


# Transport policy optimization with AVs

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**1 ABSTRACT**

2 Autonomous vehicles (AVs, here self-driving and driverless vehicles, SAE (1) levels 4 and 5)  
3 are becoming more clearly a reality. Potential services based on AVs, their detailed design for  
4 high performance, and their consequences for the transport system are of increasing impor-  
5 tance. This paper investigates policy combinations for a world with such services. The policy  
6 measures investigated are pricing of public transport (through subsidies), pricing of private  
7 motorized transport (through taxation or mobility pricing), and the organization of AV services  
8 (monopoly vs. oligopoly, with or without ride-sharing). Further, the perception of travel times  
9 for autonomous private cars is considered.

10 All combinations of policies (respectively two to four levels each) are implemented in a simula-  
11 tion to determine their synergies. The applied model is the agent-based transportation simulation  
12 MATSim. The scenario employed for the tests is the agglomeration of Zug, Switzerland.

13 The results suggest that, given the current spatial distribution of the demand and the current  
14 transport system, AV systems are only able to reduce travel times at the cost of substantial mode  
15 shifts and additional vehicle kilometers driven. Of the tested policy measures, although all  
16 showed the expected causality, only the organizational form of the AV service had a statistically  
17 significant effect.

18 Therefore, this paper suggests that policy makers are critical when assessing the promises of  
19 future transport services. To invest the benefits of automation into an improvement of the  
20 existing transport system might be a good alternative.

## 1 INTRODUCTION

2 Autonomous vehicles (AV), in this paper driverless and self-driving vehicles (SAE (1) level 4  
3 and 5), promise to revolutionize the transport system. The possibility of driverless relocations  
4 in shared vehicle systems, a substantial cost reduction in public transport operations (2), and  
5 driving transformed into productive time are just a few of the revolutionary features expected  
6 from AVs (for a comprehensive overview see (3)).

7 Such fundamental changes of the transport system were topics of early papers on AVs (e.g.  
8 (3–5)). Recently however, the focus shifted to more detailed questions. While insight on the  
9 required fleet sizes to serve a city (6–10), or the organization of new services (11–14) is back-  
10 ground knowledge on the possibilities offered by AVs, they are years, maybe decades away from  
11 implementation.

12 Thanks to this background knowledge however, it is now possible to return to the fundamental  
13 question of transport system organization: Given all these new opportunities, but also given the  
14 current system as a starting point, and given financial and political constraints, how should the  
15 future transport system best be organized?

16 This paper aims to assess different possibilities AVs allow for future transport services given  
17 their benefits and costs for society. It evaluates policy measures available to policy makers to  
18 influence and shape the transport system, in order to make the most out of the benefits AVs  
19 could possibly bring.

20  
21 Finding a preferred combination of policy measures is a classic optimization problem (15–  
22 17). A target function is evaluated in a multi-dimensional space of possible measures and their  
23 respective implementation ranges. It is evaluated in an appropriate model of the transport system,  
24 meaning that it has to be able to represent the system dynamics and responses to the proposed  
25 policy measures. At the same time, it should be fast enough to test many policy combinations.  
26 While an appropriate model is certainly most important, another fundamental part is the defini-  
27 tion of the possible policies (15). Policy makers have the following possibilities to influence  
28 the transport system: Through direct management they can optimize the usage of existing  
29 infrastructure (e.g. traffic management), or, assumed sufficient financial means, they can provide  
30 new or extend infrastructures and/or public transport services. Using taxes (incl. mobility  
31 pricing) and subsidies, they can change the costs of certain modes versus others and of the  
32 transport system overall, and using legislation, they can regulate the organization and usage of  
33 the transport system (e.g. speed limits, priority lanes, etc.). And finally yet importantly, using  
34 advertising campaigns, they can (try to) influence general attitudes towards different modes.

35 The third element is the definition of the target function. The goal of any transport system should  
36 be to move people and goods fast, cheap, easy, safe, and sustainable. An optimal transport  
37 system maximizes all these targets at the same time. However, as long as safe and cheap  
38 beaming is not possible, trade-offs need to be assessed and priorities need to be set. While  
39 endless variations in target weighting exist and any choice can be debated, the list of goals per  
40 se is manageable and indicators can be found (18).

41 In summary, as literature shows (15–17), combining the available possibilities to influence the  
42 system with a comprehensive target function and an appropriate transport model effectively  
43 allows identifying high-performing transport policy strategies.

44  
45 While the above is an established methodology, attempts applying it to investigate how a  
46 socially beneficial AV based transport system could and should look like are very limited so far.  
47 Literature is so far mostly restricted to either describing the system qualitatively or focuses on  
48 detailed, mostly operational questions.

1 This study is an attempt to fill this gap. Starting from the current system and considering  
2 financial and legislative constraints, this paper focuses on policies to influence the price of  
3 existing transport services and the organization of future, AV-based transport services. Given the  
4 importance of the value of travel time in AVs, but also its uncertainty, these policies are tested  
5 against three assumed perceived travel times in AVs.

6 This set is evaluated against two performance indicators (instead of a single target function).  
7 These are the total travel time of all trips in the area, representing the "output" of the transport  
8 system, and total vehicle kilometers traveled (VKT) representing the costs required and external-  
9 ities produced.

10 The methodology is applied to the region of Zug, Switzerland. The region is modeled with  
11 an agent-based transport model (MATSim, (19)), which, given its ability to represent single  
12 individuals (agents), is particularly suitable to investigate the impact of policy measures. In fact,  
13 the impact at the systemic level is the consequence of individual reactions to the policies.

14  
15 In this paper, the next section describes the methodology, the chosen policy measures and  
16 objectives in more detail. The section *Transport Model* introduces MATSim and describes the  
17 Zug model. Next, specific sections present, and discuss the results. The section *Conclusion*  
18 presents policy recommendations based on the results and concludes the paper.

## 19 **METHODOLOGY**

20 The methodology followed was proposed by May et al. (15) for the development of optimal  
21 integrated transport policy strategies. They applied it to different European cities to evaluate  
22 combinations of transport policies. Here, given that it is unknown when AVs will be available  
23 and to account for the many other uncertainties on the future transport system, a simplified  
24 version of the original methodology is used. The temporal aspects of the policy measure staging  
25 are neglected and the policies are less detailed.

26  
27 The methodology consists of three parts:

28 First, development of possible policy measures including a respective range for each policy.

29 Second, definition of an appropriate objective function that evaluates how well different combi-  
30 nations work.

31 Third, their application in a model of the transport system.

32 With an analysis of the full policy ranges, not only the preferred strategy can be identified,  
33 but also the transport system's sensitivity to the different individual policy measures can be  
34 evaluated. The model used is a MATSim scenario of the Swiss area of Zug. An introduction to  
35 MATSim and a description of the scenario follows in the next section.

## 36 **Policy Measures**

37 The selection of policy measures depends not only on the system characteristics, but also on  
38 external restrictions. On top of the obvious ones, such as physical feasibility and financial  
39 restrictions, the required political support is also a major condition, if not the most important  
40 one. The policy measures proposed here were designed and selected with this in mind.

41 As mentioned earlier, the number of possible ways for policy makers to influence the transport  
42 system are limited. Investments in services or infrastructure, influencing price through taxes (incl.  
43 mobility pricing) or subsidies, legislative measures, direct traffic management, and advertisement  
44 campaigns are the main ones. The policies investigated are selected from this set. Most policy  
45 measures allow for a continuous or near-continuous range in their application. For simplicity

1 however, only discrete levels were investigated here.

## 2 *Policy Measures for Existing Modes*

3 Existing modes include mass transit public transport (PT), the slow modes (SM) walk and bike,  
4 and motorized individual transport (MIT). For PT and MIT, the respective autonomous version  
5 is assumed (aPT and aMIT).

6 The two policy measures aPT pricing and aMIT pricing were selected. Other possible measures  
7 are not further investigated either for their political and/or financial feasibilities (e.g. infrastruc-  
8 ture projects), or for their impact being difficult to quantify (e.g. advertisement campaigns). A  
9 closer investigation of other possible measures is part of future work.

10 These two are complemented by different assumptions on the possible comfort changes through  
11 automation.

- 12 • *Pricing of aPT* represents any policy measures increasing or decreasing the user price  
13 of aPT. The main policy lever is the level of subsidies. The automation of aPT (busses)  
14 was estimated to half its production cost (2). As today subsidies cover 50% of the cost of  
15 Swiss PT (20), the following three levels of aPT subsidies are investigated: No subsidies,  
16 which results in the same price for aPT as for PT today (0.27 CHF/km (2)); the same  
17 relative level of subsidies (50%) as today, which results in half the price for aPT as for PT  
18 today (0.13 CHF/km); and the same absolute level of subsidies as today, which results in  
19 a free at the point of use aPT.
- 20 • *Pricing of aMIT* aims at increasing or decreasing the average cost per distance for aMIT.  
21 The main policy instruments to achieve this are taxes (e.g. on fuel or vehicles) or mobility  
22 pricing (for areas or road categories). Bösch et al. (2) found the cost of aMIV to be similar  
23 to today's MIV costs. Therefore, two possibilities were assumed here: first, a similar level  
24 of taxes and/or mobility pricing as today which results in the same marginal cost of aMIV  
25 as MIV today (0.18 CHF/km (2)); and second, new taxes or mobility pricing for aMIV in  
26 the range of 25% of today's cost of MIV, resulting in 0.22 CHF/km.
- 27 • *Comfort changes of aMIT* is not actually a policy measure, but represents the expected  
28 benefit of autonomous driving technology to transform driving into productive time. It  
29 thus reduces the negative value of travel time (VOT) in aMIT. Three levels are investigated  
30 here: The same VOT as today, that is as if driving (23.29 CHF/h (21)); the same VOT  
31 for aMIT as for PT (14.43 CHF/h (21)); and, given that other passengers represent for  
32 most people a negative factor of traveling with PT (22), a 25% lower negative VOT for  
33 the individual aMIT as for PT, resulting in 10.82 CHF/h.

## 34 *Organizational Form of Future Modes*

35 Future modes represented here are all based on autonomous taxis, which can be operated as a  
36 traditional taxi service (aTaxi) or as a ride-sharing service (aRS). They can be operated by a  
37 public agency or by a private company, which can provide different comfort and price levels.  
38 Other models and forms of future modes, such as for example autonomous mini-buses, point-to-  
39 point shuttles, etc. are neglected here.

40 The future form of organization of such services is an important question policy makers should  
41 start to think about. If they will wait too long before taking action, the market will organize  
42 itself. This might result in a suboptimal system from a societal point of view.

43 To represent these different forms of organization, the following services are proposed as "policy  
44 measures": a monopoly aTaxi service, a monopoly aRS service, and an oligopoly in which six

1 different services compete (3 aTaxi and 3 aRS).  
 2 Following the above assumptions, negative VOT is assumed to be the same for aRS as for PT,  
 3 while for aTaxis it is assumed 25% less negative (more comfortable). The monetary prices per  
 4 passenger kilometer (PPKM) for the services follow (2). The fleet sizes for the services were  
 5 estimated based on (10). They found that for a good level of service, one aTaxi could replace  
 6 four private cars. Here, the monopolist's fleet was expected to serve 25% of the population  
 7 with such a level of service. Therefore, 25% of 25% of the current car fleet of Zug (96'000  
 8 (23)) results in 6'000 aTaxis. For aRS, a 33.3% smaller fleet was assumed (4'000 vehicles).  
 9 In the competitive situation, each of the services is assumed to have a fleet of one third of the  
 10 respective monopolist (rounded up to the next 500 vehicles). This results in total 6'000 aTaxis  
 11 and 4'500 aRS AVs in the area, which increases to total fleet by 75% resp. 162.5% compared to  
 12 the monopolistic cases. This is realistic, as each service requires a substantial fleet to offer a  
 13 good service in the area.

14 This results in the following four cases:

- 15 1. A *monopoly* service offering 6'000 aTaxis for *individual transport* (VOT: 10.82 CHF/h,  
 16 PPKM: 0.46 CHF/km).
- 17 2. A *monopoly* service offering 4'000 AVs for *ride-sharing* (VOT: 14.43 CHF/h, PPKM:  
 18 0.30 CHF/km).
- 19 3. An *oligopoly* of services, represented here by six services, three different experiences  
 20 (VOT as above, -25%, and +25%) and matching prices (price as above, +25%, and -25%)  
 21 and each with aRS (1'500 vehicles per service) or as aTaxis (2'000 vehicles per service).  
 22 4. No AV-based service (base case).

23 This results in  $(3 \times 2 \times 3 \times 4 =)$  72 different transport scenarios. The policy measures and their  
 24 ranges, as well as the assumed levels of comfort of aMIT are summarized in Table 1.

**TABLE 1 Overview of the policy measures investigated in this paper.**

| Policy measure          | Level 0   | Level 1           | Level 2         | Level 3  |
|-------------------------|-----------|-------------------|-----------------|--|
| Pricing of aPT          | No change | -50%              | -100%           | -  |
| Pricing of aMIT         | No change | +25%              | -               | -  |
| Comfort changes of aMIT | No change | as PT             | as PT - 25%     | -  |
| Future modes            | None      | Monopoly<br>aTaxi | Monopoly<br>aRS | Oligopoly<br>(6 services:<br>3 comfort-price levels,<br>aTaxi / aRS) |

## 25 Performance Indicators

26 Instead of a single objective function, two performance indicators are used. The first, total  
 27 travel time (TT), represents the performance of the system in providing access to activities. The  
 28 second, total vehicle kilometers traveled (VKT), represents monetary costs and externalities  
 29 of the transport system (18). While more detailed analysis is required for the assessment of  
 30 individual solutions, the reduction to these two indicators allows comparing the solutions without  
 31 politically influenced weights (as it would be the case for single target function values).  
 32

1 Total VKT are often used in transport studies as the direct and single indicator to calculate  
2 various costs of the system. Examples range from the pure monetary cost (fuel and vehicle cost  
3 per VKT), health cost (accidents per VKT), negative externalities (noise per VKT), to ecologic  
4 costs (e.g. CO<sub>2</sub> per VKT) (18). Here, for each case, the total VKT are provided directly as a  
5 proxy for the overall cost of the transport system. They are calculated as the sum of VKT of all  
6 modes.

7  
8 The total TT of all trips in the analysis area represents the transport system's performance  
9 in providing access to activities. It serves as an illustrative and direct indicator for the per-  
10 formance as the number of trips and their origins and destinations remain constant across all  
11 scenarios.

12  
13 For the monopolist scenarios, profitability represents a third factor. It is calculated by multiply-  
14 ing the total passenger kilometers of the AV service with the passenger price and comparing  
15 this to the cost per VKT multiplied with the total VKT of the service. Profitability indicates the  
16 requirement for subsidies under the proposed pricing scheme.

## 17 **TRANSPORT MODEL**

### 18 **MATSim**

19 The transport model used here is a MATSim model. MATSim, an agent-based transport model  
20 (19), is chosen for its suitability for the evaluation of transport policies targeting individuals and  
21 their traveling decisions and because of its computational performance.

22 MATSim uses a co-evolutionary, iterative optimization process to identify the user equilibrium  
23 of a transport system. A population of agents with daily plans, listing activities to be executed  
24 and routes and modes to get from one activity location to the next, represents transport demand.  
25 Each iteration, a random sample of agents can mutate their plans (change modes, routes, or  
26 departure times). Then, the transport simulation simulates a full day with all agents executing  
27 their daily plan. A queue model is used to simulate traffic (24). After the simulation, each agent  
28 scores his plan with a scoring function. It rewards activity time and punishes travel time and  
29 cost. During the iterative process, plans with good scores are kept, while plans with bad scores  
30 are discarded.

31  
32 The MATSim functionality particularly important for this study, is the simulation of AVs  
33 (14, 25). In the basic configuration used here, it simulates AV-based taxi services organized  
34 by a central dispatcher. Agents, which would like to use a taxi, place a request at the central  
35 dispatcher, which looks for the closest free taxi and assigns it to the agent. The taxi serves the  
36 agent and waits at the agent's destination for the next assignment. Relocation is not included.  
37 The taxis are initially placed based on population density.

38 Additionally, it also allows for the simulation of ride-sharing (25). With ride-sharing, as long as  
39 the first passenger's additional travel time remains less than a given threshold (here 800 seconds),  
40 the dispatcher can pool another passenger.

### 41 **Region of Zug**

42 The city of Zug is a mid-size town located about halfway between Zurich and Lucerne. It has  
43 29'000 inhabitants and is the capital of the canton of Zug with 120'000 inhabitants (23). The  
44 canton approximately represents the agglomeration of Zug (26).



1 From a simulation point of view, Zug is very suitable for this study as it is a large enough town to  
2 have its own agglomeration and its own public transport system (27) densely covering the main  
3 settlement area (Figure 1), but also small enough to allow for quick computation times even  
4 if the full population is represented by agents. This representation is required to get realistic  
5 results on the usage of public transport and taxi services (28).

6 Additionally, Zug attracts increasing attention for transport experiments in Switzerland. It was  
7 selected for an AV shuttle experiment by the Federal Swiss Railways (29). Starting summer 2017,  
8 an AV shuttle will connect Zug main train station with a nearby research campus. Recently, the  
9 canton of Zug was also selected by the Swiss Federal Government for a study on the potentials  
10 and the possible effects of mobility pricing (30). A study on future transport systems and suitable  
11 transport policies for Zug is therefore a good fit with these events.

## 12 **MATSim Model of Zug**

13 The MATSim model of Zug used for this study is cut from a recently developed 2015 MATSim  
14 model for Switzerland (see (31) for a detailed description). The model covers all agents having  
15 their home within the area, that is the agglomeration of Zug (Figure 1), and all agents of the  
16 full Switzerland scenario which have an activity in the area or pass through the area. Within  
17 the area, the modeled infrastructure (street network, public transport, facilities) is fully detailed  
18 as described in (31). Outside of the area, the street network is modeled on the level of arterial  
19 roads (capacity min. 1'000 veh./h) and public transport is reduced to rail lines only. AV services  
20 are restricted to trips within the area and empty rides with private AVs are excluded.

21  
22 The scenario represents the full population, which means that every agent in the simulation  
23 represents one real person (assuming no error in the available statistics). In 2015, the population  
24 of canton Zug consisted of 117'695 persons (23). To avoid border effects however, analysis  
25 of the simulations is focused on the densely populated main settlement area of Zug and its  
26 inhabitants only ((32), outlined in Figure 1).

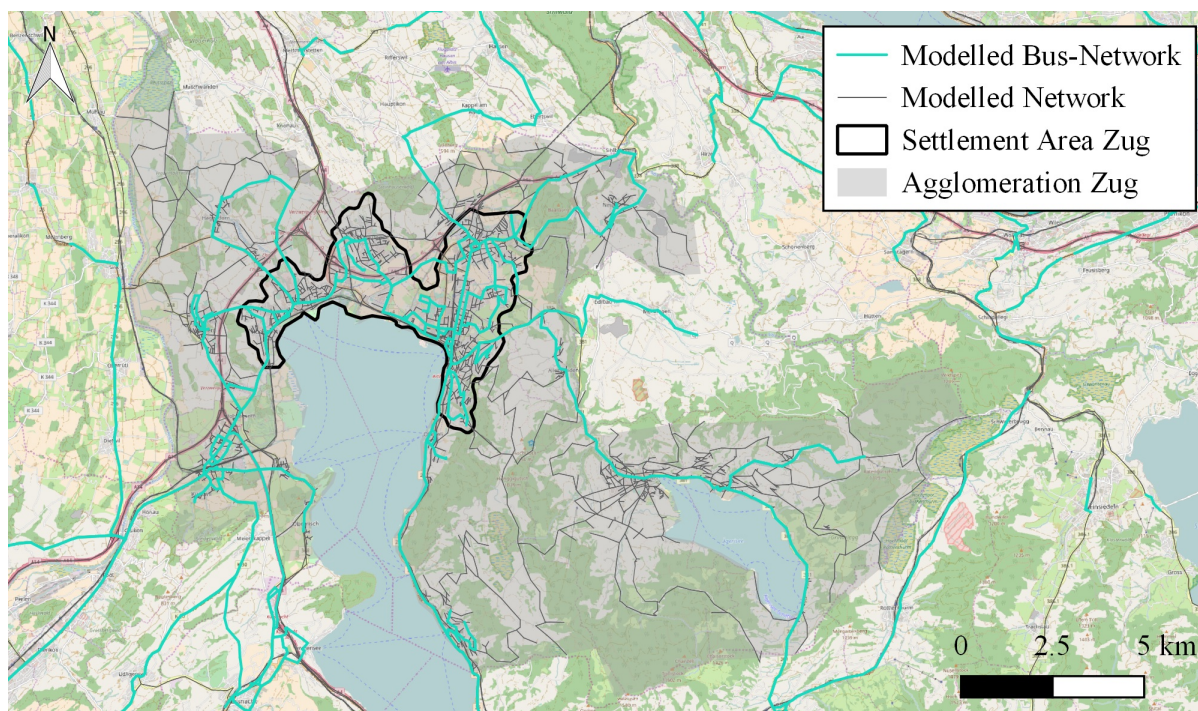
27 In the baseline scenario, the trip-based modalsplit of these agents is 14% PT, 42% MIT, and  
28 44% SM. Compared to the official statistics (14% PT, 37% MIT, 48% SM, (33)), there is a  
29 slightly higher use of MIV at the expense of SM. This is balanced however, by the average  
30 distance traveled per agent per day with 8km/d PT, 21km/d MIT, and 3.1km/d SM compared to  
31 the official 7km/d PT, 26.6km/d MIT and 3.5km/d SM (34). This leads to the conclusion that the  
32 model fits well and that the deviations are likely due to the different sampling processes. This is  
33 further supported by the reasonably fitting average speeds (Model: 17.3km/h PT, 48.7km/h MIV,  
34 2.6km/h SM; (34): 20.2km/h PT, 46.9km/h MIV, 5.9km/h SM).

## 35 **RESULTS**

36 In total 72 scenarios were simulated. Each simulation was run for 250 iterations. This is a low  
37 number of iterations for MATSim runs but considered sufficient for an indication of the system  
38 development. Nevertheless, results indicate that AV-based services might gain more mode share  
39 until user equilibrium. The following results should therefore be seen as conservative indications  
40 on the user potential of AV based services.

## 41 **Organizational Forms of Future Modes**

42 This subsection compares all scenarios. It focuses on the performance of the different organiza-  
43 tional forms of the AV based services. For each scenario, Figure 2 presents the total TT of all



Source: Background from openstreetmap.org

**FIGURE 1 Zug area.**

1 agents versus the total VKT in the area, differentiating the scenarios based on the organizational  
2 form of the AV based service.

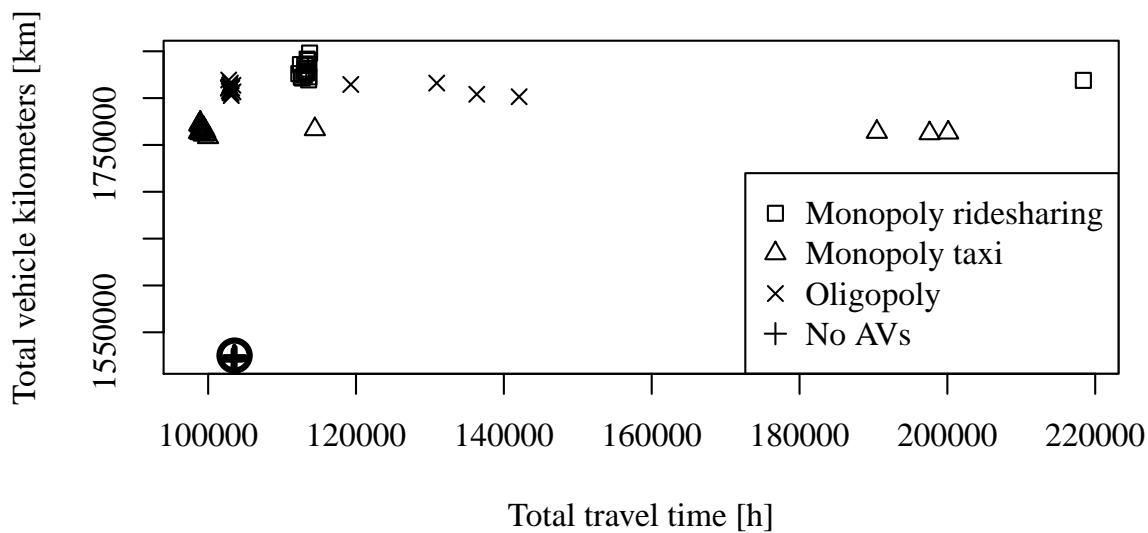
3 Figure 2, especially Figure 2(b), shows that monopoly aTaxi services have the potential to  
4 reduce TT. But this improvement comes at a great cost: 4.1% reduction in TT for 16.0% increase  
5 in VKM (averages across all combinations without outliers). The other policy configurations  
6 show a similar increase in VKM, but they are not able to reduce the overall TT. With aTaxis,  
7 the expected pick-up and drive time are 2.6 minutes and 2.4 minutes, while for aRS these are  
8 12.4 minutes and 10.9 minutes, despite similar served average Manhattan trip distances (aTaxi:  
9 1.28km, aRS: 1.32km). The reason is that, in its current implementation, aRS gives always  
10 priority to bundling of trips vs. single trips, even if this means substantial detours. Oligopolies,  
11 consisting of both aTaxi and aRS services, lie in between the other two clusters.

12 The tight clustering of configurations shows that the chosen organizational model is the most  
13 important determinant for future performance of the system. Other policy measures (price of  
14 aMIT and aPT, VOT of aMIT) appear to have only a minor effect within the cluster.

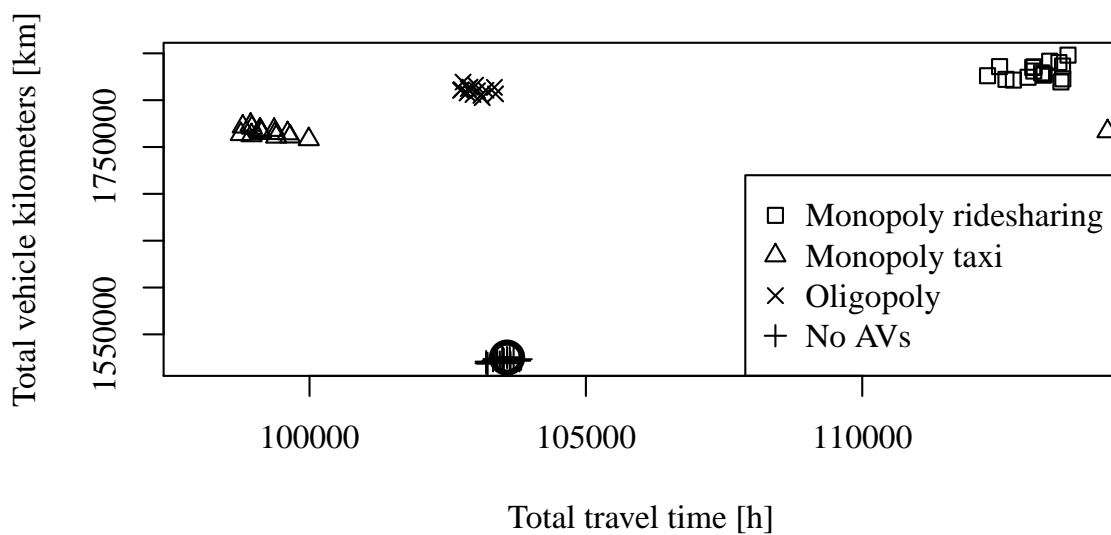
15 Several AV scenarios produce substantially more TT than the rest of their service's cluster. These  
16 are considered outliers. Analysis showed that major traffic congestion was the reason for these  
17 outliers. No clear common reason could be identified however, which indicates that, independent  
18 of the chosen policy measures, the additional VKM are bringing the system generally closer to  
19 breakdown (major congestions) with occasional tipping.

## 20 Effect of Policy Measures on Total Travel Time

21 To analyze the effect of the different policy measures, Table 2 presents a multiple linear regression  
22 analysis of all scenarios except the outliers. The system performance, i.e. total TT, is the response  
23 variable of the model. The model shows that, as expected from Figure 2, indeed the influence of



(a) Complete set of configurations.



(b) Focus on main configuration clusters.

**FIGURE 2 TT-VKT trade-off by market configuration (reference scenario, i.e. no AV service and no policy implemented, highlighted with a circle).**

**TABLE 2 Multiple linear regression analysis of total travel time with policy measures as variables (outliers excluded from analysis).**

| Coefficients                    | Estimate  | Std. Error | t value |     |
|---------------------------------|-----------|------------|---------|-----|
| (Intercept)                     | 103665.31 | 373.51     | 277.54  | *** |
| Price of aPT                    | 85.11     | 97.24      | 0.87    |     |
| Price of aMIT                   | -247.46   | 322.63     | -0.76   |     |
| VOT of MIT - PT                 | 109.63    | 102.65     | 1.06    |     |
| VOT of MIT - PT_plus            | 64.68     | 98.64      | 0.65    |     |
| AV organization - RS monopoly   | 9672.90   | 107.73     | 89.79   | *** |
| AV organization - Taxi monopoly | -4276.57  | 114.02     | -37.50  | *** |
| AV organization - Oligopoly     | -492.51   | 113.87     | -4.32   | *** |

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.05 '.' 0.1 ' ' 1

1 the organizational models is highly significant while the other measures have no statistically  
 2 significant effect. This is surprising as the interventions are substantial. It seems that, at least  
 3 within the degrees of freedom of the model (e.g. no activity location adaptation), neither a  
 4 substantial price reduction of aPT (-50% and -100%) could significantly reduce the total TT, nor  
 5 could a substantial increase in the price of aMIT (+25%).

6 Concerning the observed relations, the model represents expected associations. A reduction of  
 7 the price of aPT seems to lead to lower travel times (positive estimate), while a reduction of the  
 8 price of aMIT increases total TT (negative estimate). Also, an increase in attractiveness of aMIT  
 9 (i.e. decrease in VOT) leads to the expected decrease in total TT (positive estimate).

## 10 Monopolist aTaxi Strategies

11 Under the chosen pricing scheme and the provided fleet sizes, none of the aTaxi monopolists  
 12 could operate profitable. Excluding the outliers from the analysis, the average passenger trip  
 13 with an aTaxi was 1.84km long. To serve this trip, the average pick-up distance (driving distance  
 14 from the closest free aTaxi to the passenger) was 2.13km, leading to a productive to total VKT  
 15 ratio ( $= \frac{1.84km}{1.84km+2.13km}$ ) of 46%.

16 Here, for a more detailed picture, the neutral aTaxi monopolist scenario is compared to the  
 17 reference scenario. The neutral scenario is chosen to avoid random influences of other policy  
 18 measures (see above). By multiplying the total travel time of each mode with its VOT, the  
 19 TT improvement of the aTaxi scenario vs. the reference scenario can be monetarized. This  
 20 approach results in perceived travel cost savings of CHF 185'000 per day. These savings  
 21 could be obtained by accepting an increase of 15.7%, i.e. 240'000 km, in VKM per day. The  
 22 modalsplit of the aTaxi scenario is 32.9% aTaxi, 35.5% car, 11.7% PT, and 19.9% slow modes.  
 23 Compared to the reference scenario (47.9% car, 16.0% PT, and 36.0% slow modes), this means  
 24 aTaxi gains substantially from all three traditional modes, but most from slow modes (16.1  
 25 percentage-points).

## 26 DISCUSSION

27 The results presented in this paper surprise in the sense that literature (e.g. (9, 11)) usually  
 28 assumes - more or less explicitly - that shared AV fleets improve the transportation system. Here,  
 29 comparing different possible systems with shared AVs and especially, comparing them with the

1 case without such services, reveals that such an improvement depends heavily on the chosen  
2 implementation. Additionally, while positive effects of shared AV fleets can be expected, e.g.  
3 12.4 percentage points of mode share switching from private cars to aTaxis which would result  
4 in a substantial fleet size reduction (10), they might also come with a great cost in additional  
5 VKM, and an increased risk for congestion as suggested by the presence of the outliers. The  
6 additional VKT originate from empty rides, but also from substantial mode share changes from  
7 the VKM-neutral modes aPT and SM to aTaxis (16.1 percentage points from SM and 4.3 from  
8 aPT).

9 The example of Uber in Manhattan (35) indicates that this is indeed a valid observation. There,  
10 additional empty miles by Uber taxis combined with attraction of former pedestrians or PT users,  
11 led to an increase of VKT in a system already operating at its limits and thus a worsening of the  
12 overall situation.

13  
14 Another surprise from the results is that policy measures (pricing of aMIT and aPT and reduction  
15 of VOT of aMIT), while showing the expected relations, seem to have no statistically significant  
16 effect on the total TT - or at least a negligible one compared to the chosen implementation of  
17 AVs. This was certainly expected differently and will be subject of future work.

18 The same applies to the observation that aRS services reached substantial mode shares (in  
19 average 13%) despite being very inefficient (8.4km of average driving distance for trips with an  
20 average Manhattan origin-destination distance of only 1.3km). While this indicates a remarkable  
21 attractiveness of these services, it also shows the importance of careful system and pricing  
22 scheme design. The latter further emphasized by the non-profitability of the aTaxi services.

23  
24 This leads to the discussion of the transport model. Even though the transport model sce-  
25 nario reproduces the existing transport situation well, parameter choices and design of the  
26 offered AV based services indicate future work. The fleet sizes were estimated based on an  
27 educated guess. As required fleet sizes heavily depend on local context (e.g. car ownership  
28 rates, spatial structure, PT infrastructure), a more in depth analysis of the required fleet size will  
29 be part of future work. The same applies for the chosen level of prices. Although based on a  
30 detailed estimation (2), the assumptions leading to the estimated prices did not fully apply to the  
31 scenario at hand and are, together with the sub-optimal fleet sizes, a suspected reason for the  
32 non-profitability of the aTaxi services. The simulation of the AV fleets themselves is - up to now  
33 - also rather simple. Relocation to minimize pick-up distances and more complex assignment  
34 algorithms are in development and might be applied to future studies.

35  
36 These limitations should be considered when interpreting the results. But nevertheless, the  
37 results represent valuable indications that the introduction of services based on shared AVs  
38 might come with considerable additional VKM and not always with an improvement of total  
39 TT. Having systematically reached this conclusion certainly adds to the present discussion on  
40 possible AV based services.

## 41 CONCLUSION

42 In this paper, different policy measures for future transport systems were investigated. They  
43 included different levels of subsidies for aPT, of pricing of aMIT, and different organizational  
44 frameworks (monopoly vs. oligopoly) for AV based services (Table 1). This was complemented  
45 with different assumptions on the future VOT of aMIT, which means how comfortable private  
46 AVs will be.

1 Following (15), different possible combinations of these policies and assumptions were simu-  
2 lated in a scenario of the agglomeration of Zug, Switzerland, using MATSim (19). Zug is small  
3 enough to allow simulating the substantial number of scenarios, but large enough to produce  
4 relevant outcomes.

5 The results of these simulations showed that scenarios including AV services, independent of  
6 their organizational form, increased total VKM substantially (Figure 2). More VKT means more  
7 externalities, more intense infrastructure usage, and a less SM friendly environment. Reasons  
8 for this increase are, besides empty pick-up rides, substantial mode shifts from aPT and SM to  
9 AVs. If these additional VKM and mode shifts are accepted however, AVs have the potential to  
10 reduce total TT. Even without sophisticated pricing, vehicle relocation, etc., here, CHF 185'000.-  
11 per day in reduced travel time cost could be achieved with aTaxis.

12 Focusing on the accompanying measures, the results did reveal the expected effects; price  
13 reduction of aPT and price increase in aMIT each leading to a decrease in total TT, while a  
14 reduced travel time burden in aMIT leads to an increase in TT. These effects however, could  
15 only be observed in a statistically non-significant range (Table 2).

16  
17 In terms of policy recommendations, these results suggest to be careful with new AV based  
18 services. Policy makers are well advised to be critical about promises of such new services and  
19 to evaluate in detail how they fit into their particular transport system. While having the potential  
20 to reduce total TT and costs (as for example also shown by Merlin (36) for Ann Arbor), they  
21 likely increase traffic. This increases the risk for traffic jams and additional waiting times for  
22 customers and other traffic participants. A real life example for this is what happened with Uber  
23 in Manhattan (35). In this sense, the results also suggest policy makers and society to prepare  
24 for an "it will get worse before it gets better".

25 Small-scale experiments with AVs and the development of new services are to be encouraged as  
26 long as it does not cause too much additional traffic and does not disturb the existing system.  
27 When the day for large-scale introduction comes, policy makers should be aware however, that  
28 such a system would likely represent a very attractive competitor for existing PT solutions and  
29 SM.

30 Until this day comes however, policy makers are suggested to use the benefits of automation for  
31 the improvement of the existing system - a finding also supported by other recent studies (37, 38).

32  
33 To conclude, it might not be as clear that services based on shared AVs will actually improve  
34 the overall performance of the system as often suggested. The existing system has grown  
35 and evolved during the past century. It is about 100 years, since affordable private cars came  
36 on the market, and thus the last major "game changer" in transport was introduced. Since  
37 then the system has been improved and a good balance between externalities, affordability  
38 and accessibility has been found which has supported the economic growth experienced in the  
39 decades since. If empty rides of private autonomous cars can be prevented or at least kept within  
40 reasonable limits, the results of this study suggest that the existing balance between mass transit  
41 and private transport is very suited to serve the current society and its spatial distribution. New  
42 services might lead to new spatial distributions leading to new requirements, which they will be  
43 more suitable to serve, but until then, one needs to be careful with what is to lose, when thinking  
44 about what could be won.

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