

1 **SIMULATION OF POLICIES FOR AUTOMATED RIDE-HAILING AND**  
2 **RIDE-POOLING SERVICES**

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6 **Grace Kagho, Corresponding Author**

7 IVT

8 ETH Zürich

9 CH-8093 Zurich

10 grace.kagho@ivt.baug.ethz.ch

11 ORCID: 0000-0002-3350-9044

12

13 **Milos Balac**

14 CSFM

15 ETH Zürich

16 CH-8092 Zurich

17 milos.balac@csfm.ethz.ch

18 ORCID: 0000-0002-6099-7442

19

20 **Michael van Eggermond**

21 University of Applied Sciences Northwestern Switzerland

22 CH-4132 Muttenz

23 michael.vaneggermond@fhnw.ch

24 ORCID: 0000-0002-0329-7853

25

26 **Alexander Erath**

27 University of Applied Sciences Northwestern Switzerland

28 CH-4132 Muttenz

29 alexander.erath@fhnw.ch

30 ORCID: 0000-0002-3494-6617

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**1 ABSTRACT**

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

15

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

## 1 INTRODUCTION

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

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

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

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

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

## 37 BACKGROUND

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

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

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

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

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

34 None of these simulation studies directly integrate estimated behavioral mode-choice mod-  
35 els within an agent-based simulation for automated on-demand services. The only known two  
36 studies by the authors are Oh et al. (18) and Hörl et al. (20) where Oh et al. (18) combine an  
37 activity-based model with an agent-based simulation to forecast mobility patterns for Singapore in  
38 2030. The study utilizes a previously conducted stated preference survey on automated mobility to  
39 predict agents' transport mode choices. The results suggest that around 40% of the trips cannot be  
40 shared and that most of the shared rides consist of four passengers. However, the shared rides do  
41 not compensate for the increase in VKT, which increases between 11 and 42% depending on the  
42 adoption and pricing rate.

43 Hörl et al. (20) conducted a similar study in Zurich by combining a mode-choice model  
44 focusing on automated mobility with an agent-based simulation. However, the scenarios simulated  
45 only included single-occupancy vehicles. Findings suggest that the introduced services' impacts

1 are generally negative with the modal shift from more sustainable modes and increased congestion  
 2 in residential areas. Therefore, the authors suggest that shared on-demand automated service needs  
 3 to be regulated to avoid negative environmental impacts.

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

## 7 METHODS

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

### 14 Mode-choice model

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

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

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

$$28 \quad u_{\text{walk},i} = \alpha_{\text{walk},i} + \beta_{\text{tt,walk},i} \cdot \text{tt}_{\text{walk}} \cdot \xi_{\text{walk},i}^{TD} \quad (1)$$

$$29 \quad u_{\text{bike},i} = \alpha_{\text{bike},i} + \beta_{\text{tt,bike},i} \cdot \text{tt}_{\text{bike}} \cdot \xi_{\text{bike},i}^{TD} + \beta_{\text{age,bike},i} \cdot (\text{age} \geq 60) \quad (2)$$

$$30 \quad u_{\text{car},i} = \alpha_{\text{car},i} + \beta_{\text{tt,car},i} \cdot \text{car} \cdot \xi_{\text{car},i}^{TD} \cdot \text{tt}_{\text{car}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot \text{cost}_{\text{car}} \quad (3)$$

$$31 \quad u_{\text{pt},i} = \alpha_{\text{pt},i} + \beta_{\text{ivt,pt},i} \cdot \xi_{\text{pt},i}^{TD} \cdot \text{ivt}_{\text{pt}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot \text{cost}_{\text{pt}} + \beta_{\text{tt,pt},i} \cdot \text{tt}_{\text{pt}} + \beta_{\text{hw,pt},i} \cdot \text{hw}_{\text{pt}} + \beta_{\text{tr,pt},i} \cdot \text{nr}_{\text{pt}} + \beta_{\text{aet,pt},i} \cdot \text{aet}_{\text{pt}} \quad (4)$$

$$\begin{aligned}
u_{aRP,i} = & \alpha_{aRP,i} + \\
& \beta_{ivt,aRP,i} \cdot \xi_{aRP,i}^{TD} \cdot ivt_{aRP} + \\
& \beta_{cost} \cdot \xi_{CD} \cdot cost_{aRP} + \beta_{rt,aRP,i} \cdot rt_{aRP} + \\
& \beta_{aet,aRP,i} \cdot aet_{aRP}
\end{aligned} \tag{5}$$

$$\begin{aligned}
u_{aRH,i} = & \alpha_{aRH,i} + \\
& \beta_{ivt,aRH,i} \cdot \xi_{aRH,i}^{TD} \cdot ivt_{aRP} + \\
& \beta_{cost} \cdot \xi_{CD} \cdot cost_{aRH} + \beta_{wt,aRH,i} \cdot wt_{aRH}
\end{aligned} \tag{6}$$

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

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

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

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
	$\lambda_{CD}$ 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
	$\lambda_{TD}$ 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
	$\lambda_{TD}$ 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
	$\lambda_{TD}$ 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
	$\lambda_{TD}$ 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
	$\lambda_{TD}$ 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
	$\lambda_{TD}$ 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

## 1 Cost model

2 Traveling by car is priced at 0.26 CHF per kilometer. Traveling by public transport is priced at 0.6  
3 CHF per kilometer with a minimum fare of 2.7 CHF in case one does not own a public transport  
4 subscription. Individuals with a "Generalabo" (GA) subscription, which allows unlimited PT usage  
5 throughout Switzerland, incurred zero costs. Those with a "Halbtax" subscription paid half the  
6 price. Individuals with a regional subscription ("Verbundabo") paid nothing within the designated  
7 regional area. For aRP and aRH, the fare consists of the base fare and the variable distance base  
8 fare. For aRH, the car per distance fare was used with the assumption that the service would be  
9 privately run and companies would tend to maximize demand and profit. Similarly, the per distance  
10 fare for PT was initially applied for aRP assuming it would be a part of public service. These prices  
11 and factors like travel and wait times influence traveler decision-making in the simulation regarding  
12 whether to use the on-demand services. The corresponding fares defined for different scenarios can  
13 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

## 1 **Car ownership**

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

## 11 **Calibration**

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

- 15 •  $\alpha_{\text{car}} = 0.262$
- 16 •  $\alpha_{\text{bike}} = 0.9428$
- 17 •  $\alpha_{\text{walk}} = 3.1781$
- 18 •  $\lambda_{\text{TD,bike}} = 0.4$
- 19 •  $\lambda_{\text{TD,pt}} = -0.672$

20 and for Zurich:

- 21 •  $\alpha_{\text{car}} = 1.7447$
- 22 •  $\alpha_{\text{bike}} = -0.0514$
- 23 •  $\alpha_{\text{walk}} = 2.0501$
- 24 •  $\lambda_{\text{TD,bike}} = 0.35$

25 Original mode-choice parameters had to be calibrated due to the constraints of the SP  
 26 mode-choice survey which targeted individuals above 18 and those trips longer than two kilome-  
 27 ters.

## 28 **aRH and aRP configurations**

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

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

## 5 Scenarios

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

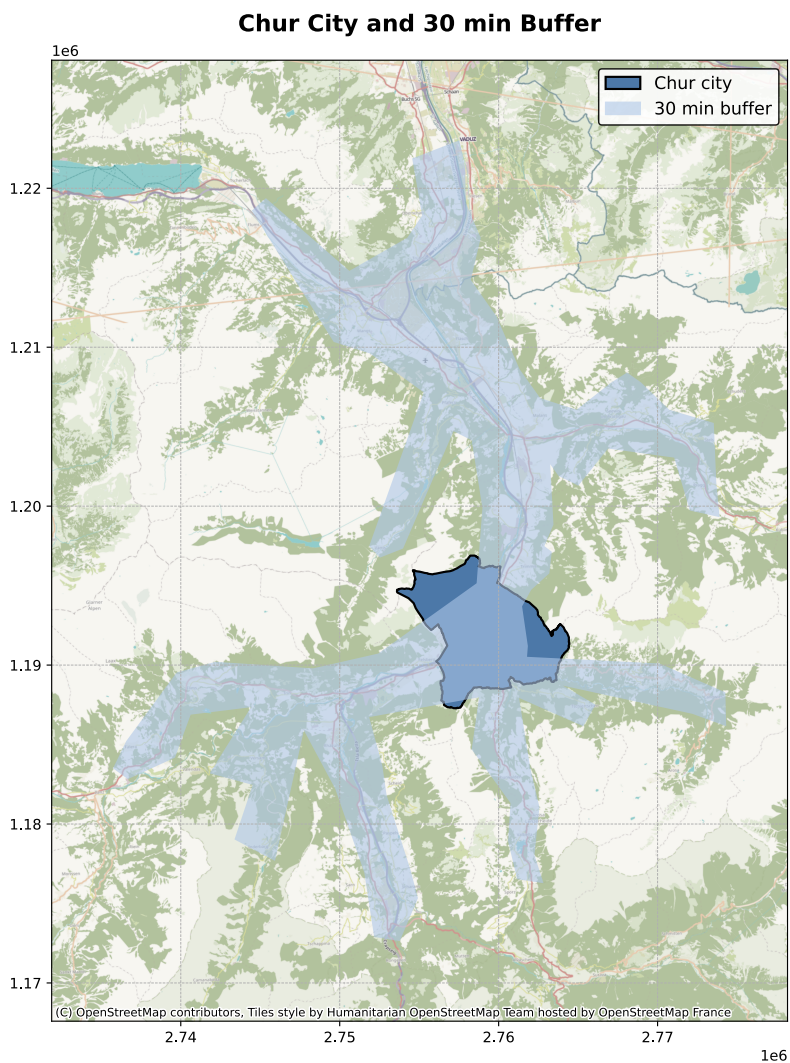
13 The covered area in the case of Chur was selected based on a travel time threshold of 30  
 14 min by car from Chur's city center. For Zurich, the study region contains the area of the city of  
 15 Zurich plus a 5km buffer (see also Figures 1, and 2).

## 16 Policies

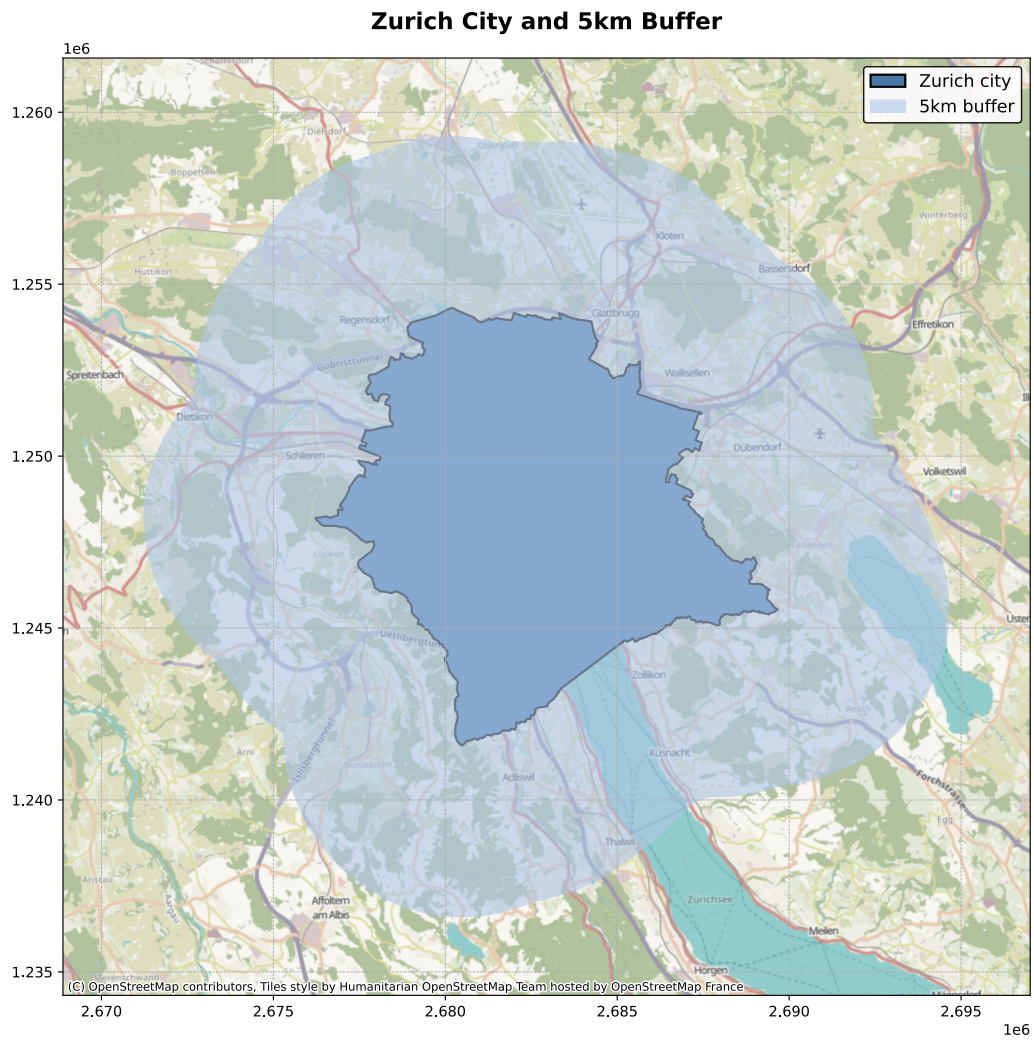
	Zurich	Chur
Scenario A: Pull	Subsidy on ridepooling cost depending on PT connection quality (worst category for start and end of trip): A: 0%; B: 20%; C: 40%; D: 60%; no class: 80%	
Scenario B: Push	Cordon pricing (in-bound to the boundary of the city of Zurich) for non-pooled vehicles: 6 CHF	
Additional 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

17 Based on findings from earlier studies, a key concern with the introduction of automated  
 18 vehicles is the potential for increased traffic volume and resulting higher rates of congestion (23).  
 19 As travel time is perceived as less negative when motorists are freed from the driving task, traveling  
 20 by automated car becomes more attractive. Additionally, ride-hailing and ride-pooling services  
 21 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

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

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

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

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

## 30 RESULTS

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

35 Throughout the section, the following scenario labels are used:

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

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<sup>1</sup>1 CHF = 1.12 USD, 22.07.2024

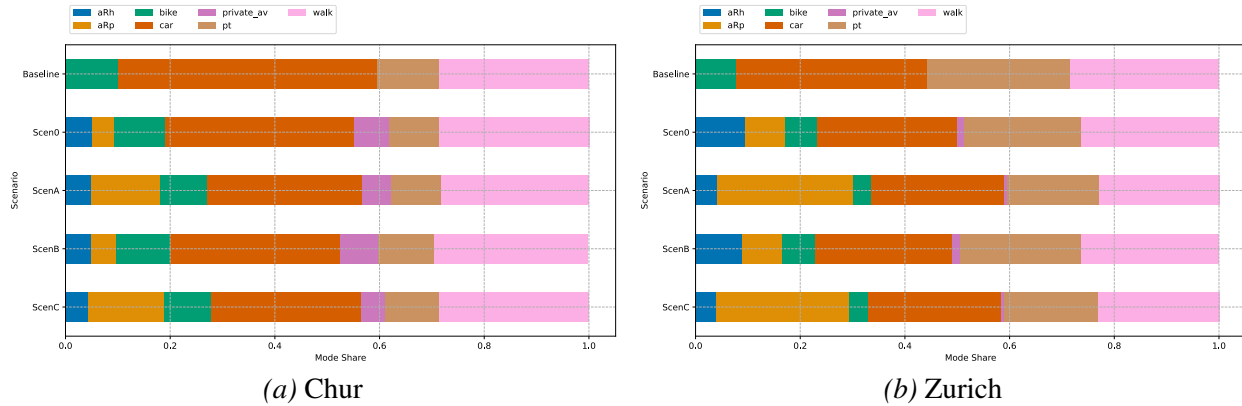


FIGURE 3: Mode share by trip in Zurich

- 1        • Scen C - representing Scenario C with combined pull and push measures from scenarios  
 2            A and B and increased fleet size by 20% over Scenario 0  
 3        The Zurich simulations for Scenarios 0 to C use 10% of the population for computational  
 4 reasons. The results are not scaled up to 100% but have been left to represent 10% of the popula-  
 5 tion.

## 6 System perspective

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

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

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

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

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

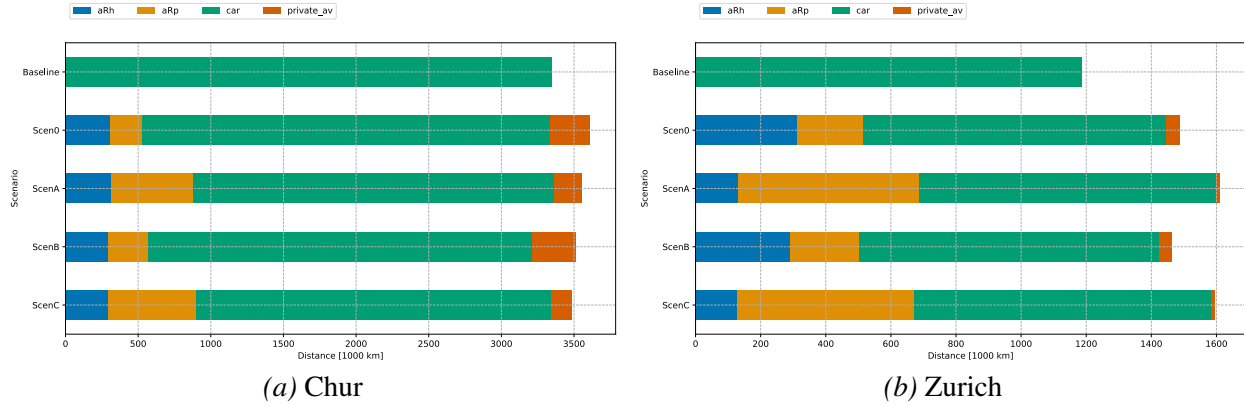


FIGURE 4: Total vehicle distance

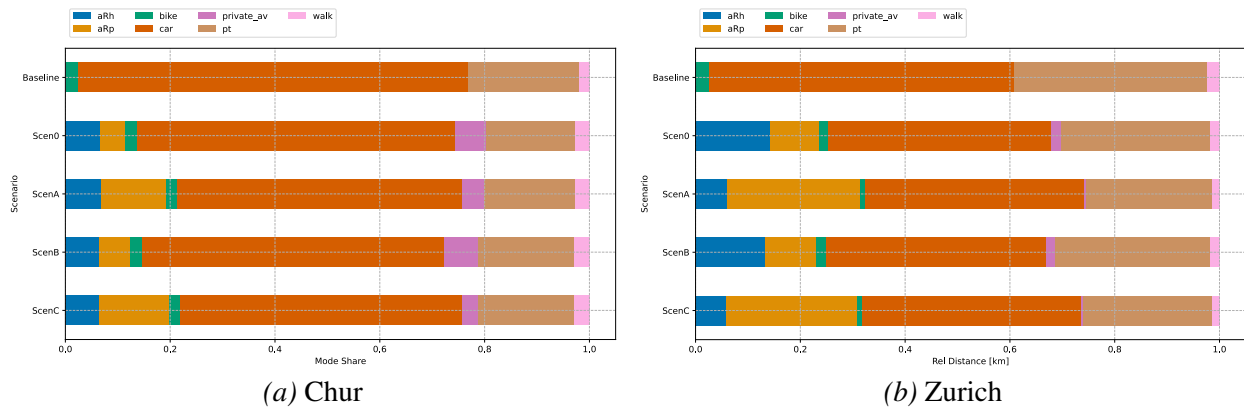
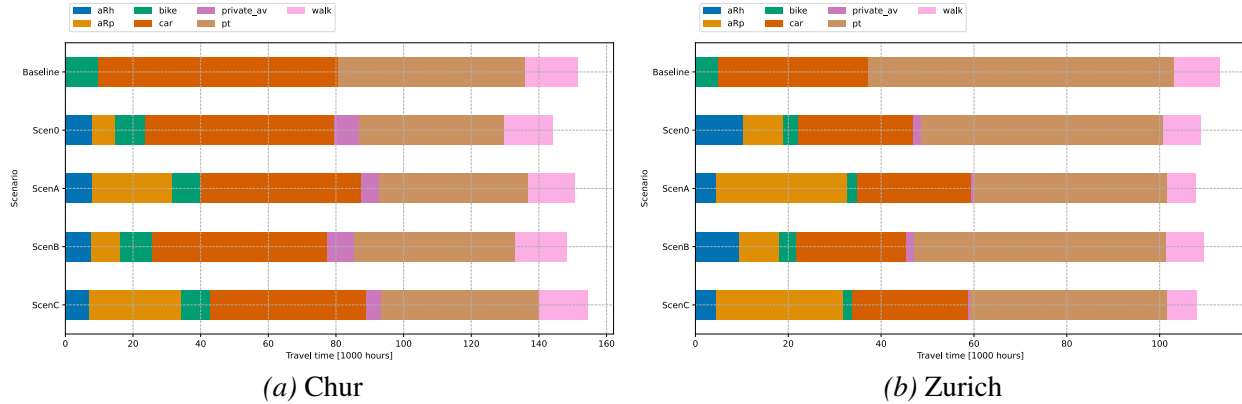


FIGURE 5: Mode share by distance

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

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

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



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

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

## 8 Operator perspective

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

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

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

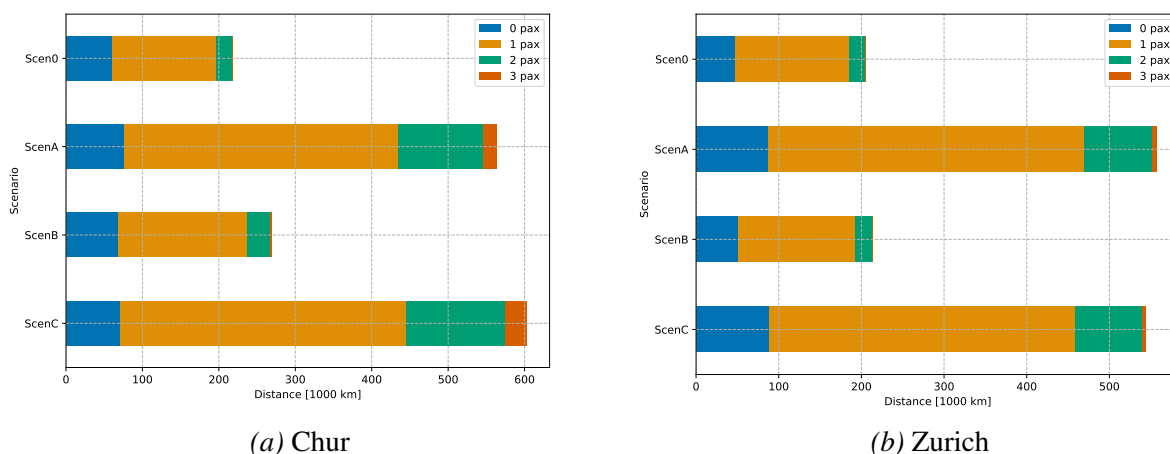
30 *Profitability:* The effects of the policy measures are similar for both regions. The pull

Scenario Vehicle	Scen0		ScenA		ScenB		ScenC	
	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 Vehicle	scen0		scenA		scenB		scenC	
	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.



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

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

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

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

## 23 DISCUSSION AND RECOMMENDATIONS

24 The findings in both regions show that mode share on a trip level of automated vehicles would be  
 25 around 20%, which could increase to around 35% given proposed policy measures. This consider-  
 26 able mode-share of AVs also translates to larger vehicle kilometers traveled (VKT). Zurich, being a  
 27 more public transport-oriented city than Chur, also witnesses a larger percentage increase in VKT.  
 28 Finally, there is limited impact on cycling and walking demand, showing the benefit of including a

1 base fare and restricting the aRH and aRP modes to trips longer than 250 meters.

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

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

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

## 18 **Recommendations for transport policy and future research**

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

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

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

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

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## 11 **AUTHOR CONTRIBUTIONS**

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

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