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SIMULATION OF POLICIES FOR AUTOMATED RIDE-HAILING AND RIDE-POOLING SERVICES

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ABSTRACT

Automated vehicles are becoming more prevalent, and the disruption they would cause in combination with ride-hailing and ride-pooling services could be tremendous. Therefore, this study investigates the impacts of ride-hailing and ride-pooling automated fleets in two Swiss cities, Chur and Zurich, and potential policy measures to steer their operations towards more sustainable solutions. We employ the results of the stated preference survey and combine the estimated mode-choice and car ownership model results with the agent-based simulation, MATSim, to simulate the impacts of various scenarios. We find that automated ride-hailing (aRH) and automated ride-pooling (aRP) services do not seem to be competing for the same demand. In general, these services would lead to a reduction in total travel time but an increase in total vehicle distance, which is more substantial in transit-oriented Zurich than in car-oriented Chur. Furthermore, we found that even though the proposed policies increased vehicle occupancy, they did not manage to overcome the increase in VKT, signaling the need for more targeted policies and operational strategies. Finally, we provide recommendations for transport policy and future research based on our findings.

Keywords: automated vehicles, pooling, policies, agent-based, MATSim

INTRODUCTION

The arrival of ride-hailing services more than a decade ago has caused a substantial disruption in the transportation service market by providing a service that can be ordered conveniently on a smartphone and is less expensive than a conventional taxi. Even today, the market in certain parts of the world has not stabilized, and new services are emerging. In Switzerland, Uber launched its services in 2013. For a long time, it was the only operator until recently, when, in 2024, Bolt started its operations in Zurich, creating a competing environment.

Over the years, even though in Switzerland the data is lacking, we have observed worldwide that the impacts of these services range from negative (e.g., higher congestion, higher emission, competition with public transit) to positive (e.g., increased accessibility, increased flexibility, synergies with public transit). In most cases, single-occupancy services, often called ride-hailing, increase the total vehicle mileage of the transportation sector due to the large number of empty vehicle kilometers traveled and people switching from public transport. On the other hand, services where riders can pool together referred to as ride-pooling, could reduce total vehicle kilometers traveled, however, at the reduced comfort and higher travel times, often compensated with a reduced fare.

The full automation of vehicles and their deployment promises to further disrupt the transportation system by considerably reducing operating costs (*1*). In combination with ride-hailing and ride-pooling services, the effects could be overwhelming. Ride-pooling, combined with automation, has the potential to combine the advantages of public transport (higher vehicle occupancy) and private vehicles (direct trips) and hence could allow for substantial accessibility gains and reduction of cost, especially in rural areas and during times of the day for which conventional public transport services cannot be efficiently operated.

However, the potential impacts of automated ride-pooling services are insufficiently understood from behavioral and operational perspectives, especially when competing with ride-hailing services. Moreover, the potential measures and their effects to steer the users towards more sustainable pooled services must be further explored and tailored to studied regions. Therefore, in this paper, we will explore the potential impacts of pooled automated vehicle service while competing with ride-hailing services based on the models estimated from the data collected through stated preference surveys, an agent-based simulation, and carefully devised policy measures. We will show our findings for two distinctive regions: Zurich and Chur.

The remainder of the paper is structured as follows: The Background section will present the most relevant state-of-the-art research on automated ride-hailing and ride-pooling services. This will be followed by the Methods section, explaining the tools and methods used and the study's setup. Finally, before discussing the results and making policy recommendations, we present the most substantial findings.

BACKGROUND

On-demand mobility services such as ride-hailing and ride-pooling enable users to request rides whenever and wherever they need them, enhancing overall transport system efficiency. The benefits of these services include increased accessibility, flexibility, positive environmental impacts, and sustainability (*2–5*). However, existing on-demand systems such as ride-hailing services have also been linked to increased emissions, congestion, and other transport-related issues (*6–8*). This has led to a shift towards pooling services, which are seen as potential solutions to mitigate the negative impacts of single-occupancy ride-hailing.

Full vehicle automation promises further disruption. Market projections indicate that the global automated vehicle market is expected to reach USD 52 billion by 2031, growing at a CAGR of 12.1% (*9*). Advancements in artificial intelligence, modern car features, battery innovations for electric vehicles, and the proliferation of smartphones and the Internet of Things drive this shift. This growth suggests a large potential for automated vehicles in ride-hailing and ride-pooling services. As these services evolve and automated vehicles become more prevalent, understanding their combined impact is important. Recent studies examine the effects of on-demand services on existing transport systems and suggest developing suitable policy measures to maximize the benefits while reducing negative impacts (*10, 11*). Hu et al. (*10*) argue that shared pooled mobility is essential to decarbonize the transport sector by 2060. Similarly, Creutzig et al. (*11*) argue that shared pooled mobility, particularly when combined with automated vehicles, could offer significant benefits for climate protection and urban mobility. They emphasize the need for a deep understanding of how to approach implementation to leverage the potential of these technologies. Essentially, policymakers can influence the adoption of pooled mobility through infrastructure investments, financial levers, and urban planning.

Agent-based simulations have been the most widely used to evaluate the impacts of shared automated vehicles on a large scale. This is because of the ability of agent-based models to provide a more detailed representation of persons, vehicles, and their interactions. Well-established agent-based models that have been used for on-demand mobility simulations include MATSim (*12*), SimMobility (*13*), and POLARIS (*14*).

Early simulation studies focused on the impacts of single-occupancy on-demand services, with the general findings showing a high potential of the service to reduce the vehicle fleet and the number of parking spaces at the expense of increased vehicle kilometers traveled (VKT). This led to several studies on ride-pooling as a potential solution to the increase of VKT. (*15–19*).

For example, Gurumurthy and Kockelman (*15*) used the cellphone data from Orlando, Florida, to investigate the potential of ride-pooling if all current car travelers would, instead of their private vehicle, use shared automated vehicles for their daily travel needs. They found that almost 60% of all trips could be shared with less than 5 min of added travel or waiting time. Simulation studies in Austin (*16*) gave findings that suggest that average vehicle occupancy could rise to 1.48, with a 4.5% increase in VKT. The congestion pricing experiment they conducted also shows an increase in pooling with only a 2% increase in VKT. Vosooghi et al. (*17*) investigate the potential impacts of shared automated vehicles service in the Rouen Normandie metropolitan area in France. (*19*) investigate the potential demand for shared automated vehicles in Munich.

None of these simulation studies directly integrate estimated behavioral mode-choice models within an agent-based simulation for automated on-demand services. The only known two studies by the authors are Oh et al. (*18*) and Hörl et al. (*20*) where Oh et al. (*18*) combine an activity-based model with an agent-based simulation to forecast mobility patterns for Singapore in 2030. The study utilizes a previously conducted stated preference survey on automated mobility to predict agents' transport mode choices. The results suggest that around 40% of the trips cannot be shared and that most of the shared rides consist of four passengers. However, the shared rides do not compensate for the increase in VKT, which increases between 11 and 42% depending on the adoption and pricing rate.

Hörl et al. (*20*) conducted a similar study in Zurich by combining a mode-choice model focusing on automated mobility with an agent-based simulation. However, the scenarios simulated only included single-occupancy vehicles. Findings suggest that the introduced services' impacts are generally negative with the modal shift from more sustainable modes and increased congestion in residential areas. Therefore, the authors suggest that shared on-demand automated service needs to be regulated to avoid negative environmental impacts.

Consequently, this study overcomes some of these gaps by simulating the impact of various policy measures on automated ride-pooling and ride-hailing services based on an empirical survey integrated into the simulation.

METHODS

To perform the study, we use the multi-agent transport simulation framework (MATSim (*12*)) and two of its modules: discrete-mode choice (DMC) and demand responsive transit (DRT). DMC module developed by Hörl et al. (*21*) allows the integration of estimated mode-choice models with the microsimulation of MATSim, therefore replacing the scoring of MATSim with a more traditional discrete mode-choice approach. The DRT module enables the simulation of shared, automated, and pooled vehicles in MATSim.

Mode-choice model

The mode-choice model was estimated based on a large-scale survey conducted in 2022 and 2023. The sample was drawn in collaboration with the market research firm intervista AG following a stratified sampling strategy. The target population was defined as all residents over the age of 18 years who live in a Swiss city or urban agglomeration and regularly travel to an activity that requires a trip longer than two kilometers.

Representative quotas for this target population were derived from the national travel survey conducted in 2015 regarding car availability, age groups, employment status, sex, language, and spatial type of residence municipality.

For the purpose of conciseness, we will only present the specification of the MNL model (equations 1 to 8) here. For the sake of brevity, in the equations, each constant represents the sum of all constants for that mode given the mobility tool ownership. The outcomes of the model estimates are shown in Table 1. A more interested reader is pointed to the official report on the survey design and outcomes (*22*).

$$\begin{aligned} u_{\text{walk,i}} = &\alpha_{\text{walk,i}} + \\ &\beta_{\text{tt,walk,i}} \cdot tt_{\text{walk}} \cdot \xi^{TD}_{\text{walk,i}} \end{aligned} \tag{1}$$

$$\begin{aligned} u_{\text{bike,i}} = &\alpha_{\text{bike,i}} + \\ &\beta_{\text{tt,bike,i}} \cdot tt_{\text{bike}} \cdot \xi^{TD}_{\text{bike,i}} + \\ &\beta_{\text{age,bike,i}} \cdot (\text{age>=60}) \end{aligned} \tag{2}$$

$$\begin{aligned} u_{\text{car,i}} = &\alpha_{\text{car,i}} + \\ &\beta_{\text{tt,car,i}} \cdot_{\text{car}} \cdot \xi^{\text{TD}}_{\text{car,i}} \cdot \mathtt{tt}_{\text{car}} + \\ &\beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{car}} \end{aligned} \tag{3}$$

$$\begin{aligned} u_{\text{pt,i}} = &\alpha_{\text{pt,i}} + \\ &\beta_{\text{ivt,pt,i}} \cdot \xi^{TD}_{\text{pt,i}} \cdot ivt_{\text{pt}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{pt}} + \\ &\beta_{\text{tt,pt,i}} \cdot tt_{\text{pt}} + \beta_{\text{hw,pt,i}} \cdot hw_{\text{pt}} + \\ &\beta_{\text{tr,pt,i}} \cdot ntr_{\text{pt}} + \beta_{\text{aet,pt,i}} \cdot aet_{\text{pt}} \end{aligned} \tag{4}$$

$$u_{\text{aRP,i}} = \alpha_{\text{aRP,i}} + \beta_{\text{ivt,aRP,i}} \cdot \xi^{TD}_{\text{aRP,i}} \cdot ivt_{\text{aRP}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRP}} + \beta_{\text{rt,aRP,i}} \cdot rt_{\text{aRP}} + \beta_{\text{aet,aRP,i}} \cdot aet_{\text{aRP}} \tag{5}$$

$$u_{\text{aRH,i}} = \alpha_{\text{aRH,i}} + \beta_{\text{ivt,aRH,i}} \cdot \xi^{TD}_{\text{aRH,i}} \cdot ivt_{\text{aRP}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRH}} + \beta_{\text{wt,aRH,i}} \cdot wt_{\text{aRH}} \tag{6}$$

$$\xi^{TD}_{\text{i,j}} = \left(\frac{d}{\theta_{distance}}\right)^{\lambda_{TD,i,j}} \tag{7}$$

where d is the Euclidean distance and $\theta_{distance}$ is the reference distance for the mode i and purpose j.

$$\xi^{CD}_{\text{i,j}} = \left(\frac{d}{\theta_{distance}}\right)^{\lambda_{CD,i,j}} \tag{8}$$

where d is the Euclidean distance and $\theta_{distance}$ is the reference distance for the mode i and purpose j.

TABLE 1: Behavioral parameters

Mode	Parameter	commuting	leisure	shop	other
All modes	Cost	-0.096	-0.096	-0.096	-0.096
	λ_{CD} cost-distance	-0.513	-0.513	-0.513	-0.513
Car	Constant	0.000	0.000	0.000	0.000
	In-vehicle travel time [min^{-1}]	-0.053	-0.043	-0.035	-0.039
	λ_{TD} in-vehicle time-distance	-0.354	-0.354	-0.354	-0.354
PT	constant	0.000	0.000	0.000	0.000
	In-vehicle travel time [min^{-1}]	-0.045	-0.028	-0.034	-0.040
	λ_{TD} in-vehicle time-distance	-0.472	-0.472	-0.472	-0.472
	Transfer time [min^{-1}]	-0.025	-0.053	-0.040	-0.037
	Headway	-0.012	-0.013	-0.013	-0.012
	Number of transfers	-0.205	-0.207	-0.379	-0.250
	Access time [min^{-1}]	-0.071	-0.067	-0.029	-0.073
	PT Quality A	0.000	0.000	0.000	0.000
	PT Quality B	-0.366	-0.366	-0.366	-0.366
	PT Quality C	-0.346	-0.346	-0.346	-0.346
	PT Quality D	-0.277	-0.277	-0.277	-0.277
	PT Quality E	-0.146	-0.146	-0.146	-0.146
	Half-fare card	0.381	0.381	0.381	0.381
	GA	0.317	0.317	0.317	0.317
	Regional travel card	0.932	0.932	0.932	0.932
aRP	Constant (incl. innovation)	-1.365	-1.365	-1.365	-1.365
	In-vehicle travel time [min^{-1}]	-0.043	-0.041	-0.041	-0.041
	λ_{TD} in-vehicle time-distance	-0.181	-0.119	-0.119	-0.119

Mode	Parameter	commuting	leisure	shop	other
	Half-fare card	0.446	0.446	0.446	0.446
	Response time [min^{-1}]	-0.024	-0.024	-0.024	-0.024
aRH	Constant (incl. innovation)	-1.208	-1.208	-1.208	-1.208
	In-vehicle travel time [min^{-1}]	-0.057	-0.049	-0.049	-0.049
	λ_{TD} in-vehicle time-distance	-0.322	0.000	0.000	0.000
	Half-fare card	0.326	0.326	0.326	0.326
	GA or regional travel card	0.357	0.357	0.357	0.357
	waiting/response time [min^{-1}]	-0.023	-0.023	-0.023	-0.023
Bike	Constant	0.152	0.152	0.152	0.152
	Travel time [min^{-1}]	-0.352	-0.286	-0.232	-0.261
	λ_{TD} travel time-distance	-0.800	-0.800	-0.800	-0.800
	high_age	-2.659	-2.659	-2.659	-2.659
Walk	constant	0.590	0.590	0.590	0.590
	travel time [min^{-1}]	-0.128	-0.105	-0.085	-0.095
	λ_{TD} travel time-distance	-0.267	-0.267	-0.267	-0.267
Reference distance [km]	PT, car, aRP, aRH	28.4	30.3	30.0	30.0
	Bike	4.0	4.0	4.0	4.0

Cost model

Traveling by car is priced at 0.26 CHF per kilometer. Traveling by public transport is priced at 0.6 CHF per kilometer with a minimum fare of 2.7 CHF in case one does not own a public transport subscription. Individuals with a "Generalabo" (GA) subscription, which allows unlimited PT usage throughout Switzerland, incurred zero costs. Those with a "Halbtax" subscription paid half the price. Individuals with a regional subscription ("Verbundabo") paid nothing within the designated regional area. For aRP and aRH, the fare consists of the base fare and the variable distance base fare. For aRH, the car per distance fare was used with the assumption that the service would be privately run and companies would tend to maximize demand and profit. Similarly, the per distance fare for PT was initially applied for aRP assuming it would be a part of public service. These prices and factors like travel and wait times influence traveler decision-making in the simulation regarding whether to use the on-demand services. The corresponding fares defined for different scenarios can be seen in Table 2.

TABLE 2: Fleet sizes and fare structure as applied for the case studies

Mode	Indicator	Chur	Zurich
aRH	Fleet size base case and policy scenario	800	1200
	Base fare [CHF/trip]	2.5	2.5
	Distance-based fare [CHF/km]	0.26	0.26
aRP	Fleet size base case	1000	1400
	Fleet size policy scenario	1200	1700
	Base fare [CHF/trip]	2.5	2.5
	Distance-based fare [CHF/km]	0.5	0.5

Car ownership

We also applied an estimated car ownership model to different regions to anticipate future changes in car ownership. In this model, the utility of each alternative was described as a linear combination of an alternative-specific constant, an inertia variable representing current car availability, and additional variables capturing the impact of travel card ownership, demographic profile including income, and openness to mobility innovations. As a result, in Chur 20.2% of individuals above the age of 18, with residents in the region purchase a PAV, and 14.5% give up car ownership; the rest keep owning a conventional vehicle. In Zurich, 19.6% of individuals above 18 with residents in the studied region purchase a PAV, while 14% give up car ownership. It must be noted that the car ownership model was not applied to through traffic as their place of residence is unknown.

Calibration

Each simulated scenario is calibrated to match the total and distance-based mode share in the region. The parameters adjusted through the calibration process, similar to the one described in (*20*) are for Chur:

- $\alpha_{\text{car}} = 0.262$
- $\alpha_{\text{bike}} = 0.9428$
- $\alpha_{\text{walk}} = 3.1781$
- $\lambda_{\text{TD,bike}} = 0.4$
- $\lambda_{\text{TD,pt}} = -0.672$

and for Zurich:

- $\alpha_{\text{car}} = 1.7447$
- $\alpha_{\text{bike}} = -0.0514$
- $\alpha_{\text{walk}} = 2.0501$
- $\lambda_{\text{TD,bike}} = 0.35$

Original mode-chocie parameters had to be calibrated due to the constraints of the SP mode-choice survey which targeted individuals above 18 and those trips longer than two kilometers.

aRH and aRP configurations

- Operating hours: The aRH and aRP operators operate 24 hours a day, providing door-to-door services
- Passenger capacity: aRH vehicles can only pick up one passenger, while aRP vehicles can accommodate up to four passengers.
- Vehicle placement: The operators do not have a centralized depot where the vehicles begin their trips. Rather, the vehicles are initially placed according to the population density of the modeled regions to anticipate the strong morning demand in those areas, assuming that the necessary parking space is available.
- Rebalancing strategy: A Fast-Heuristic rebalancing strategy in MATSim is used such that every 30 minutes, vehicles relocate to meet the demand.
- Fleet size: The fleet size for both operators is determined through a grid search approach to identify the fleet size that operates at a profit while maximizing the demand. In policy scenarios the fleet of aRP is increase by approximately 20% to anticipate the increase in demand.
- Trip constraints: a minimum distance limit of 250 meters was imposed to ensure aRH

and aRP are not used in competition with walking or cycling (the lack of data on those physically unable to walk prevents us from identifying those individuals) . A shapefile constraint was added to ensure aRP and aRH are only chosen for trips within the defined case study regions.

Scenarios

Two case study regions have been defined to keep the computation of agent-based transport simulation feasible while still being able to distinguish how the popularity of aRH and aRP depends on the spatial context. These include Chur and Zurich. While both regions are composed of an urban core and its surrounding catchment area, they differ with regard to the population size and density as well as the spatial character, rates of car ownership, and the quality of public transport. Therefore, the two regions are well suited to test how the spatial context influences the attractiveness of aRH and aRP services.

The covered area in the case of Chur was selected based on a travel time threshold of 30 min by car from Chur's city center. For Zurich, the study region contains the area of the city of Zurich plus a 5km buffer (see also Figures 1, and 2).

Policies

	Zurich	Chur
Scenario A: Pull	Subsidy on ridepooling cost depending on PT connection quality (worst category for start and end of trip): A: 0%; B: 20%; C: 40%; D: 60%; no class: 80%	
Scenario B: Push	Cordon pricing (inbound to the boundary of the city of Zurich) for non-pooled vehicles: 6 CHF	
Additional distance-based externality tax for non-pooled vehicles: car and private AV: +0.2 CHF/km; aRH: +0.25 CHF/km		
Scenario C: Push and Pull	Combination of A and B	
Population size	10%	100%

TABLE 3: Overview of policy scenarios

Based on findings from earlier studies, a key concern with the introduction of automated vehicles is the potential for increased traffic volume and resulting higher rates of congestion (*23*). As travel time is perceived as less negative when motorists are freed from the driving task, traveling by automated car becomes more attractive. Additionally, ride-hailing and ride-pooling services provided by automated vehicles offer new travel options for people who do not own a car or hold a

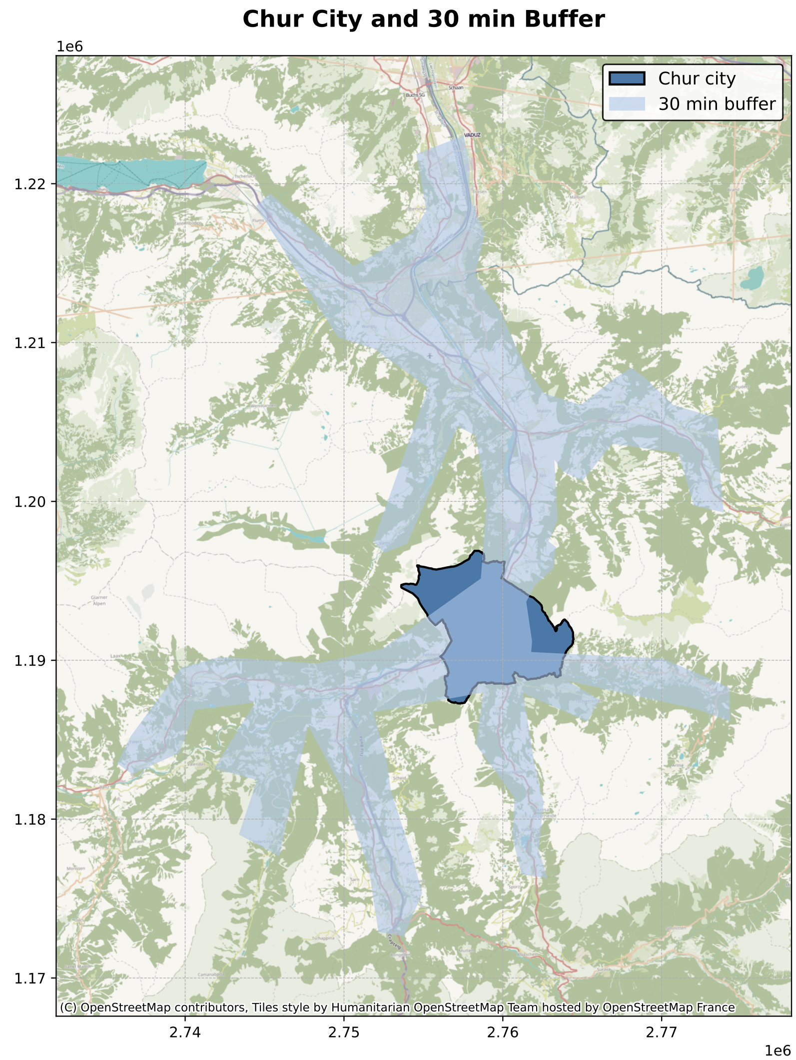


FIGURE 1: Chur case study region

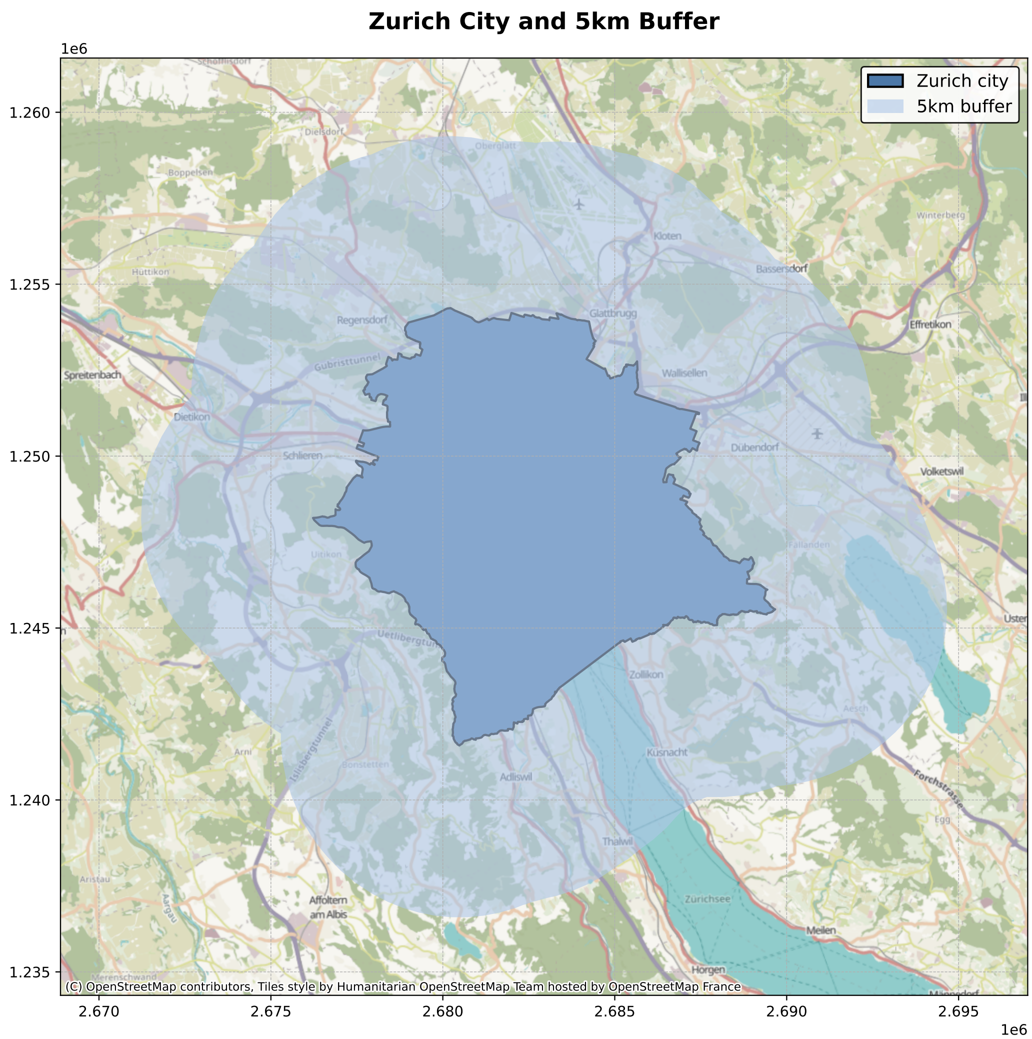


FIGURE 2: Zurich case study region

driving license. If individuals transition from active modes of transport or public transport to these new modes, the number of vehicles on the road and overall traffic levels will rise. Additionally, automated vehicles traveling without passengers to pick up the next rider or to find cheaper parking will further increase vehicle mileage.

Table 3 provides an overview of pull and push measures, which define the three policy scenarios applied to each case study region. In Scenario A, the pull measure for the two regions includes subsidies for ride-pooling trips based on the public transport service quality (ÖV-Güteklasse) at the trip's origin and destination, with the lower quality of the two being the determining factor. This measure aims to enhance ride-pooling attractiveness and increase vehicle occupancy rates in areas where public transport is less competitive with individual modes of transport. The subsidy rates are informed by current cost coverage rates of public transport in different spatial contexts. While public transport is nearly self-financing in urban areas, in Switzerland, it is considered acceptable for bus services to cover only 20% of their operating costs in regions where public transport primarily ensures basic mobility provision.

Different push measures are applied in Scenario B depending on the case study regions. For Zurich, a cordon pricing scheme is introduced, imposing a charge of CHF 6[1] for any non-pooled vehicle trip entering the city's boundary. This road pricing scheme primarily aims to increase vehicle occupation rates for trips into the city center. Such a levy also impacts mode choice regarding car trips outwards from the city center as travel cost is evaluated based on tours and not individual trips. In Chur, travel demand is less concentrated towards the urban core, but more spread across the agglomeration. Therefore, an additional distance-based externality tax is applied, amounting to CHF 0.20 per kilometer for private cars and CHF 0.25 per kilometer for ride-hailing vehicles. The lower levy for private cars addresses the situation that average vehicle occupancy is higher for cars than for ride-hailing trips. However, since none of the employed MATSim models explicitly simulate joint trips, implementing a scheme where the levy directly depends on actual vehicle occupancy was not feasible.

Scenario C combines the pull and push measures defined for each case study region to test whether they enhance each other and result in stronger behavioral shifts than implementing either measure independently.

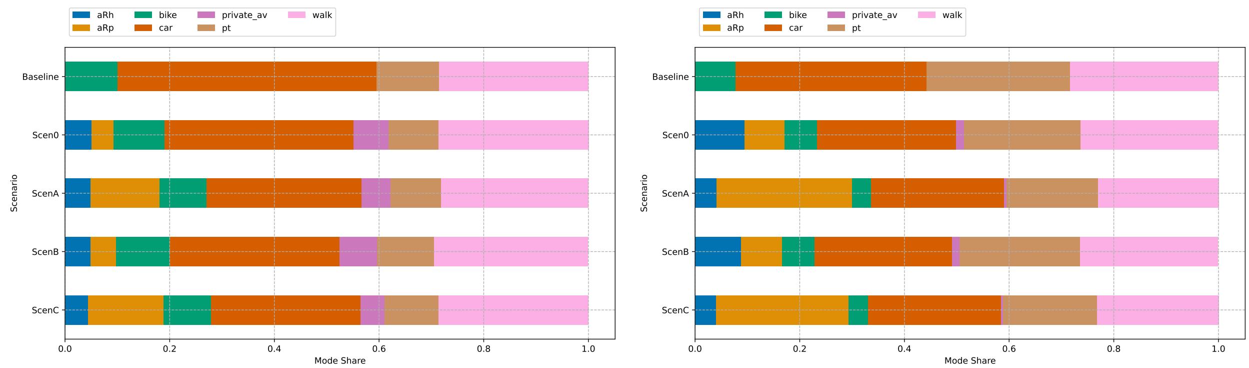
RESULTS

This section presents the simulation results for the two study regions, Chur, a car-oriented city, and Zurich, a PT-oriented city. To fully understand the impacts of the pull and push policies described above on the two regions, the results are presented from the system-wide and aRP and aRH operator perspectives.

Throughout the section, the following scenario labels are used:

- Baseline - representing the status-quo situation
- Scen 0 - representing the scenario with automated vehicles and fleet-sizing based on cost coverage optimization
- Scen A - representing scenario A with pull measure and increased fleet size by 20% over Scenario 0
- Scen B - representing Scenario B with push measure and increased fleet size by 20% over Scenario 0

[1] 1 CHF = 1.12 USD, 22.07.2024



(a) Chur *(b)* Zurich

FIGURE 3: Mode share by trip in Zurich

- Scen C - representing Scenario C with combined pull and push measures from scenarios A and B and increased fleet size by 20% over Scenario 0

The Zurich simulations for Scenarios 0 to C use 10% of the population for computational reasons. The results are not scaled up to 100% but have been left to represent 10% of the population.

System perspective

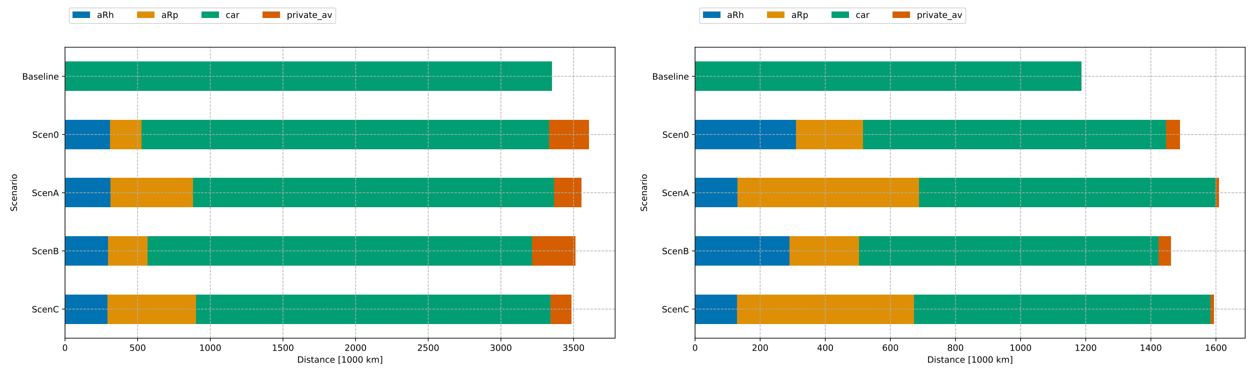
Mode shares and modal shift: Figure 3a shows the mode shares on a trip level for different scenarios for Chur. People in the studied region around Chur highly prefer the car as the mode of travel, with almost 50% mode share as seen in the Baseline. The mode share of public transport stands at a low of 12%, while the rest is taken up predominantly by walking at 28.5%. Figure 3b shows the mode shares on a trip level for Zurich. As expected, the Baseline scenario shows the high transit share for the region at 27% with car mode share at 36.4%, followed by walking at 28%.

Introducing aRP and aRH mainly affects motorized means of travel in the car-oriented region of Chur, while all modes of transport are affected in the transit-oriented region. Cycling and walking in Chur remain stable at around 10% and 28%, respectively. In Zurich, interestingly, the impact is strongest on private cars, whose share falls to 26.7%, followed by public transport, whose share falls to 22.3%.

Once the aRH and aRP policies are introduced, one can immediately see that only the pull policies of Scenarios A and C have a substantial impact on the demand for aRP and aRH. However, in comparing aRP and aRH, there appears to be low competition between them as aRH demand remains stable for the Chur region, while the share of aRP increases at the expense of all modes, especially for Zurich.

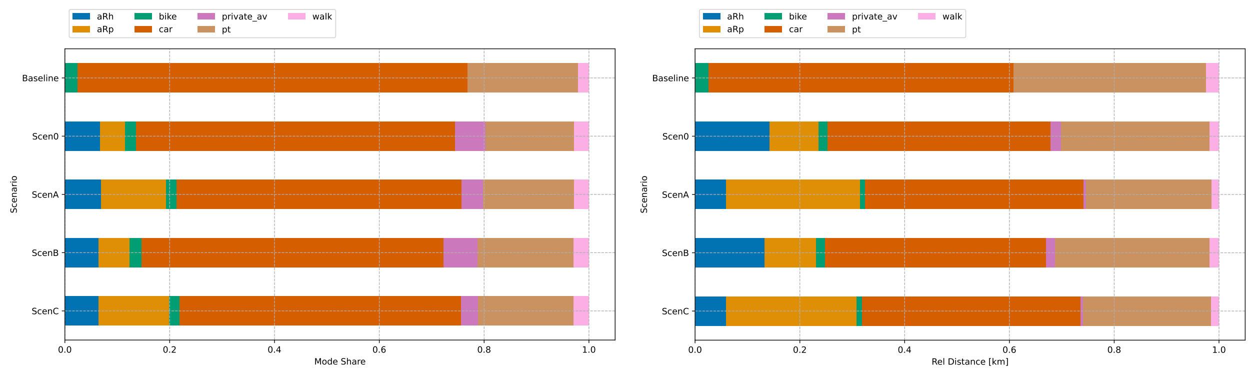
The push policy of Scenario B in Chur shows an increase in the mode share of all modes at the expense of the private car, though with only a slight rise in aRP and aRH shares. In Zurich, the push measures have only a minimal impact, as only traffic that crosses the cordon and starts within the 5 km buffer area, which is generally served well by public transport, is affected by the cordon toll (see Figure 2).

VKT and travel time: Figure 4a shows the total vehicle distance per transport mode for Chur and Figure 4b for Zurich. These distances are from the perspective of vehicles, not passengers (public transit is not shown as it stays constant between the scenarios). Therefore, the empty



(a) Chur *(b)* Zurich

FIGURE 4: Total vehicle distance



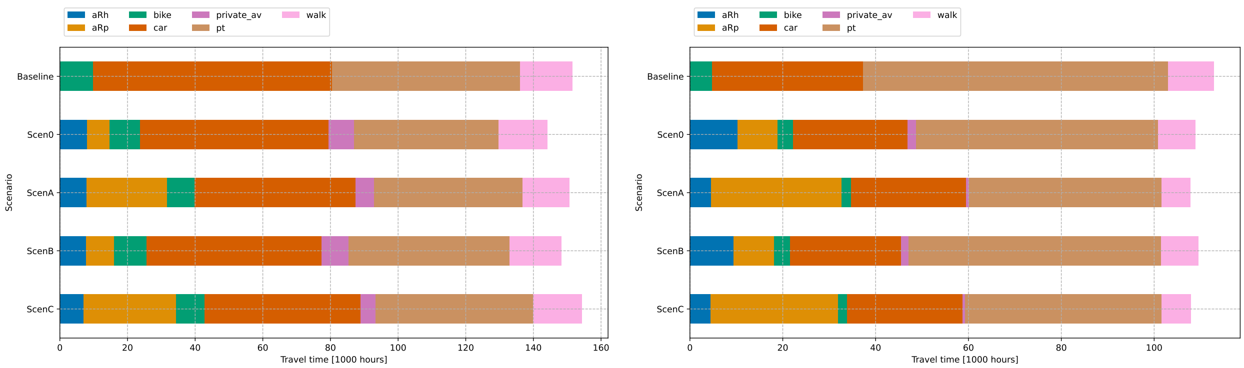
(a) Chur *(b)* Zurich

FIGURE 5: Mode share by distance

distance is also included for aRH and aRP. The results show that introducing automated services increases the total system vehicle kilometers traveled in all scenarios for the two regions. This increase slightly differs depending on the region and policy measure. For both regions, push scenario B has a more substantial effect in reducing the VKT than the pull measures. Pull policy measures bring about a lower increase in VKT compared to Scenario 0 in Chur, but an increase in Zurich. Particularly for the transit-oriented Zurich, the VKT increases by around 33% compared to the baseline scenario.

When the distances are observed by mode as shown in Figure 5a for Chur and Figure 5b for Zurich, where no policies are implemented, the mode share by distance of motorized travel (aRP, aRH, and car) increases to 78% compared to the Baseline where it stands at 74.5% for Chur and while for Zurich the motorized distance increases from 60% to 68%. Pull measures in Zurich lead to a further increase in the share of motorized travel to 73%, where public transport distance share is affected the most. In Chur, however, the implemented policies have a positive effect on reducing the motorized distance traveled. However, only slightly, with the largest reduction in Scenario C (76.5%), which still stands higher than in the Baseline. This statistic only includes the passenger-driven kilometers, and it does not look at the empty mileage of aRP and aRH, as discussed above.

On the other hand, the total system travel time is reduced once aRP and aRH services are



(a) Chur *(b)* Zurich

FIGURE 6: Travel time by mode (Note: not including the waiting time for aRP and aRH)

introduced in these regions for all scenarios, except in the scenario C of Chur. See Figure 6a for Chur and Figure 6b for Zurich. The total travel time is reduced due to fewer walking, cycling, and public transport trips and the higher efficiency of automated vehicles. In Chur's Scenario C, the total travel time is increased due to more detours for pooled rides. Moreover, it is important to remember that although waiting time is also considered as a travel time element for aRP and aRH, it is not included here as waiting time can be spent at the activity location from which door-to-door service picks up the passenger.

Operator perspective

Here, wait times, the share of empty distance traveled, and profitability are addressed as key metrics for operators to compare across the policy scenarios for the two regions. Tables 4 and Table 5 show key statistics of the aRP and aRH services for different policy scenarios. The results show obvious trade-offs between empty vehicle distance ratio (efficiency perspective), waiting times (user perspective), and profit (operator perspective). However, there is no obvious winner among the tested scenarios.

Wait times: The effect of the scenarios on the average wait times is similar in the two regions, as the wait times for aRH and aRP depended on the impact of the policy scenarios on demand. In Scenario 0, aRH had higher wait times due to higher demand since the service is cheaper than aRP. However, when pull effects are tested in Scenarios A and C, they mostly increase the demand for aRP (with an increase of more than 300%); thus, the customers experience much higher average waiting times. Similarly, in the push scenario, there are increased wait times but half as much compared to the pull scenarios, whose aRP demand is triple the demand achieved in the push scenarios.

Empty distances: In general, the share of the distance that the vehicles drive empty is around 25% for both services in Chur, with the notable exception that the empty ratio falls to around 12% for the aRP service in the pull scenarios of Scenarios A and C when the demand for aRP is the highest. In Zurich, when the aRP and aRH services are introduced, the share of the distance that the vehicles drive empty is mostly above 25%, while it falls to 16% in push scenarios for aRP. The push policy seems to have no substantial effect on aRP demand, and this is reflected in Scenario C, where the two policies are combined.

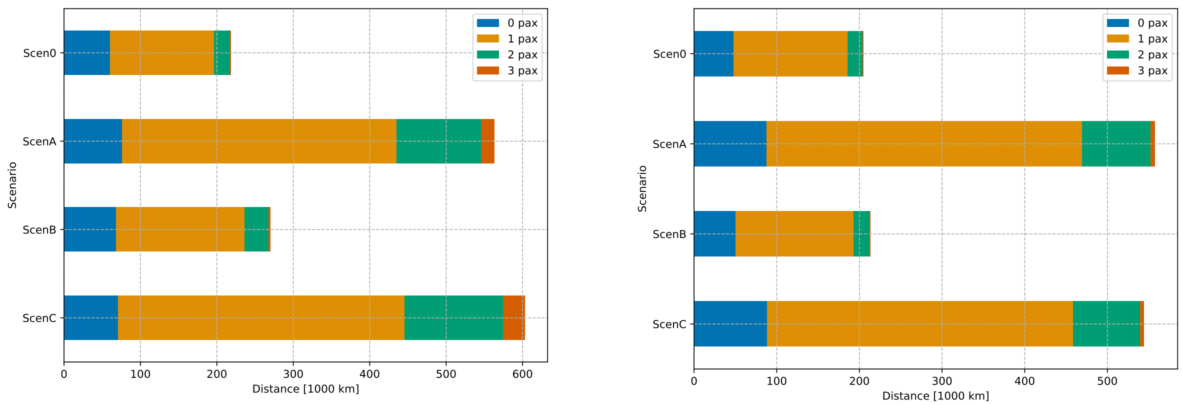
Profitability: The effects of the policy measures are similar for both regions. The pull

Scenario	Scen0		ScenA		ScenB		ScenC	
Vehicle	aRH	aRP	aRH	aRP	aRH	aRP	aRH	aRP
Avg Waiting Time [min]	4.35	2.95	7.91	11.72	4.08	3.08	4.94	13.44
Passenger distance [1000 km]	232.05	181.84	236.48	648.58	219.52	236.93	209.28	748.21
Total vehicle driven distance [1000 km]	309.74	218.54	315.00	567.26	297.26	269.71	292.01	610.43
Total vehicle occupied distance [1000 km]	232.05	158.33	236.48	490.90	219.52	201.45	209.28	539.78
Total empty vehicle distance [1000 km]	77.69	60.21	78.52	76.36	77.74	68.26	82.74	70.65
Cost [1000 CHF]	74.09	69.61	74.27	121.55	72.51	76.17	70.97	128.48
Revenue [1000 CHF]	135.55	118.98	134.26	249.61	189.94	148.42	177.50	284.34
Net income [1000 CHF]	61.46	49.37	59.99	128.06	117.43	72.25	106.53	155.86
Empty ratio	0.25	0.28	0.25	0.13	0.26	0.25	0.28	0.12
Number of rides	27 837	21 941	26 925	69 329	26 876	26 072	24 138	76 530

TABLE 4: Most relevant operational statistics of aRP and aRH in Chur.

Scenario	scen0		scenA		scenB		scenC	
Vehicle	aRH	aRP	aRH	aRP	aRH	aRP	aRH	aRP
Avg Waiting Time [min]	3.88	3.08	4.00	8.88	3.76	3.08	4.60	7.40
Passenger distance [1000 km]	234.14	177.16	90.83	563.48	213.91	184.31	88.12	547.26
Total vehicle driven distance [1000 km]	311.06	204.76	130.70	557.47	290.43	213.30	128.49	544.47
Total vehicle occupied distance [1000 km]	234.14	157.05	90.83	469.59	213.91	162.90	88.12	456.23
Total empty vehicle distance [1000 km]	76.92	47.71	39.87	87.88	76.52	50.40	40.37	88.24
Empty ratio	0.25	0.23	0.31	0.16	0.26	0.24	0.31	0.16
Number of rides	34 320	26 129	15 686	88 771	31 941	26 811	15 390	86 618
Cost [1000 CHF]	93.30	86.48	68.64	144.53	90.39	87.57	68.31	142.45
Revenue [1000 CHF]	155.23	118.27	70.10	273.42	205.61	121.27	97.63	267.36
Net income [1000 CHF]	61.93	31.79	1.46	128.89	115.22	33.70	29.32	124.91

TABLE 5: Most relevant operational statistics of aRP and aRH in Zurich.



(a) Chur *(b)* Zurich

FIGURE 7: Total vehicle distance by occupancy for aRP in Zurich

policy in scenario A, where aRP fares are lowered, led to a substantial increase in demand for aRP (see Chur's increase from about 21 000 to 69 000). This brought higher profits mainly for aRP operators, demonstrating the success of the pull measure. Though scenario B's push policy, which included taxing private cars and aRH, increased overall revenue and profits, the revenue includes the externality taxes that would obviously have to be transferred to a government body implementing the charge. Therefore, aRH operators are not necessarily better off.

Scenario C, which combined both pull and push measures, achieved the highest overall profit and the highest profit for aRP. Although the performance of aRH was slightly worse than in Scenario B in terms of demand, the combined policy shows that combining incentives for ride-pooling with disincentives for ride-hailing and private car use can result in balancing trade-offs between profit and efficiency.

Pooling: Figures 7a and 7b show the distance driven per occupancy for the aRP service in different scenarios for Chur and Zurich, respectively. For both regions, Scenarios with pull policies A and C positively affect the pooling frequencies, leading to an increase of the pooling rate (not considering empty trips) from 1.13 up to 1.20 for Chur and from 1.15 up to 1.35 for Zurich. However, there is a difference in impact on empty distances between the regions. In Chur, the increase in pooling by the pull policies brought with it an insignificant increase in the empty distance, however in Zurich the increase is larger. Still, in Zurich, the marginal gain in kilometers traveled for vehicles with occupancy two or three is higher. The push measures in Scenario B only slightly increase the number of trips with two passengers in Chur, while in Zurich, the push policy increases the distance traveled of vehicles with occupancy one and two, but at the expense of more empty kilometers traveled.

DISCUSSION AND RECOMMENDATIONS

The findings in both regions show that mode share on a trip level of automated vehicles would be around 20%, which could increase to around 35% given proposed policy measures. This considerable mode-share of AVs also translates to larger vehicle kilometers traveled (VKT). Zurich, being a more public transport-oriented city than Chur, also witnesses a larger percentage increase in VKT. Finally, there is limited impact on cycling and walking demand, showing the benefit of including a base fare and restricting the aRH and aRP modes to trips longer than 250 meters.

In general, aRH and aRP do not seem to be competing for the same customers, as pull policy measures in both regions seem to pull, percentage-wise, more users from other transport modes.

Pooling levels for aRP mode are, in general, low. The reasons lie in the low spatial and temporal density of trips to allow for higher pooling frequencies and not modeling group travel due to lack of behavioral data (see also for some consequences in Kagho and Balac (*24*)). To further promote pooling, a possible further development would be to consider the possibility of reservation or dedicated pickup/dropoff location that will enable more efficient routing and pooling possibilities at the expense of additional access and egress walking.

From the user perspective, the average waiting times are consistently below five minutes between the scenarios, except for pull and push scenario C, where aRP has the highest demand. Therefore, it is expected that some individuals who repeatedly face large waiting times might, in practice, opt out of using this service in the future, meaning that the forecasted demand in these policy scenarios is overestimated. At the same time, given the high profitability of aRP operations in this scenario, one would expect other operators to enter the market or regulators to mandate bigger fleets to ensure better service quality.

Recommendations for transport policy and future research

In what follows are the general policy recommendations and pointers for future work based on our findings:

- **AV fleets increase accessibility but also traffic levels:** In both case studies, the introduction of aRH and aRP fleets led to a reduction in total travel time while the total vehicle distance increased. None of the tested policy scenarios reduced vehicle mileage compared to a situation without aRP and aRH services. It seems that further policy measures targeting higher vehicle occupancy in both private and commercial vehicles are needed to ensure that the accessibility gains provided by automated vehicle fleets do not lead to increased congestion and other externalities. Such measures could include implementing dynamic road charges based on vehicle occupancy or introducing initiatives to reduce car ownership.
- **Regulation of AV fleet operators:** The case studies demonstrate that operating a fleet of aRH and aRP vehicles in Swiss cities and their surroundings is a profitable business. We expect trips with an origin or destination in the city core to be more profitable than those in the outskirts, where aRP leads to higher vehicle occupancy rates and hence increases the efficiency of the transport system. Therefore, a regulation should be implemented that requires automated vehicle fleet operators to maintain a particular service quality for trips starting or ending in areas with low public transport service quality and to adopt a fare structure that cross-subsidizes these trips.
- **Mobility pricing:** Both the distance-based externality tax in Chur as well as the cordon pricing in Zurich resulted in a moderate increase in aRP and aRH usage. This shift led to a notable reduction in car usage, consequently decreasing the total vehicle distance traveled. However, the total travel increased slightly in all regions. For future simulation studies, we suggest evaluating more targeted mobility pricing measures. Additionally, we recommend including a feedback loop where road usage charges incurred by shared vehicles are considered additional operating costs and passed on to their users. Moreover,

the impact of a marginal pricing approach, which promises to be the most economically efficient method of mobility pricing, should be tested with simulations.

- **Complementing PT:** Public transport schedules were not adapted in reaction to aRP and aRH offer. Introducing aRP and aRH services will lead to a decrease in public transport ridership. At the same time, automated buses would lead to lower operating costs for public transport and provide opportunities to offer more frequent services to be served with smaller vehicles. Future studies should examine how public transport and automated ride-pooling can be planned to complement each other in such a mobility landscape.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study design: G. Kagho, M. van Eggermond, M. Balac, A. Erath; data collection and preparation: M. van Eggermond, A. Erath; study implementation and result generation: G. Kagho, M. van Eggermond, M. Balac; interpretation of results: G. Kagho, M. Balac, A. Erath; draft manuscript preparation: G. Kagho, M. Balac, A. Erath. All authors reviewed the results and approved the final version of the manuscript.

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