section for all SAEV  
21 trips in the whole area and at any time.

22 In the first part (4.1), we describe the general usage of SAEV vehicles in the simulated scenarios.  
23 The second part (4.2) addresses the question of how agents with different socioeconomic charac-  
24 teristics use the SAEV vehicles.

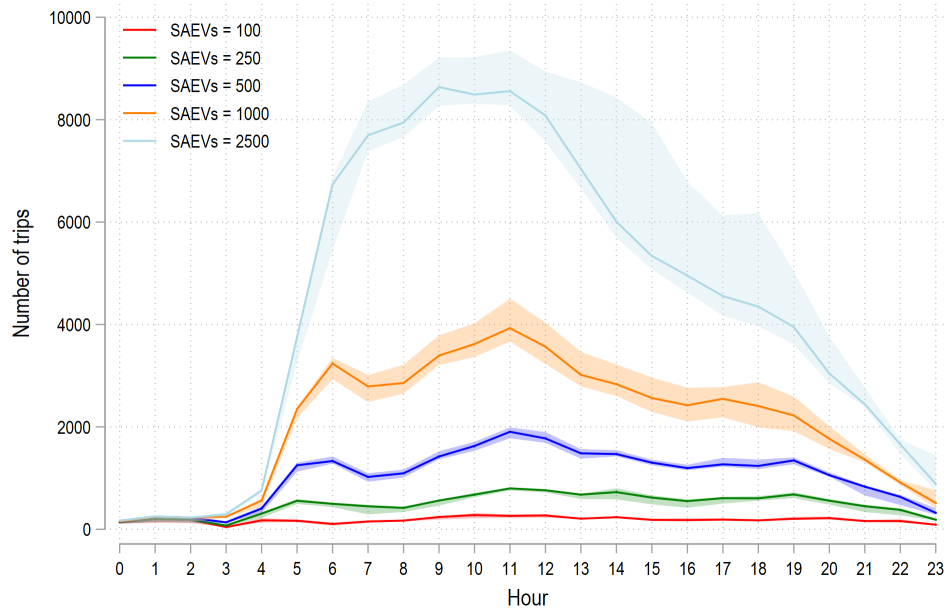
## 25 **General analysis of the scenarios**

### 26 *Use of SAEV vehicles*

27 The distributions of SAEV trips over the day does not follow the typical camel function in trans-  
28 portation which reflects traffic peaks in the morning and afternoon rush hours. Instead, the demand  
29 usually remains stable over the day and peaks in the late morning hours (see Fig. 3). For larger  
30 fleet sizes, a higher deviation in the number of trips becomes apparent which holds true especially  
31 in the afternoon.

32 An interesting phenomenon is the increasing number of trips for fleet sizes of 500, 1000 and  
33 2500 vehicles when the SAEV fares increase (Fig. 4 a)). This is a very counter-intuitive behavior  
34 of the agents as one would expect a decreasing number of trips with SAEV for increasing fares. It  
35 is also remarkable that for fleet sizes of up to 1000 vehicles the number of trips reach its maximum  
36 at a price of 0.40 EUR/min. We found a plausible explanation for this pattern by considering the  
37 average driven distance and duration of trips with SAEVs. It is clearly visible that the average trip  
38 duration - which is highly correlated to the average trip distance – decreases for higher time-based  
39 fares. The product of these two measures represents the total usage time of SAEV vehicles and  
40 shows the expected decrease for increasing fares (Fig. 4c)).

41 Another conspicuousness are the results for small fleet sizes and especially for the fleet of 100  
42 vehicles. Neither the total number of trips nor the average trip duration follow strictly the observed

**FIGURE 3 Use of SAEVs by time of day**

NOTE: Dark lines show the median (50th percentile) and the bands show 10-90th percentiles for the different pricing schemes.

1 pattern of the other fleets. We therefore conclude that a density of 0.05 SAEV vehicles per 1000  
2 agents is too low to fulfill the demand for this service.

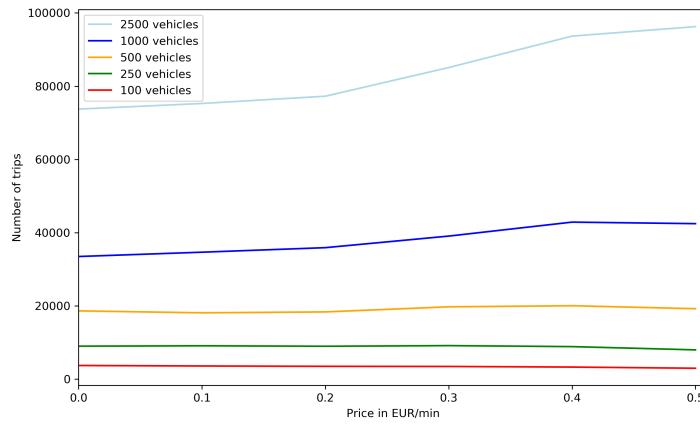
### 3 *Mode switch to SAEV*

4 The modal split of SAEV increases with a larger availability of vehicles and lower fares. While  
5 the share is still 0.5% for 100 vehicles, it grows to as much as 14% for 2500 vehicles.

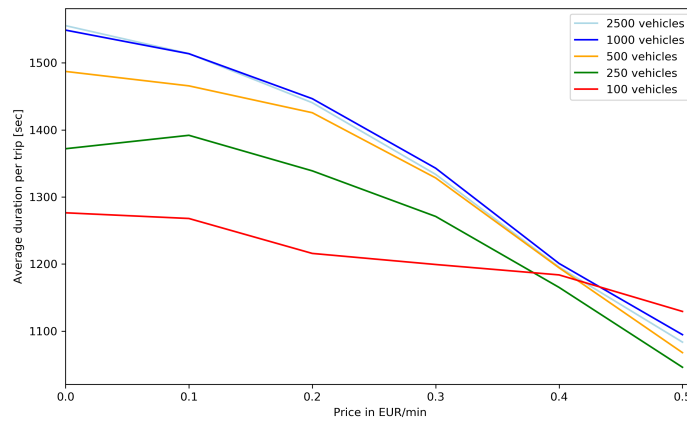
6 Fig. 5 shows the share of trips that switched from other modes to SAEVs as the main mode.  
7 The x-axis represents the different pricing schemes (0.00 EUR/min to 0.50 EUR/min) while the  
8 colors represent the different SAEV fleet sizes introduced on the roads. The percentage share  
9 of trips that switched to SAEVs is plotted on the y-axis. Since trips can be multi-modal in the  
10 simulation and thus consists of different modes for each leg, a main travel mode for each trip is  
11 elicited based on the hierarchy provided in “ÖU13/14”. The sequence of prime modes is defined  
12 as PT > Car > Bike > Walk. For the purpose of this paper, we also assume that SAEVs trump  
13 all other modes or SAEVs > PT. Since the simulations provide unique identifiers to each trip, it is  
14 possible to compare the main modes across different experiments.

15 The biggest switches happen from biking and public transport (PT). The introduction of  
16 SAEVs strongly impacts trips with walking (Fig. 5a) and biking (Fig. 5b) as the main modes.  
17 The higher the price and the larger the fleet, the more likely is it that agents switch from bike or  
18 walk to SAEV. This result is not surprising as we have revealed that trip distances and durations  
19 decrease for higher fares. These trips are more typically done by using bike or walk as main mode.  
20 The strong cannibalization of PT trips can be explained by a missing car availability of agents. By  
21 providing a new mode opportunity, travel time savings become very likely for those people. We

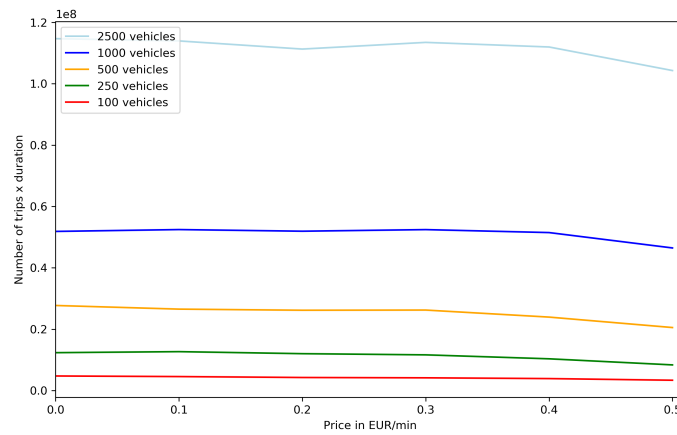
**FIGURE 4** Number of trips, average duration and total usage time of drt vehicles



(a) Number of trips with SAEV



(b) Average duration of SAEV trips

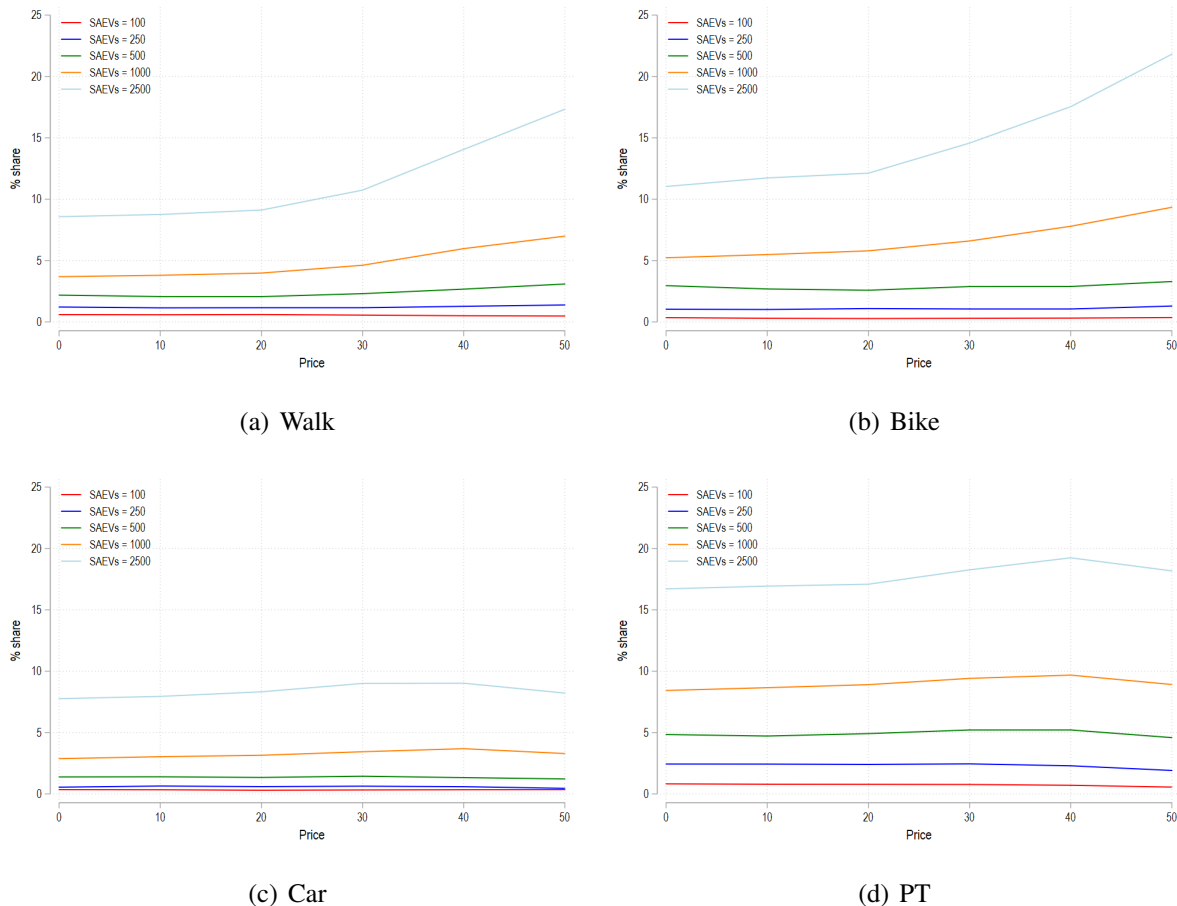


(c) Number of SAEV trips  $\times$  average duration of SAEV trips

1 will have a closer look at car availability in 4.2.1.

2 Cars travelers have the lowest response to the introduction of SAEVs with less than 10%  
 3 switching even with 2500 SAEVs on the road. Both car and PT trips are sensitive to prices changes  
 4 and show a reduction in demand for SAEVs at the highest price level.

**FIGURE 5 Share of trips that switch to SAEVs by main mode**



## 5 SAEV as ridesharing service

6 An essential characteristic of SAEV vehicles is the option for ridesharing. Agents do not neces-  
 7 sarily take the direct way to their next activity but accept a bearable detour on their trip if another  
 8 agent requests to share the ride. This detour factor compares the rate of the actual taken route with  
 9 the most direct connection that the agent would have taken if it would not share the vehicle. Du-  
 10 ration detour factors are naturally higher because the routed duration is taken as reference which  
 11 does not consider congestion or other delays. This number therefore cannot be considered as factor  
 12 to compare SAEV trip durations to car trip durations.

13 The analysis of the detour factors for the trip distances show no remarkable change for the  
 14 different fleet sizes. They mostly remain between 1.11 and 1.16. Higher prices result in higher  
 15 distance detour factors. This holds also for detour factors of the trip duration. In contrast to  
 16 the distance detour, this measure increases for larger fleets (up to 2.20 for 2500 vehicles, 0.50

1 EUR/min). We expect that these results originate from the shorter distances of trips. As described  
2 in 3.1.5, the agent's trip duration is increased by one minute for boarding and alighting the vehicle.  
3 Other passengers in the vehicle will be affected by this rule. For shorter trips, this setting becomes  
4 more visible in the duration detour factor.

5 The occupancy rate of vehicles shows a clear pattern over all scenarios. It is higher for  
6 lower prices, and higher for larger fleet sizes. For a SAEV fleet of 100 vehicles, it ranges between  
7 1.55 (0.00 EUR/min) and 1.49 (0.50 EUR/min), whereas it drops from 1.78 to 1.58 in the scenarios  
8 with 2,500 SAEV vehicles. This measure is calculated as average of the occupancy rates of vehicles  
9 which is observed every 5 minutes. Therefore, the results reflect the higher attractiveness of SAEVs  
10 if the price is lower.

11 Another interesting figure is the share of vehicles that is not driving. For scenarios with  
12 a fleet size of up to 500 vehicles, this share increases for higher fares (from 58% to 66%). For  
13 large fleet size, this share remains similar over all prices (1000: 64%, 2500: 70%). A similar  
14 pattern occurs for the average kilometer driven by a SAEV. In scenarios with 100, 250 or 500 vehi-  
15 cles, the average distance drops from around 295 km/veh (0.00 EUR/min) to 230 km/vehicle (0.50  
16 EUR/min). The larger the fleet size, the smaller the is the difference among all pricing schemes.  
17 For 1000 vehicles, the average is between 250 and 243 km/veh and for 2500 vehicles between 202  
18 and 198 km/vehicle. These numbers are similar, though slightly lower than reported average trip  
19 distances of taxis in urban areas (e.g. New York: 290 km/shift (32), Hangzhou is 336 km/day (33)).  
20

## 21 **Use of SAEV in different socioeconomic groups**

22 While describing the general use of SAEVs in 4.1, we will now look closer of how agents with spe-  
23 cific socio-demographic characteristics use SAEVs. The distinction of subpopulations as described  
24 in 3.1.4 is a convenient way to implement the various mode choice behavior of people. However,  
25 the interpretation of the results under the consideration of subpopulations remains difficult. A  
26 main issue is the characterization of the subpopulations which does not follow standardized social  
27 milieus. Therefore, we will present the analysis of the scenarios along common socioeconomic  
28 characteristics to facilitate the understanding and transferability of the results.

29 In the beginning, we have a closer look at two variables that might influence different use of  
30 SAEVs: gender and car availability in the household. To reveal differences in the usage behavior of  
31 the agents, we will redo some of the previous analysis in 4.1 by separating the data sets according  
32 to the social characteristic. After that, we will additionally look at the age distribution of SAEV  
33 users. Finally, we will use a scenario as an example to describe which agents benefit from the  
34 introduction of a SAEV service.

### 35 *Gender and car availability*

36 Separating the number of SAEV trips by gender does not reveal significant differences in the  
37 general pattern (Fig. 6a)). It is however apparent that women use this service slightly more often  
38 than men. This difference becomes more pronounced with higher fares and larger fleet size. The  
39 analysis of trip durations reveal that female agents do in average shorter trips with SAEV vehicles  
40 in all scenarios.

41 The availability of a car in the household is an interesting characteristic to look at as SAEV bears  
42 the chance to eventually reduce car ownership. In the scenarios with no or low fares for SAEVs,  
43 there are significantly less SAEV trips done by agents that have no car available in their household

1 (around 20-25% less). However, this difference disappears with higher pricing schemes. The  
2 SAEV trips of agents with no car in their household are in average a bit shorter in scenarios with  
3 low pricing schemes (Fig. 6b)). These numbers are becoming more similar for higher fares.  
4 Fig. 6c) shows the average age of agents that used SAEV vehicles. There is a clear gap between  
5 the group of agents who have a car available and those who do not. Agents with access to a private  
6 car are in some scenarios in average more than six years older. This phenomenon may occur since  
7 agents without a car in their household are younger on average. In terms of gender, we see a  
8 difference of three to four years in average age. Across all scenarios, women who use the SAEV  
9 service are older than men.

#### 10 *Benefits of SAEV for socioeconomic groups*

11 In this last section we leave the method of scenario comparison and instead take one example  
12 scenario as an experiment for our analyses. We are interested to which extent certain population  
13 groups benefit from the introduction of SAEVs in the market. For this purpose, we focus on travel  
14 time savings as a success indicator.

15 As benchmark experiment we consider the scenario with 1000 vehicles and a fare of 0.30  
16 EUR/min. Table 3 provides a summary of travel time savings by different socioeconomic groups  
17 resulting from the introduction of SAEVs. The first two columns show the average travel times per  
18 trip over all trips in the experiment. Column 3 indicates the share of trips that switched to SAEVs  
19 which can be regarded as the modal split of SAEVs in this particular population group. The last  
20 two columns show the average travel time of those trips that were made in the experiment with a  
21 SAEV.

22 It is no surprise that the overall effect of SAEV on travel time savings is not remarkable.  
23 For the specific trip, however, the agent saves on average more than 12 minutes. The strongest  
24 drop is observed of those with no car availability in their household. This also explains the high  
25 attractiveness of the service which results in the highest modal split of SAEV among all population  
26 groups. Also agents with age over 35 years and those who live in urban areas are more likely to  
27 take the SAEV vehicles than other ones. Agents in rural areas make below-average use of the  
28 service which clearly results from the comparable low travel time savings.

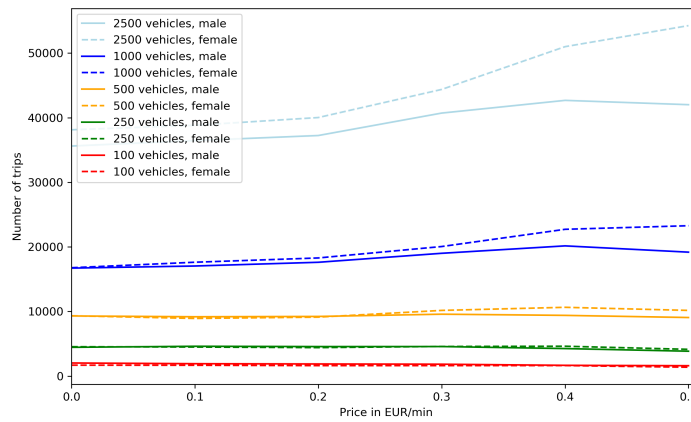
## 29 **DISCUSSION**

30 In this paper, we described the preparation of a MATSim model for Vienna and added a new ser-  
31 vice of shared autonomous electric vehicles as transportation mode to it. While impacts of SAEV  
32 fleets have often been described in literature under the aspect of spatial heterogeneity, we focus in  
33 our work on the socioeconomic heterogeneity. Our MATSim model takes different behavioral pat-  
34 terns of people into account by splitting the population in subpopulations based on socioeconomic  
35 characteristics. We discuss different scenarios which vary in the number of SAEV vehicles and the  
36 time-based price that is charged. These settings are considered as different policy options, so that  
37 the results of this paper can also be taken as guidance for policy makers in promoting or restricting  
38 the operation of this service in future.

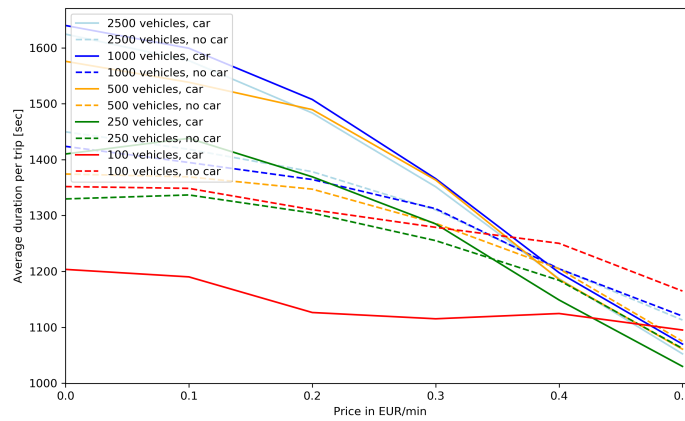
39 Before describing the main findings of our study, we want to consider the limitations of  
40 our approach. A very general aspect that a MATSim model cannot reflect is the varying demand  
41 for mobility needs. Travel time savings as consequence of SAEV services will therefore always  
42 be beneficial for the system, though there have been various studies on the phenomenon of in-  
43 duced traffic (34). Apart from these general issues, scholar might argue that the chosen number of



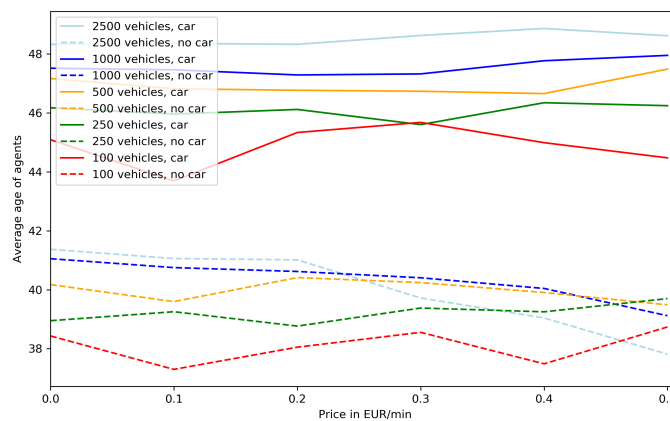
**FIGURE 6** Number of trips separated by gender, average duration for SAEV trips separated by car availability and average age of agents separated by car availability.



(a) Number of trips with SAEV separated by gender



(b) Average duration of SAEV trips separated by car availability



(c) Duration

**TABLE 3 Socioeconomic variables and travel time savings with SAEVs for the scenario with fleet size 1000 vehicles and a fare of 0.30 EUR/min (=Experiment). Columns 1–2 show the average travel time per trip in minutes. Column 3 lists the share of trips that switched to SAEV as the main mode. Columns 4–5 consider only the trips that switched to SAEVs.**

	All trips			SAEV as main mode	
	(1) Baseline	(2) Experiment	(3) % switch	(4) Baseline	(5) Experiment
Overall	30:57	30:21	5.89	34:58	22:22
Male	32:10	31:30	6.08	36:25	23:40
Female	29:52	29:20	5.71	33:36	21:09
Rural	33:04	33:11	3.72	29:45	21:00
Urban	30:15	29:25	6.60	35:56	22:38
Single: No	31:12	30:40	5.68	34:50	22:40
Single: Yes	30:03	29:15	6.62	35:24	21:29
Age $\leq$ 35	31:42	31:05	5.62	36:14	23:31
Age $>$ 35	28:47	28:14	6.64	31:53	19:35
Car: No	31:44	30:29	7.10	39:06	21:52
Car: Yes	30:31	30:17	5.21	31:53	22:45
Employed: No	28:22	27:47	5.63	32:36	19:44
Employed: Yes	33:26	32:50	6.13	37:05	24:44
Income high: No	31:48	31:02	6.29	36:53	22:42
Income high: Yes	29:51	29:28	5.36	32:03	21:53

1 subpopulations seems arbitrary and not well motivated in our approach. We admit that this gran-  
2 ularity of distinction was a first assumption that we pursued further, since the parameters for the  
3 utility functions showed a plausible ratio of variability. Future research on the effects of different  
4 numbers of subpopulations may help to solve this open issue.

5 Another critical point is that we currently do not focus on underlying business models. We  
6 assume instead that costs are covered for the provider, and the fleet provider would not be able to  
7 increase its profits by reducing the fleet size.

8 The MATSim model allows a more precise formulation of the business models. Not only can time  
9 and distance dependent price tariffs be selected, but also different service models can be chosen. In  
10 addition to the door-to-door service simulated by us, the business area can be limited to a section  
11 of the simulation area, or only certain stops can be selected as pick-up and drop-off stations. An  
12 option not yet used in our simulations is the iterative adjustment of the SAEV distribution. In the  
13 presented version of the scenarios, the vehicles are placed at the initially selected locations in each  
14 iteration. This can optionally be controlled in such a way that the locations of the last drop-offs  
15 from the previous iteration are selected. Thus, the SAEV distribution will be adapted to the needs  
16 of the agents throughout the iterations and another important insight for operators and planners can  
17 be gained from the model. Likewise, the frequency of vehicle reallocation (currently 30 min) is  
18 variable.

## 19 CONCLUSION

20 One main finding of our paper is that the number of SAEV trips does not decrease if the fares are  
21 higher. Our simulation shows that up to a certain price – in our case 0.40 EUR/min – people will  
22 use the service even more. However, the average trip duration decreases when the service gets  
23 more expensive.

24 A positive effect of SAEVs is the better accessibility of places. Travel time savings for the  
25 trip that a SAEV was chosen for are about 10 to 12 minutes on average. A particularly large reduc-  
26 tion in travel time is achieved by people who do not have a car in their household. SAEVs are far  
27 better accepted in urban than in rural areas. We conclude that there are other policy interventions  
28 necessary to promote SAEVs in the suburbs. Occupancy rates range from 1.5 to 1.7 and are hence  
29 above the average of 1.15 to 1.3 for private cars in Austria (35). The time that a vehicle is not  
30 in use (max. 70%) is also far lower than for private vehicles. A spatial optimized distribution of  
31 vehicles will be even more beneficial.

32 The fact that shorter trips are preferred for higher SAEV fares also results in a high mode  
33 switch from pedestrians and cyclists to SAEVs, especially for higher fares. Public transport is  
34 highly cannibalized by the new service regardless of the price, whereas SAEVs would always  
35 replace no more than 10% of car trips. As the common goals for policy makers is to promote  
36 active mobility, it remains a challenge to formulate appropriate policies that have the desired effect  
37 of bringing car drivers to SAEVs and other environmentally friendly mobility modes.

38 Further information about the AIT's MATSim model Vienna can be found in the corre-  
39 sponding github repository (<https://github.com/dts-ait>). The MATSim software is openly  
40 available at <https://github.com/matsim-org/matsim/releases>.

1 **AUTHORS CONTRIBUTION**

2 The authors confirm contribution to the paper as follows:

3 study conception and design: Müller, Naqvi, Peer, Richter, Rudloff, Straub;

4 data collection: Müller, Peer, Richter, Rudloff, Straub;

5 analysis and interpretation of results: Müller, Naqvi

6 draft manuscript preparation: Müller, Naqvi, Peer, Richter, Rudloff, Straub;

7 All authors reviewed the results and approved the final version of the manuscript.

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