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Pooling and its behavioural foundations

Verhaltensbezogene Grundlagen und Potenzial von Ride Pooling mit autonomen Fahrzeugen in der Schweiz

Bases comportementales et potentiel du covoiturage avec des véhicules autonomes en Suisse

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Summary

Overview and objective

Digitisation will significantly change future mobility. Services, as well as vehicles, will increasingly benefit from this digitisation. The advent of autonomous vehicles (AVs) provides policy-makers, manufacturers and consumers use of autonomous opportunities while they have to accept their risks. AVs are expected to increase traffic safety and allow for more efficient use of the road network due to shorter headways. At the same time, AV could also generate empty vehicle kilometres traveled and increase the demand for car travel. Not only can the time for driving be spent otherwise (e.g., working, reading, etc.), but AV will also increase the access to transport services for a broader audience. The likely significant increase in traffic volume can pose major problems (e.g. congestion, noise, pollution etc.), especially in urban regions.

Ride-pooling, combined with AV technology (aRP), has the potential to combine the advantages of public transport (higher vehicle occupancy) and private vehicles (direct trips) and hence allows for substantial accessibility gains, especially in rural areas and during times of the day for which conventional public transport services cannot be efficiently operated. In addition, the transition from aRP into a normal bus service is gradual as the vehicle becomes larger and the timetable/route becomes more regular. At the same time, it is likely that commercially operated AV fleets will offer not only ride-pooling but also ride-hailing (aRH) services, where travelers are picked up from a single point of origin and transported directly to their destination, much like a taxi today.

Neither the acceptance nor the operation of aRP are sufficiently well understood. From a long-term planning perspective, the understanding of the factors influencing the choice of travel using aRP and tools to model demand and supply of aRP are incomplete and therefore addressed in this research which pursues the following objectives:

1. Investigating the willingness-to-share (i.e., ride-pooling) for Switzerland, discovering the relevant drivers and barriers of ridepooling with and without driver.

2. Quantifying travel behavior associated with ride-hailing and ride-pooling services provided by autonomous vehicle fleets by designing and implementing a new stated preference survey.

3. Developing optimal planning/dispatching algorithms that allow for dynamic pick-up and drop-off locations to improve overall travel times.

4. Incorporating survey results into an agent-based transport demand model of Switzerland and pairing the choice model with operational characteristics, e.g., vehicle type and size, pricing, waiting time, access and travel time and vehicle occupancy.

Qualitative study

A qualitative approach was used to explore drivers and barriers that determine the usage of aRP. The main objective was to identify relevant determinants of the intention to adopt aRP in the future. A further objective was to pretest information materials for the explanatory videos in the stated choice survey. Semi-structured qualitative interviews were conducted and narrative storytelling and projective interview techniques were used to uncover implicit attitudes and perceptions.

The interviews were analyzed in a two-step process along the procedure of a structured content analysis. Interviews were first coded by two independent coders along the determinants derived from a theoretical background. In a second step, additional codes were assigned when necessary.

The results of the qualitative interviews confirm the relevant psychological factors determining the acceptance of ridepooling found in previous research. They can be structured

along the technology acceptance model based on the Unified Theory of Acceptance and Use of Technology. The qualitative interviews reveal many relevant factors concerning performance expectancy (perceived usefulness) that determine the acceptance of aRP. These are determinants such as safety of the concerning technology, waiting time and travel time, environmental considerations, reliability, flexibility, availability, or comfort. Notably, none of these factors are distinctly perceived as a barrier or a driver. For example, there is a controversial perception of safety: aRP is perceived as an unsafe technology that is associated with risks, as much as it is perceived as a safer transportation mode as compared to conventional cars driven by humans. In this way, all of these factors have been associated with motivating arguments and demotivating arguments.

For some factors (time, flexibility, availability, comfort, and environmental considerations), the classification as barrier or driver depends on whether ridepooling is assessed relative to a private car or public transport. For example, a private car is perceived as more reliably available than ridepooling in autonomous vehicles (hence availability is perceived as a barrier); but ridepooling in autonomous vehicles is perceived as more flexibily available than public transport (hence availability is perceived as a driver). For time, flexibility, availability, and comfort factors, this comparison leads to a favourable evaluation of ridepooling in comparison with public transport and an unfavorable perception when compared with a private car. Another relevant factor is reliability. Our research underscores the importance of reliability, particularly in the Swiss context, where public transport is punctual.

With regard to effort expectancy, the factors and the derived arguments are less controversial. Factors such as planning and information on the app are clearly perceived as drivers. These are also the most frequently mentioned factors. The concerns related to perceived ease of use appear to be smaller than the perceived benefits.

Concerning perceived costs, we observe the same mechanisms as described for some of the performance factors: ridepooling in autonomous vehicles is perceived as more expensive than public transport and as cheaper than a private car.

Finally, social aspects have been discussed with regard to security as much as with regard to socializing. Surprisingly, security was brought up only by a few participants. Regarding an inclusive and accessible transportation system, it is important to consider aspects of security of the public space within an AV.

Stated choice survey

To understand and quantify how aRH and aRP impact travel behaviour, a stated choice survey was conducted. The sample was drawn by a panel of a market research firm with quotas to ensure the respondents represent the target population well, i.e. 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 2 kilometers. Representative quotas were set for car availability, age groups, employment status, sex, language, and spatial type of the residence municipality. Persons holding a national travel card (GA) or regional travel card were oversampled to more reliably test whether people who frequently use public transport differ from other people with regards to aRP and aRH preference.

The survey is composed of two web-based questionnaires which the respondents fill in two waves to allow for a pivot design mode choice experiment. In the first questionnaire, data on regularly conducted utilitarian and leisure trips was collected, as well as information on mobility tool ownership. The second questionnaire included two mode choice experiments which included ride-hailing and ride-pooling alternatives as new modes. Depending on the availability of public transport connections between the origin and the destination of the reported trip, the ride-pooling and ride-hailing alternatives were either defined as a direct trip or intermodal trip.

To ensure a common understanding among all respondents how ride pooling works and can be operated with autonomous vehicles, we produced explanatory videos that the respondents watched before answering the mode choice experiments. In between the two choice

experiments, the respondents were asked to indicate whether they would consider adapting car ownership given a situation were AVs can be privately owned and used by large fleet operators to provide ride-hailing and ride-pooling services. After the mode choice experiment, respondents indicated their willingess to purchase travel cards for ride-pooling services and indicated their attitudes towards ride-pooling.

A key challenge of the pivot design approach was to ensure, through the sampling of reported routes, that autonomous vehicles (AVs) were included in decision scenarios as both mono- and intermodal route alternatives. Furthermore, the experimental design needed to ensure that the decision scenarios presented meaningful trade-offs between the various alternatives while simultaneously reflecting realistic travel time and cost ratios.

Fig. I illustrates the share of the three transport mode alternatives across all decision experiments. It differentiates between cases where car or public transport was used in the reported reference trip and whether the autonomous vehicle alternative was specified as a monomodal or intermodal option.

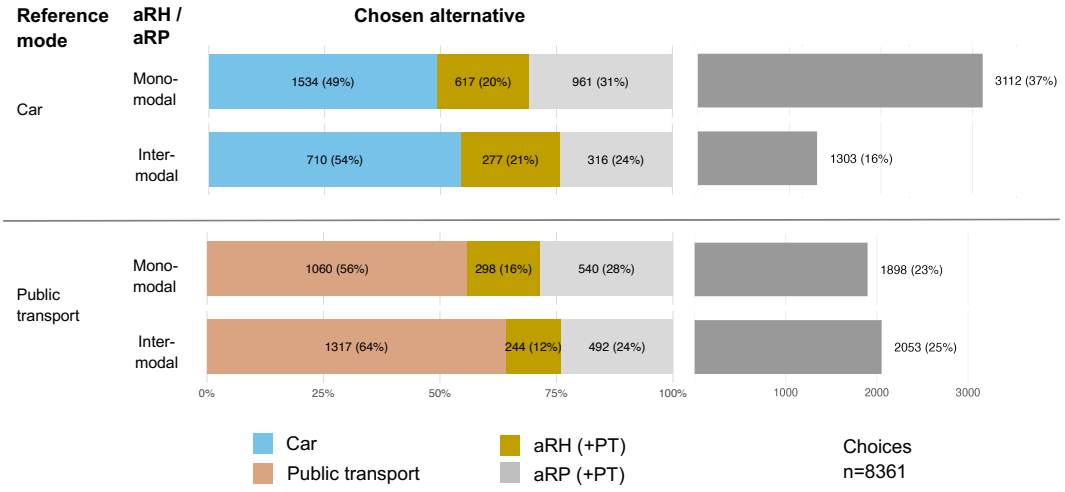


Fig. I *Share of chosen mode alternative by reference mode and trip type*

In approximately 50% to 65% of cases, the mode of transport used for the reference trip was retained. The alternatives aRH and aRP were selected in 12% to 31% of cases. This demonstrates that the experiment design strategy worked as expected and that the sample is suitable for estimating meaningful choice models independent of the reference mode and aRH and aRP trip type. Through careful sample selection, a sufficiently large number of observations was also obtained for each type of decision experiment.

The results of the mode choice model show that travel time is valued more negatively for both aRP and aRH compared to public transport and private cars. The travel time savings offered by these modes relative to public transport, combined with their reduced cost compared to private cars, enable them to attract market shares from both existing modes. This suggests that the benefits of aRP and aRH, in terms of efficiency and cost-effectiveness, position them as competitive alternatives capable of drawing users away from both public transport and private cars.

The negative alternative-specific constants for aRP and aRH alternatives capture the mean of all unobserved effects and hence could be interpreted as a general reluctance among respondents to choose these new modes, which directly affects their anticipated market shares. The constant is less negative for ride-pooling as compared to ride-hailing and among individuals who are more open to mobility innovations compared to the general population. It is reasonable to expect that such reluctance will generally diminish over time as users become more familiar with these new travel modes.

Fig. II shows the value of travel time (VOT) based on travel distance for cars, public transport, and both aRP and aRH, as direct and intermodal trips. For all modes, VOT increases with trip distance which derives from a distance-based elasticity parameter specification. The slopes for car and public transport confirm the findings of earlier studies which show higher VOT values for work than leisure trips and increasing differences between VOT for work and leisure trips by public transport for longer trip distance as compared to car.

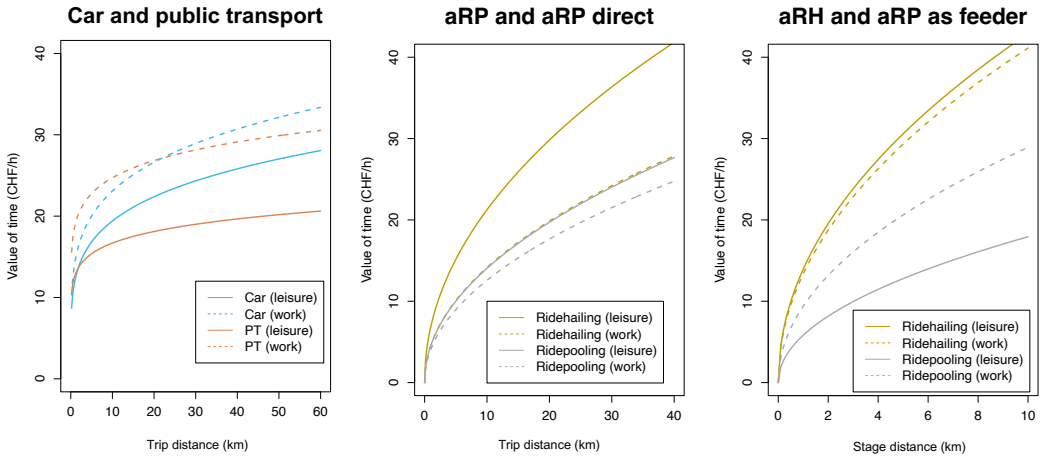


Fig. II *Value of time by mode and trip distance*

The slopes for aRP and aRH as direct modes show a more pronounced increase in VOT values with longer trip distances compared to car and public transport. This suggests that travel comfort with these modes is perceived less favorably for longer trips, which intuitively makes sense: in public transport, different types of vehicles are used to serve various trip lengths, whereas respondents likely assumed that the same type of vehicle would be used for aRP and aRH regardless of distance. For aRP, VOT is higher for utilitarian trips compared to leisure trips. This finding aligns with the results of this and earlier studies regarding car and public transport. The fact that for aRH trips VOT was estimated to be lower than for leisure trips could be explained by the potential to work in an AV while commuting but should be verified in future studies.

The graph indicates that travel time reductions of the feeder segment are generally higher valued as compared to travel time in public transport. This particularly applies to aRH. The respondents might particularly prefer shorter travel times, as this could be seen as reducing the likelihood of missing the connection with the subsequent train segment.

However, certain aspects of the travel experience with aRP and aRH, which differ from existing modes, were not fully captured by the variables describing these alternatives, but may partially explain the observed reluctance. For instance, using aRP and aRH typically requires making reservations through an app, increasing the burden to plan and conduct a trip. Additionally, demand and supply for aRH and aRP fluctuate by time of day and location, creating an aspect of planning uncertainty that can only be partially addressed in stated preference surveys. Furthermore, fleet operators are likely to implement dynamic pricing to manage these fluctuations, which could further increase the planning burden for customers.

The mobility tool experiment reveals a general reluctance to relinquish car ownership, even if fleets of shared autonomous vehicles could provide comprehensive personal mobility without a private vehicle. Fig. III illustrates which shares of respondents who currently have a car available in the household would either give up car ownership or buy an private AV if those became available for purchase at different price premiums against conventional cars.

As expected, the proportion of respondents willing to purchase a private autonomous vehicle is lowest at the highest tested price level. At a premium of CHF 9,000, approximately 10% of respondents expressed interest in acquiring such a vehicle. Interestingly, the highest

percentage of respondents willing to purchase a private autonomous vehicle was 31% at a premium of CHF 6,000. At a premium of CHF 3,000, this share was slightly lower at 26%. Given the relatively small sample size, these differences could be due to statistical error, but they might also indicate varying expectations regarding the technological feasibility of private autonomous vehicles across different price points. The latter argument would also serve as an explanation why the share of respondents to give up car ownership consistently increases with a higher premium.

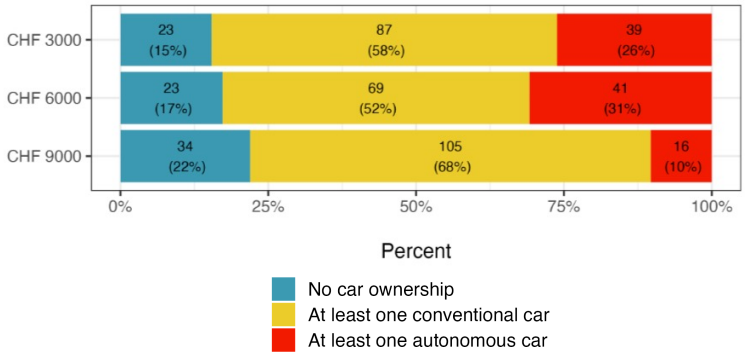


Fig. III *Intention to adapt car ownership as a function of the presented price premium for an autonomous car*

Conversely, respondents exhibited a strong willingness to purchase a discount card for aRP, particularly those who currently use public transport infrequently and do not hold a travel card or only possess a Half-Fare card (see Fig. 15). While some of this effect observed in the survey may be influenced by framing effects, it underscores the market potential for discount cards for both aRP and aRH.

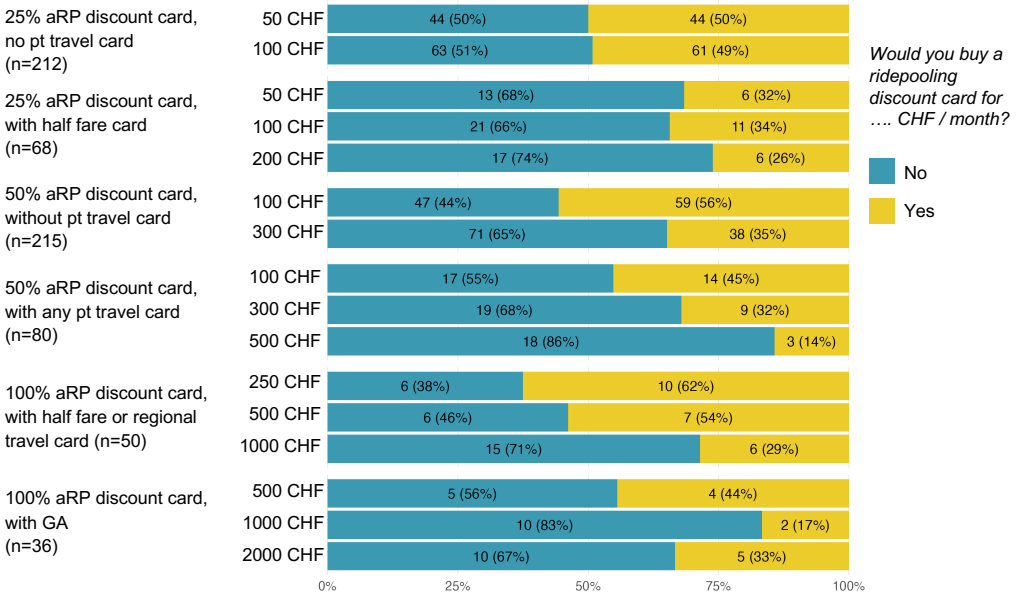


Fig. IV *Intention to purchase an aRP travel card depending on existing travel card ownership and price level*

Optimisation of ride-pooling fleet operation

A versatile real-time simulation framework was developed, which allows us to account for varying traffic conditions when optimizing the allocation of the ride-pooling fleet to the fluctuating demand. This framework incorporates advanced algorithms that can adapt in real-time

to changes in passenger requests and traffic patterns, ensuring efficient use of the fleet.

Using this framework, it was shown, through extensive simulations utilizing online optimization with dedicated solving algorithms, that it is possible to accommodate 97% of taxi rides in Manhattan (New York, USA) using only 2,000 ride-pooling vehicles capable of carrying up to 5 passengers each, instead of the current 13,000 taxis. These simulations demonstrated that the ride-pooling vehicles could maintain a high level of service, as these 2,000 taxis can achieve an average pick-up waiting time of less than 2 minutes and an average in-car delay of less than 7 minutes, which is acceptable for most passengers. This shows that there is substantial potential to improve traffic conditions, reduce congestion, and decrease emissions with limited impact on travel time, if a city decides to limit single-occupancy vehicles and promote shared transportation modes.

However, it also turned out that the integration of this new algorithm into the Multi-Agent Transport Simulation (MATSim) would be a laborious task that could significantly increase computation time due to the complexity of the algorithm and the high computational resources required for real-time optimization. At the same time, the impact on travel demand from the increased operational efficiency provided by the new online optimization is considered limited compared to the algorithms already implemented in MATSim, which are already quite efficient. Therefore, after careful consideration of the trade-offs between computational effort and marginal gains in efficiency, we decided not to employ the new algorithm for the case studies.

Case studies

An agent-based approach was used to evaluate the potential impacts of AVs in three urban regions in Switzerland: Chur, Fribourg, and Zurich, which are obtained by extracting the demand from a nationwide scenario, thus maintaining the through traffic. An agent-based transport model, MATSim, was combined with the mode-choice model estimated from the SP survey data to allow the individuals modeled as agents to make trade-offs between private (autonomous) car, cycling, walking, public transport, and aRH and ride-pooling aRP services. Additionally, a mobility tool ownership model was applied to the population to anticipate the change in vehicle ownership, given the widespread availability of shared autonomous services. Although autonomous vehicles could conceivably also change the range of scheduled public transport services, the case studies do not consider such changes.

For each region, the baseline scenario representing the current transport demand and supply was calibrated to match the mode shares observed in each region. Then, an appropriate fleet size for aRH and aRP services was applied based on the results of the grid search, which ensures profitability while maintaining a high level of demand and user satisfaction. Finally, the fares for aRH and aRP are designed to mimic the car and public transport fares, respectively. The reason being that aRH is considered privately owned and operated to attract high demand, while aRP is part of the public transport operations.

For each studied region, we simulated five scenarios: the current state of the system, the introduction of AVs, and three scenarios with policy measures aimed at pulling and pushing individuals towards more sustainable pooled autonomous service. As decribed in Fig. I), three policy scenarios included pull measures, which provide subsidies for aRP service depending on the public transport quality at the origin or destination, and push measures in the form of the distance-based tax (Chur and Fribourg) and cordon tax (Zurich).

From the complete transport system perspective, the results show that introducing aRP and aRH modes reduces total travel time, increases the share of motorized non-PT modes, and increases total vehicle mileage (see Fig. V, Fig. VI and Fig. VII as an example for Chur region)

Three policy measures applied show similar effects in all three studied regions. The pooling rate considerably increases at the expense of increased total vehicle distance, with the most substantial increase in Zurich.

Tab. I *Overview of policy scenarios*

	Zurich	Chur	Fribourg
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%	100%
aRP fleet size	1680	1200	2400
aRH fleet size	1200	800	1800

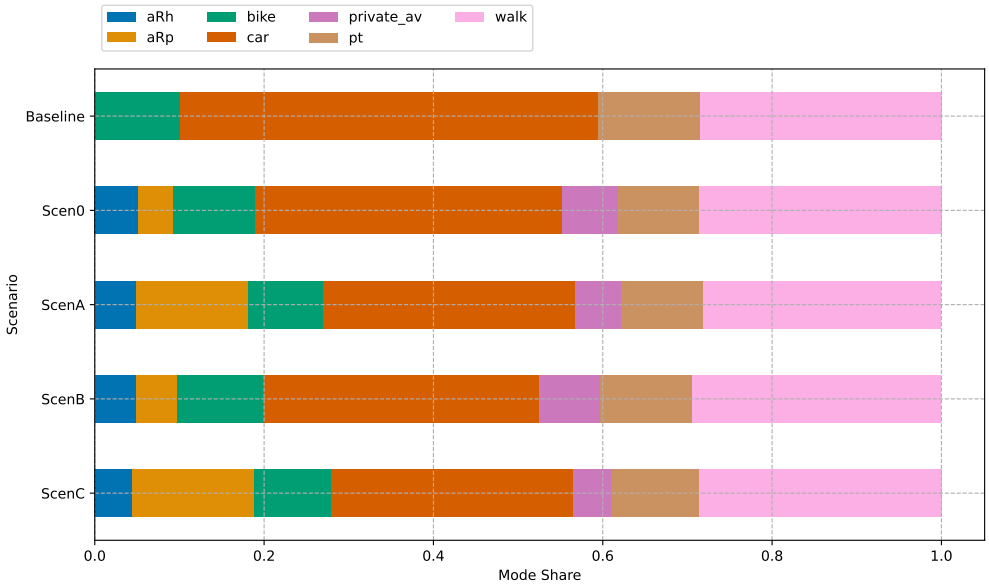


Fig. V *Mode share by trip in Chur.*

Assuming that self-driving vehicles require 17% less road space (at the penetration given in the case studies) and utilize the available network capacity more efficiently, the base scenarios for all regions show an increase in network utilization. This effect is least pronounced in the Chur region. In this area, the measures proposed in the scenario lead to minimal changes in network utilization compared to the baseline scenario without autonomous vehicles. In fact, in Scenario 3, network utilization slightly decreases.

In the Fribourg and Zurich regions, network utilization increases by 7% and 18%, respectively, across the scenarios. In Fribourg, the various measures result in a slight reduction in network utilization, although it remains above the level observed in the scenario without autonomous vehicles. In Zurich, however, the pull measures lead to a 26% increase in network utilization. This is primarily because travelers in Zurich more frequently opt for autonomous ride-pooling (aRP) or autonomous ride-hailing (aRH) services instead of public transport.

The results indicate that the tested measures are effective in less densely populated areas,

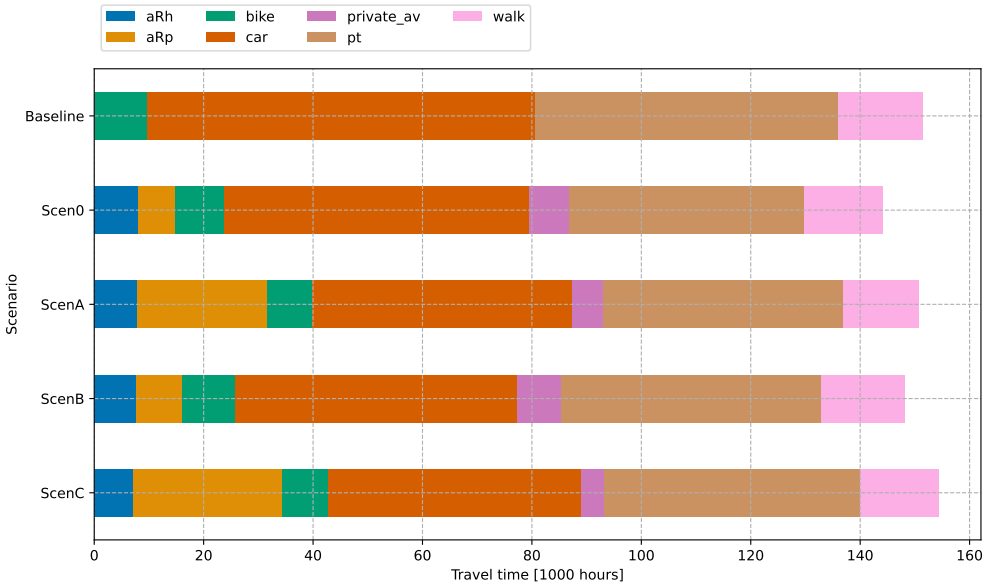


Fig. VI *Travel time by mode in Chur (Note: not including the waiting time for aRP and aRH).*

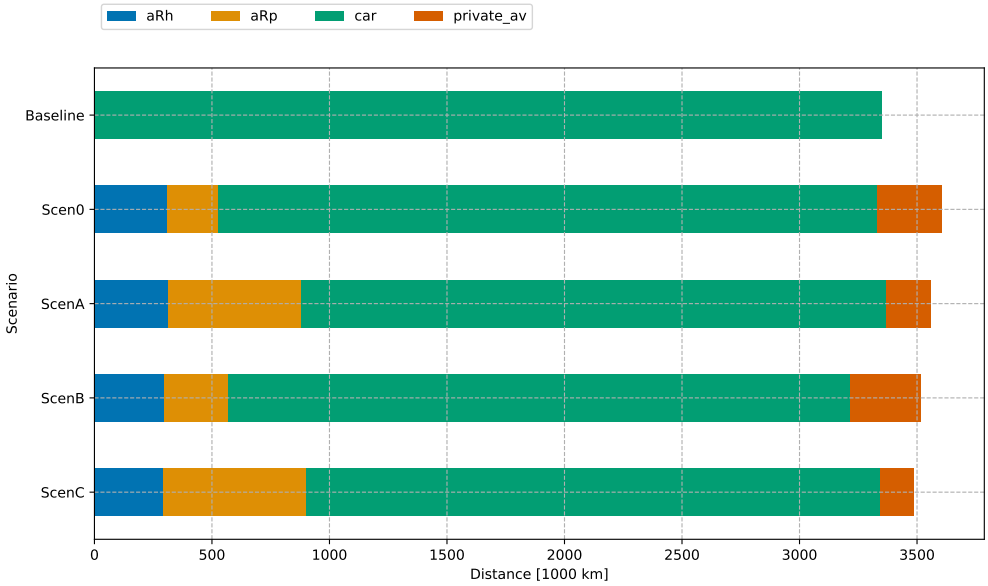


Fig. VII *Total vehicle distance in Chur.*

enhancing accessibility without increasing network utilization. However, in densely populated urban regions, different measures are needed to achieve similar outcomes in the context of autonomous vehicles.

From the aRP and aRH operator perspective, pull policy measures considerably increase the demand, especially for aRP. The highest net income for aRH and aRP services is achieved when both push and pull policies are applied.

Limitations and future research

Capturing the acceptance of aRP and aRH and modeling travel behavior in general, if AVs become widely available, involves various uncertainties. Notably, none of the participants in the qualitative interviews or choice experiments had experienced traveling with such ve-

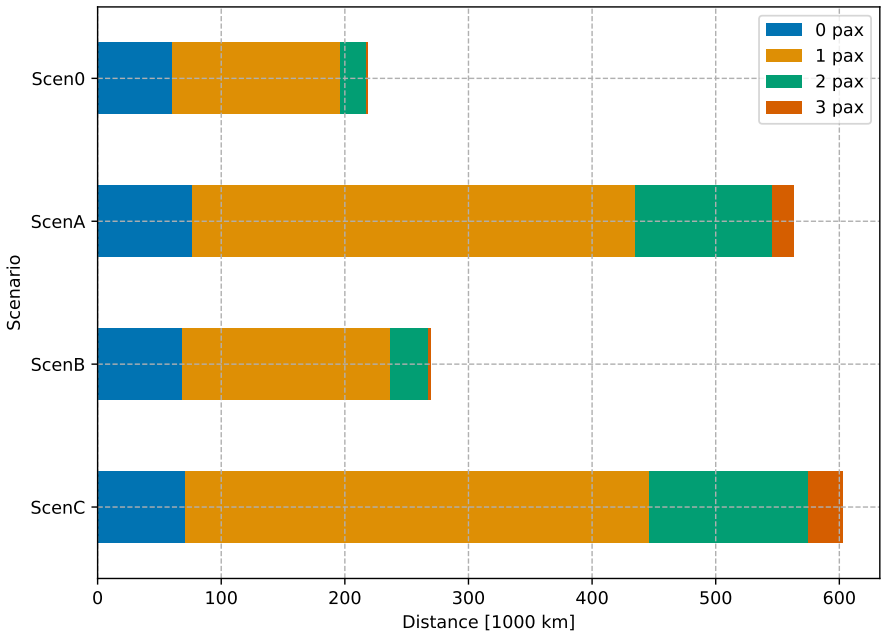


Fig. VIII *Total vehicle distance by occupancy for aRP in Chur.*

hicles. Additionally, modeling autonomous vehicles and their related transport services is inherently complex, impacting travel demand and supply across numerous interconnected dimensions. In this context, we recommend the following directions for future research:

- It would be valuable to conduct qualitative interviews and stated choice surveys with participants who have firsthand experience traveling in various forms of autonomous vehicles. Participants could be recruited in collaboration with companies that operate these vehicles commercially or through pilot projects.

- In the stated choice survey, only trade-offs between ride-pooling and ride-hailing with public transport and private motorized vehicles were tested. However, depending on the fare structure and potential travel cards, these new modes could also offer competitive alternatives to cycling and walking. Moreover, active transport modes have benefits for reducing environmental impact and public health. Therefore, we recommend that future studies explore the interplay between these new modes and active transportation options, with a focus on how transport policy measures can effectively integrate and leverage their respective advantages.

- The case studies demonstrated that simulating travel behavior with large fleets of shared autonomous vehicles in complex configurations, such as intermodal trips, is feasible. The insights gained highlight both the potential benefits and the challenges that autonomous vehicles present to the transport system. However, it is evident that these simulation results require more detailed analysis to provide a deeper understanding of how autonomous vehicles, and ride-pooling services in particular, could benefit the transport system, society, and the environment. Those insights could also inform iterative refinements and further development of the simulation scenarios which would ultimately allow to derive spatially context-aware policy recommendations.

- The availability of autonomous vehicles will significantly transform transportation and influence land use. These new transport options, including shared and private autonomous vehicles, will not only affect mode choice and vehicle ownership but also

impact destination choice and the types and frequency of activities conducted. To better understand this potential impact, it is useful to consider how mass motorization has historically changed various aspects of daily life and the built environment. Given the complexity of modeling all relevant dimensions to predict future scenarios, a backcasting approach could be valuable. By describing various potential scenarios, one can evaluate their feasibility and desirability using suitable transport models. This approach would help identify the necessary and desirable measures to guide progress towards a preferred development path.

Zusammenfassung

Überblick und Ziele

Die Digitalisierung wird die Mobilität der Zukunft massgeblich verändern. Nicht nur Fahrzeuge, sondern auch Dienstleistungen werden zunehmend von dieser Digitalisierung transformiert. Das Aufkommen autonomer Fahrzeuge (AF) bietet politischen Entscheidungstragenden, Fahrzeugherstellern und Nutzenden Möglichkeiten aber auch Risiken. Es wird erwartet, dass AF die Verkehrssicherheit erhöhen und eine effizientere Nutzung des Strassennetzes durch kürzere Wartezeiten ermöglichen. Gleichzeitig könnten AF aber auch leere Fahrzeugkilometer erzeugen und die Nachfrage nach Autofahrten erhöhen. Die Zeit, die für das Autofahren aufgewendet wird, kann nicht nur anderweitig genutzt werden (z. B. zum Arbeiten, Lesen usw.), sondern AF werden auch den Zugang zu Verkehrsdienstleistungen für ein breiteres Publikum ermöglichen. Der zu erwartende erhebliche Anstieg des Verkehrsaufkommens kann vor allem in städtischen Regionen zu grossen Problemen führen (z. B. Staus, Lärm, Verschmutzung usw.).

Mit autonomen Fahrzeugen betriebene Ride-pooling Dienste (aRP) haben das Potenzial, die Vorteile des öffentlichen Verkehrs (hoher Besetzungsgrad) und des Privatverkehrs (direkte Fahrten) zu kombinieren. Dies ermöglicht eine erhebliche Erhöhung der Erreichbarkeit, insbesondere in ländlichen Gebieten und zu Tageszeiten, zu denen herkömmliche öffentliche Verkehrsmittel nicht effizient betrieben werden können. Darüber hinaus verläuft die Trennlinie zwischen aRP und einer normalen Buslinie fliessend, je nach Fahrzeuggrösse und wie dynamische der Fahrplan und die bedienten Routen gestalten werden. Gleichzeitig ist es wahrscheinlich, dass kommerziell betriebene Flotten autonomer Fahrzeuge nicht nur Fahrgemeinschaften, sondern auch Ride-Hailing Dienste (aRH) anbieten werden, bei denen Reisende von einem einzelnen Ausgangspunkt abgeholt und direkt zu ihrem Zielort befördert werden, ähnlich wie heute ein Taxi.

Weder die Akzeptanz noch die Funktionsweise von aRP sind hinreichend gut erforscht. Aus einer langfristigen Planungsperspektive sind das Verständnis der Faktoren, welche die Wahl von Fahrten mit aRP beeinflussen, und die Instrumente zur Modellierung der Nachfrage und des Angebots von aRP unvollständig und daher Gegenstand dieser Forschung, welche die folgenden Ziele verfolgt:

1. Die Untersuchung der Bereitschaft zur Nutzung von Ride-Pooling in der Schweiz sowie die Identifizierung relevanter Treiber und Hürden für Ride-Pooling mit und ohne Fahrer.

2. Die Quantifizierung des Verkehrsverhaltens im Zusammenhang mit Ride-Hailing- und Ride-Pooling-Diensten autonomer Fahrzeugflotten durch die Entwicklung und Durchführung einer neuen Umfrage zur angegebenen Präferenz.

3. Entwicklung optimaler Planungs- und Dispatching-Algorithmen, die dynamische Abhol- und Absetzorte ermöglichen, um die Gesamtreisezeiten zu verkürzen

4. Integration der Umfrageergebnisse in ein agenten-basiertes Verkehrsmodell für die Schweiz und Verknüpfung des Verkehrsmittelwahlmodells mit betrieblichen Merkmalen wie Fahrzeugtyp und -grösse, Preisgestaltung, Wartezeit, Zugangs- und Reisezeit sowie Fahrzeugauslastung.

Qualitative Untersuchung

Um die Motivatoren und Barrieren zu analysieren, welche die Nutzung von aRP beeinflussen, wurde ein qualitativer Ansatz wurde verwendet. Das Hauptziel bestand darin, relevante Faktoren für die Verwendung von aRP zu identifizieren. Ein weiteres Ziel war die Erprobung von Informationsmaterialien, die später als Erklärvideos in der Stated-Choice-Studie verwendet wurden. Zur Aufdeckung impliziter Einstellungen und Wahrnehmungen wurden teilstrukturierte qualitative Interviews durchgeführt, bei denen narratives Storytelling und

projektive Interviewtechniken zum Einsatz kamen.

Die Auswertung der Interviews erfolgte in einem zweistufigen Prozess nach dem Verfahren der strukturierten Inhaltsanalyse. Zunächst wurden die Interviews von zwei unabhängigen Mitarbeitenden anhand von Determinanten aus dem theoretischen Hintergrund codiert. In einem zweiten Schritt wurden bei Bedarf zusätzliche Codes ergänzt.

Die Ergebnisse der qualitativen Interviews bestätigen bisherige Forschungserkenntnisse zu psychologischen Akzeptanzfaktoren von Ridepooling. Diese Faktoren wurden entlang des Technologieakzeptanz-Modells UTAUT (Unified Theory of Acceptance and Use of Technology) strukturiert. Viele relevante Faktoren beziehen sich auf den wahrgenommenen Nutzen (sog. Performance Expectancy) von aRP. Dabei handelt es sich um Faktoren wie die Sicherheit der Technologie, Wartezeit, Reisezeit, Nachhaltigkeit, Zuverlässigkeit, Flexibilität, Verfügbarkeit und Komfort. Bemerkenswert ist, dass keiner dieser Faktoren eindeutig als Motivator oder Barriere wahrgenommen wurde. Zum Beispiel wird der Aspekt der Sicherheit kontrovers diskutiert: Einerseits wird aRP als unsichere und risikobehaftete Technologie wahrgenommen, andererseits wird es auch als sicherer als von Menschen gesteuerte Fahrzeuge wahrgenommen. Somit können alle Einflussfaktoren sowohl mit Motivatoren als auch mit Barrieren für die Nutzung von aRP in Verbindung gebracht werden.

Bei einigen Faktoren (Zeit, Flexibilität, Verfügbarkeit, Komfort und Umweltaspekte), hängt die Einstufung als Barriere oder Motivator davon ab, ob Ridepooling im Vergleich zu einem privaten Auto oder zu öffentlichen Verkehrsmitteln bewertet wird. Zum Beispiel wird ein privates Auto als zuverlässiger verfüg-bar wahrgenommen als Ridepooling in autonomen Fahrzeugen (daher wird die Verfügbarkeit als Hindernis wahrgenommen); Ridepooling in autonomen Fahrzeugen werden jedoch als flexibler verfügbar wahrgenommen als öffentliche Verkehrsmittel (daher wird die Verfügbarkeit als Antrieb wahrgenom-men). Bei den Faktoren Zeit, Flexibilität, Verfügbarkeit und Komfort führt dieser Vergleich zu einer günstigen Bewertung von Ridepooling im Vergleich zum öffentlichen Verkehr und zu einer ungünstigen Wahrnehmung im Vergleich zum eigenen Auto. Ein weiterer relevanter Faktor ist die Zuverlässigkeit. Unsere Untersuchung unterstreicht die Bedeutung der Zuverlässigkeit, insbesondere im Schweizer Kontext, wo der öffentliche Verkehr pünktlich ist.

In Bezug auf die Aufwandserwartung sind die Faktoren und die daraus abgeleiteten Argumente weniger umstritten. Faktoren wie die Planung und die Informationen auf der App werden eindeutig als treibende Faktoren wahrgenommen. Dies sind auch die am häufigsten genannten Faktoren. Die Bedenken in Bezug auf die Benutzerfreundlichkeit scheinen geringer zu sein als die wahrgenommenen Vorteile.

In Bezug auf die wahrgenommenen Kosten beobachten wir die gleichen Mechanismen wie bei einigen der oben genannten Faktoren: aRP wird im Vergleich zu öffentlichen Verkehrsmitteln als teurer und im Vergleich zum eigenen Auto als billiger wahrgenommen.

Schließlich wurden soziale Aspekte sowohl im Hinblick auf die Sicherheit als auch im Hinblick auf den sozialen Kontext diskutiert. Überraschenderweise wurde das Thema Sicherheit nur von wenigen Teilnehmenden angesprochen. Im Hinblick auf ein inklusives und barrierefreies Verkehrssystem bleibt es wichtig, Aspekte der Sicherheit des öffentlichen Raums innerhalb eines AFs zu berücksichtigen.

Befragung zur Verkehrsmittelwahl mit aRP und aRH

Um zu verstehen und zu quantifizieren, wie sich aRH und aRP auf das Verkehrsverhalten auswirken, wurde eine Stated-Choice-Umfrage durchgeführt. Die Stichprobe wurde mithilfe eines Panels eines Marktforschungsunternehmens nach Quoten gezogen, um sicherzustellen, dass die Befragten die Zielpopulation angemessen repräsentieren. Diese umfasst alle Einwohner über 18 Jahre, die in einer Schweizer Stadt oder städtischen Agglomeration leben und regelmäßig zu einer Aktivität fahren, die eine Strecke von mehr als 2 Kilometern erfordert. Es wurden repräsentative Quoten für Autoverfügbarkeit, Altersgruppen, Erwerbsstatus, Geschlecht, Sprache und den Raumtyp der Wohngemeinde festgelegt. Personen mit einem Generalabonnement (GA) oder ÖV-Verbundabonnement wurden überrepräsen-

tiert, um zuverlässiger testen zu können, ob sich die Präferenzen von Personen, die häufig öffentliche Verkehrsmittel nutzen, hinsichtlich aRP und aRH von denen anderer Personen unterscheiden.

Um ein Pivot-Design-basiertes Verkehrsmittelwahlexperiment zu ermöglichen, umfasst die Umfrage zwei webbasierte Fragebögen, die von den Befragten in zwei Phasen ausgefüllt werden. Der erste Fragebogen erfasst Daten zu regelmässig durchgeführten Pendel- und Freizeitfahrten sowie Informationen zum Besitz von Mobilitätswerkzeugen. Der zweite Fragebogen umfasst zwei Verkehrsmittelwahlexperimente, die Ride-Hailing und Ride-Pooling als neue Verkehrsmittel berücksichtigen. Je nach Verfügbarkeit von ÖV-Verbindungen zwischen Start- und Zielort der angegebenen Fahrt wurden die Alternativen Ride-Pooling und Ride-Hailing entweder als Direktfahrten (monomodal) oder als intermodale Fahrten definiert.

Zwischen den beiden Verkehrsmittelwahlexperimenten wurden die Befragten gefragt, ob sie den Besitz eines Autos in Erwägung ziehen würden, wenn autonome Fahrzeuge privat erworben werden können und von grossen Flottenbetreibern für Ride-Hailing- und Ride-Pooling-Dienste zur Verfügung stehen. Um sicherzustellen, dass alle Befragten verstehen, wie Ride-Pooling funktioniert und wie dieses mit autonomen Fahrzeugen betrieben werden kann, wurden Erklärungsvideos erstellt, welche die Befragten vor den Verkehrsmittelwahlexperimenten ansahen. Im Anschluss an das Verkehrsmittelwahlexperiment gaben die Befragten an, ob sie bereit wären, Fahrkarten für Mitfahrdienste zu kaufen, und äusserten ihre Einstellungen zu diesen Diensten.

Eine Herausforderung des Pivot-Design-Ansatzes war es über die geschickte Ziehung der berichteten Wege sicherzustellen, dass in den Entscheidungssituationen autonome Fahrzeuge sowohl im Kontext von mono- als auch intermodale Wegalternativen vorgesehen werden. Zudem galt es über das Versuchsdesign sicherzustellen, dass die Entscheidungssituation interessante Abwägungen zwischen den verschiedenen Alternativen bieten und gleichzeitig realitätsnahe Reisezeit- und Kostenverhältnisse beschreiben.

Fig. I zeigt die über alle Entscheidungsexperimente ermittelten Anteile der berücksichtgten Verkehrsmittel in Abhängigkeit, ob der berichtete Referenzweg mit dem Auto oder dem ÖV zurückgelegt wurde und ob die Alternative mit autonomem Fahrzeug als monomodaler oder intermodal Weg spezifiziert wurde.

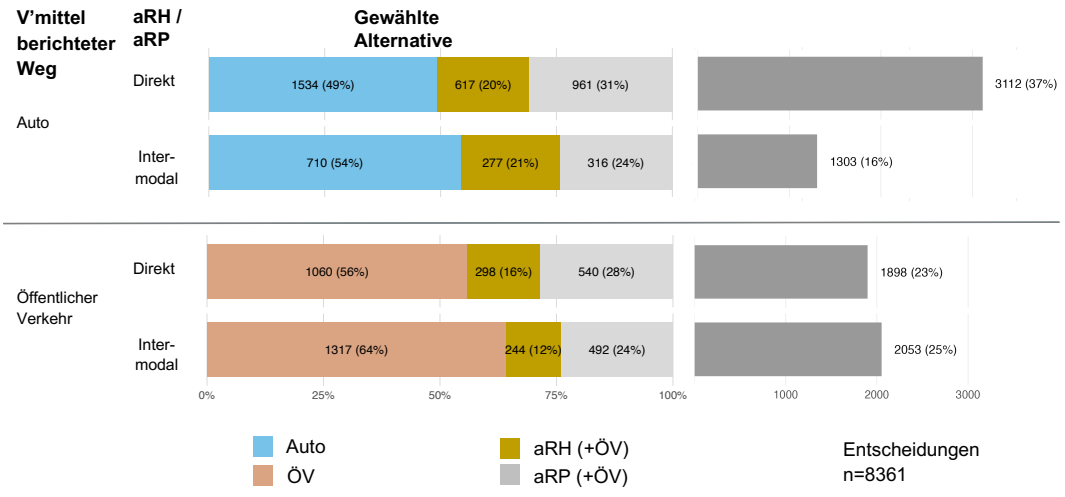


Fig. I *Anteile der gewählten Verkehrsmittel nach Wegzweck und gewähltem Verkehrsmittel für den berichteten Weg*

In rund 50% bis 65% der Fälle wurde das für den Referenzweg genutzte Verkehrmittel beibehalten. Die Alternativen aRH und aRP wurden in 12% bis 31% der Fälle gewählt. Dies zeigt, dass es mit dem Versuchsplan gelungen ist interessante Entscheidungssituationen

zu spezifizieren, die sich gut für die Schätzung von aussagekräftigen Entscheidungsmodellen eignen, unabhängig des für den berichteten Weg gewählten Verkehrsmittels und der Art wie autonome Fahrzeuge eingesetzt werden (mono- oder intermodal). Durch die gezielte Ziehung der Stichprobe ist es auch gelungen, dass für die einzelnen Arten von Entscheidungsexperimenten eine genügend grosse Anzahl an Beobachtungen vorliegt.

Die Ergebnisse des Verkehrsmittelwahlmodells zeigen, dass die Reisezeit sowohl für aRP als auch für aRH im Vergleich zu öffentlichen Verkehrsmitteln und Auto negativer bewertet wird. Die Reisezeitersparnis, welche diese neuartigen Verkehrsmittel im Vergleich zum öffentlichen Verkehr bieten, kombiniert mit ihren geringeren Kosten im Vergleich zum privaten Auto, ermöglicht, dass Marktanteile von beiden bestehenden Verkehrsmitteln gewonnen werden. Dies deutet darauf hin, dass aRP und aRH aufgrund ihrer betrieblichen Effizienz als wettbewerbsfähige Alternativen positioniert werden und Nutzende sowohl vom öffentlichen Verkehr als auch vom privaten Auto abziehen können.

Die negativen alternativen-spezifischen Konstanten für die aRP- und aRH-Alternativen erfassen den Mittelwert aller unbeobachteten Effekte und könnten daher als allgemeine Zurückhaltung der Befragten gegenüber der Wahl dieser neuen Verkehrsmittel interpretiert werden, welche sich direkt auf ihre erwarteten Marktanteile auswirkt. Die Konstante ist bei aRP weniger negativ als bei aRH. Dies gilt ebenso für Personen, die im Vergleich zur Allgemeinbevölkerung offener für Mobilitätsinnovationen sind. Es ist zu erwarten, dass diese allgemeine Zurückhaltung mit der Zeit abnimmt, wenn die Nutzer mit diesen neuen Verkehrsmitteln vertrauter werden.

Fig. II zeigt die Abhängigkeit des Zeitwerts für Fahrten mit einem Auto, öffentlichen Verkehrsmitteln sowie für aRP und aRH (monomodal oder intermodal) in Abhängigkeit der Reisedistanz. Für alle Verkehrsmittel steigt der Zeitwert mit zunehmender Reisedistanz. Der Kurvenverlauf für Auto und öffentliche Verkehrsmittel bestätigen frühere Studienergebnisse, die einen höheren Zeitwert für Arbeitsfahrten im Vergleich zu Freizeitfahrten ausweisen und die Unterschiede zwischen dem Zeitwert für Arbeits- und Freizeitfahrten bei öffentlichen Verkehrsmitteln mit zunehmender Fahrstrecke stärker ausgeprägt sind als beim Auto.

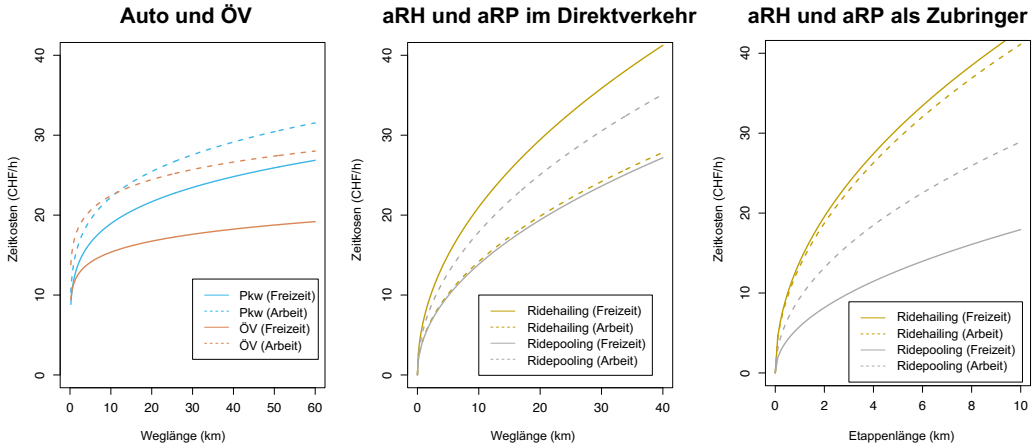


Fig. II *Zeitwerte nach Verkehrsmittel und Weg-/Etappenlänge*

Die Kurven der Zeitwerte für aRP und aRH als direkte Verkehrsmittel zeigen bei längeren Reisedistanzen einen ausgeprägteren Anstieg im Vergleich zum Auto und dem öffentlichem Verkehr. Dies legt nahe, dass der Reisekomfort mit diesen Verkehrsmitteln bei längeren Fahrten als weniger vorteilhaft wahrgenommen wird. Diese Einschätzung ist intuitiv nachvollziehbar: Im öffentlichen Verkehr werden üblicherweise unterschiedliche Fahrzeugtypen für verschiedene Streckenlängen eingesetzt, während die Befragten vermutlich annahmen, dass bei aRP und aRH unabhängig von der Entfernung derselbe Fahrzeugtyp genutzt wird.

Für aRP zeigt sich, dass der Zeitwert bei Nutzfahrten höher ist als bei Freizeitfahrten, was

im Einklang mit den Ergebnissen dieser sowie früherer Zeitwertstudien steht. Bemerkenswert ist, dass der Zeitwert bei aRH-Fahrten im Pendelverkehr niedriger eingeschätzt wurde als im Freizeitverkehr. Eine mögliche Erklärung hierfür könnte sein, dass das Arbeiten während der Fahrt in einem AV als Pendlerfahrzeug als realistische Möglichkeit wahrgenommen wurde und daher die Fahrzeit weniger stark wahrgenommen wird. Dieses Ergebnis sollte jedoch in zukünftigen Studien weiter untersucht werden.

Die Grafik zeigt, dass Reisezeitverkürzungen auf intermodale Etappen im AF zum oder vom Bahnhof im Allgemeinen stärker bewertet werden als Verkürzungen der Reisezeit im öffentlichen Verkehr. Dies gilt insbesondere für aRH. Eine mögliche Erklärung ist, dass kürzere Fahrzeiten im Zubringerbereich bevorzugt werden, um das Risiko eines verpassten Anschlusses zu reduzieren.

Bestimmte Aspekte des Reiseerlebnisses mit aRP und aRH, die sich von bestehenden Verkehrsträgern unterscheiden, wurden in der Befragung nicht vollständig durch die Variablen erfasst, welche diese Alternativen beschreiben. Diese Aspekte könnten die diesen Verkehrsmitteln gegenüber beobachtete Zurückhaltung teilweise erklären. Zum Beispiel erfordert die Nutzung von aRP und aRH häufig eine Reservierung über eine App, was den Aufwand für die Planung und Durchführung einer Reise erhöht. Zudem schwanken Nachfrage und Angebot für aRH und aRP je nach Tageszeit und Ort, was eine zusätzliche Planungsunsicherheit schafft, die in Umfragen zu den angegebenen Präferenzen nur teilweise erfasst werden kann. Darüber hinaus ist zu erwarten, dass Flottenbetreiber dynamische Preise einführen, um auf Nachfrageschwankungen zu reagieren, was den Planungsaufwand für die Kunden weiter erhöhen würde.

Im Gegensatz dazu zeigten die Befragten eine hohe Bereitschaft, eine Rabattkarte für aRP zu erwerben, insbesondere diejenigen, die derzeit selten öffentliche Verkehrsmittel nutzen und lediglich ein Halbtax-Abo oder gar kein ÖV-Abonnement besitzen. Auch wenn ein Teil des in der Umfrage beobachteten Effekts möglicherweise durch Framing-Effekte beeinflusst sein könnte, verdeutlicht dies das Marktpotenzial für Rabattkarten sowohl für aRP als auch für aRH.

Das Experiment zum Mobilitätswerkzeugbesitz zeigt eine allgemeine Zurückhaltung auf ein eigenes Autos zu verzichten, selbst wenn Flotten von geteilt genutzten autonomen Fahrzeugen ein umfassendes Mobilitätsangebot ohne eigenes Fahrzeug ermöglichen könnten. Fig. III weist aus welche Anteile der befragten Personen, die derzeit über ein Auto im Haushalt verfügen, entweder den Autobesitz aufgeben oder ein privates AV kaufen würden, wenn diese zu unterschiedlichen Preisaufschlägen gegenüber herkömmlichen Autos zum Kauf angeboten würden.

Wie erwartet ist der Anteil der Befragten, die bereit sind, ein privates autonomes Fahrzeug zu kaufen, beim höchsten getesteten Preisaufschlag am geringsten. Bei einem Aufpreis von CHF 9’000 zeigten nur rund 10% der Befragten Interesse an der Anschaffung eines solchen Fahrzeugs. Interessanterweise erreichte der Anteil mit 31% seinen Höchstwert bei einem Aufpreis von CHF 6’000, während er bei einer Prämie von CHF 3’000 mit 26% etwas geringer ausfiel.

Angesichts der relativ kleinen Stichprobengröße könnten diese Unterschiede auf statistische Schwankungen zurückzuführen sein. Es ist jedoch auch möglich, dass sie unterschiedliche Erwartungen der Befragten an die technologische Machbarkeit privater autonomer Fahrzeuge beim jeweiligen Aufpreisniveau widerspiegeln. Letzteres würde auch erklären, warum der Anteil der Befragten, die bereit wären, den Besitz eines Autos aufzugeben, mit zunehmender Prämienhöhe steigt.

Umgekehrt zeigten die Befragten eine hohe Bereitschaft, eine Rabattkarte für aRP zu erwerben, insbesondere jene, die den öffentliche Verkehr derzeit selten nutzen und entweder kein ÖV-Abonnement oder lediglich ein Halbtax besitzen (siehe Fig. IV. Auch wenn ein Teil dieses Effekts auf Framing-Effekte zurückzuführen sein könnte, verdeutlicht er das Marktpotenzial von Rabattkarten sowohl für aRP als auch für aRH.

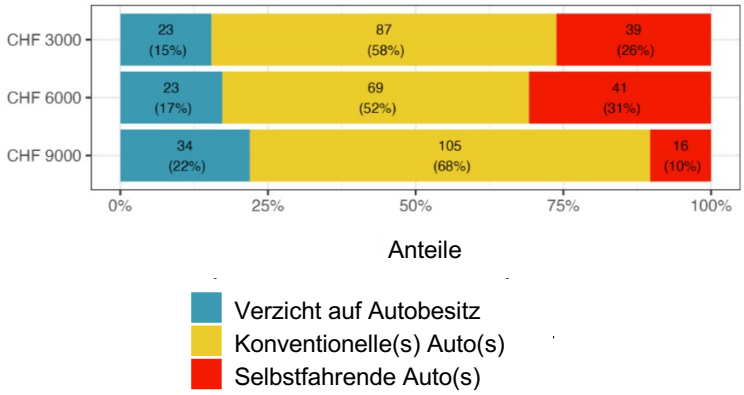


Fig. III *Absicht, den Autobesitz anzupassen, in Abhängigkeit des Aufpreises für ein autonomes Fahrzeug*

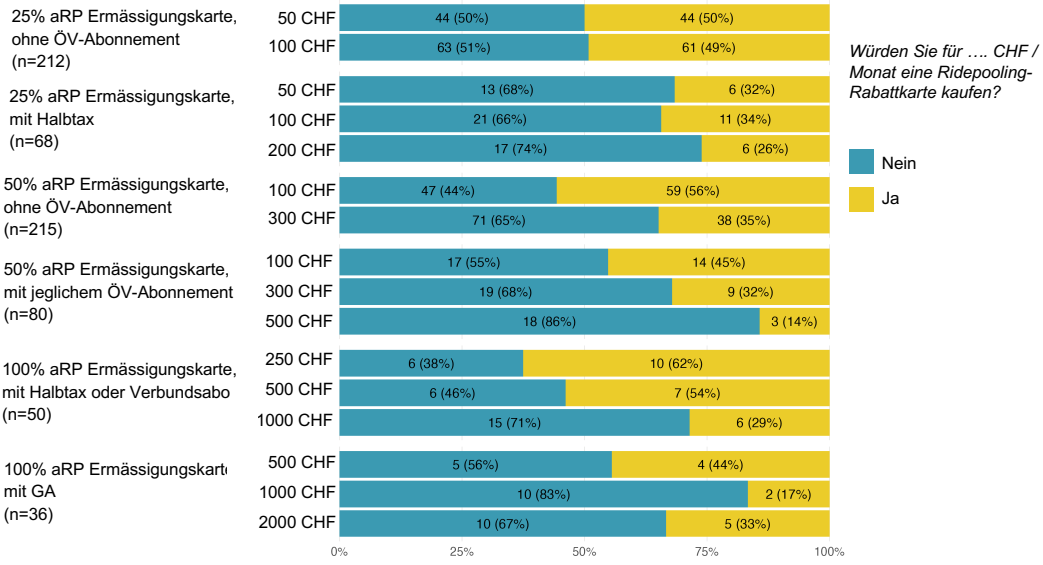


Fig. IV *Absicht, eine aRP-Abonnement zu kaufen, je nach bestehendem ÖV-Abonnementsbesitz und Preisniveau*

Optimierung des Betriebs einer Ride-Pooling-Flotte

Um den Betrieb einer Ride-Pooling-Flotte in Bezug auf die Zuweisung der Fahrzeuge auf die räumlich und zeitlich fluktuierende Nachfrage optimieren zu können, wurde eine Echtzeit-Simulationsumgebung erstellt. Die Simulationsumgebung integriert fortschrittliche Algorithmen, die sich in Echtzeit an Veränderungen in den Fahrgastanfragen und den Verkehrsmustern anpassen, um eine effiziente Flottennutzung sicherzustellen.

In dieser Umgebung wurde mithilfe einer Online-Optimierung und spezieller Lösungsalgorithmen gezeigt, dass es möglich ist, 97% der Taxifahrten in Manhattan (New York, USA) mit lediglich 2.000 Ride-Pooling-Fahrzeugen zu bewältigen, die jeweils bis zu fünf Fahrgäste transportieren können – im Vergleich zu den derzeit rund 13.000 Taxis. Die Simulationen zeigten, dass Mitfahrgelegenheiten ein hohes Serviceniveau aufrechterhalten können: Die 2.000 Fahrzeuge erzielten eine durchschnittliche Wartezeit von unter zwei Minuten bis zur Abholung sowie eine durchschnittliche Fahrzeitverlängerung von weniger als sieben Minuten, was für die meisten Fahrgäste akzeptabel ist. Dies verdeutlicht das erhebliche Potenzial die Verkehrsbedingungen zu verbessern, Staus zu reduzieren und Emissionen zu senken - bei gleichzeitig nur minimalen Auswirkungen auf die Reisezeit minimal – wenn sich eine Stadt dafür entscheidet, Ride-Hailing zu Gunsten von Ride-Pooling einzuschränken.

Es stellte sich jedoch heraus, dass die Integration des neuen Algorithmus in die Multi-Agent Transport Simulation (MATSim) mit erheblichem Aufwand verbunden wäre. Die Rechenzeiten könnten aufgrund der Komplexität des Algorithmus und der für die Echtzeitoptimierung benötigten hohen Rechenressourcen deutlich verlängert werden. Gleichzeitig wurde die durch die gesteigerte betriebliche Effizienz der neuen Online-Optimierung erzielte Wirkung auf die Verkehrsnachfrage als begrenzt bewertet, da die bereits in MATSim implementierten Algorithmen schon sehr effizient sind. Nach sorgfältiger Abwägung zwischen dem erhöhten Rechenaufwand und den marginalen Effizienzgewinnen wurde daher entschieden, den neuen Algorithmus nicht in den Fallstudien einzusetzen.

Fallstudien

Ein agentenbasierter Ansatz wurde verwendet, um die potenziellen Auswirkungen autonomer Fahrzeuge (AFs) in drei städtischen Regionen der Schweiz – Chur, Freiburg und Zürich – zu evaluieren. Dazu wurden die Verkehrsnachfrage und das Verkehrsangebot in diesen Regionen aus dem landesweiten, agentenbasierte MATSim-Modell der ETH extrahiert, wobei auch der Durchgangsverkehr berücksichtigt wurde. Die daraus entstehenden regionalen MATSim-Verkehrsmodelle wurde mit einem Verkehrsmittelwahlmodell kombiniert, dessen Verhaltensparameter auf den Resultaten der stated preference Befragung basieren. So ist es den als Agenten modellierten Individuen in der Simulation möglich, zwischen verschiedenen Verkehrsmitteln wie privaten (autonomen) Autos, Fahrrädern, Fusswegen, öffentlichen Verkehrsmitteln sowie autonomen Ride-Hailing- (aRH) und Ride-Pooling-Diensten (aRP) zu wählen, wobei bei aRH und aRP die am jeweiligen Standort und Zeitpunkt der Fahrt verfügbare Angebotsqualität berücksichtigt wird. Obschon mit autonomen Fahrzeugen denkbar wäre, dass sich auch das Angebot des liniengebundenen öffentlichen Verkehrs verändern würde, schliessen die Fallstudien solche Veränderungen aus.

Zudem wurde ein Modell für den Besitz von Mobilitätswerkzeugen auf die synthetische Population angewandt, um die potenziellen Veränderungen im Fahrzeugbesitz bei einer weit verbreiteten Verfügbarkeit von aRP und aRH zu prognostizieren. Für jede Region wurde das Basisszenario so kalibriert, dass dieses die aktuelle Verkehrsnachfrage und das Verkehrsangebot widerspiegelt und die beobachteten Verkehrsmittelanteilen denjenigen der jeweiligen Regionen entsprechen. Anschliessend wurde mithilfe der Ergebnisse einer Rastersuche eine geeignete Flottengrösse für aRH- und aRP-Dienste festgelegt, die sowohl die Rentabilität als auch eine hohe Nachfrage und Nutzendenzufriedenheit sicherstellt. Zusätzlich wurden die Tarife für aRH gemäss der Kosten für private Autos und die Tarife für aRP gemäss den ÖV-Kosten angepasst, da aRH als privat betriebene Fahrzeuge angesehen werden, während aRP als Teil des öffentlichen Verkehrs betrachtet wird.

Für jede untersuchte Region wurden fünf Szenarien simuliert: den aktuellen Zustand des Systems, die Einführung autonomer Fahrzeuge (AFs) sowie drei Szenarien mit verkehrs-

planerischen Massnahmen, die darauf abzielen, Menschen zur Nutzung des nachhaltigeren aRP zu bewegen (Tab. I). Die verkehrsplanerischen Massnahmen umfassten als Pull-Massnahmen Subventionen für aRP-Fahrten in Abhängigkeit der ÖV-Güteklasse am Start- oder Zielort, sowie als Push-Massnahmen eine distanzabhängige Strassennutzungsgebühren in Chur und Freiburg sowie eine Kordonmaut in Zürich.

Tab. I *Überblick der Szenarien*

	Zürich	Chur	Freiburg
Szenario A: Pull	Subventionierung der Ridepooling-Kosten nach ÖV-Anschlussqualität (Schwächste Klasse aus Start- und Zielort): A: 0%; B: 20%; C: 40%; D: 60%; keine: 80%		
Szenario B: Push	Cordon-Pricing (Eintritt in die Stadtgrenzen von Zürich) für nicht geteilte Fahrzeuge: 6 CHF	Zusätzliche distanzbasierte Externalitätssteuern für nicht geteilte Fahrzeuge: Auto und private autonome Fahrzeuge: +0.2 CHF/km; aRH: +0.25 CHF/km	
Szenario C: Push und Pull	Kombination von A und B		
Bevölkerungsgrösse	10%	100%	100%
aRP Flottengrösse	1680	1200	2400
aRH Flottengrösse	1200	800	1800

Aus der Perspektive des gesamten Verkehrssystems zeigen die Ergebnisse, dass die Einführung von aRP und aRH die Gesamtreisezeit verkürzt, den Anteil der motorisierten, nichtöffentlichen Verkehrsmittel erhöht und die Gesamtfahrleistung der Fahrzeuge steigert (siehe Fig. V, Fig.VI und Fig. VII als Beispiel für die Region Chur).

In Chur und Freiburg nimmt aufgrund des Angebots von aRH und aRP der Verkehrsmittelanteil des Autos am stärksten ab, während in Zürich der öffentliche Verkehr am stärksten betroffen ist. Der Besetzunggrad der aRP-Fahrzeuge ist eher gering. Die meisten Fahrten werden entweder ohne oder mit nur einem Fahrgast durchgeführt (siehe Fig. VIII für Chur).

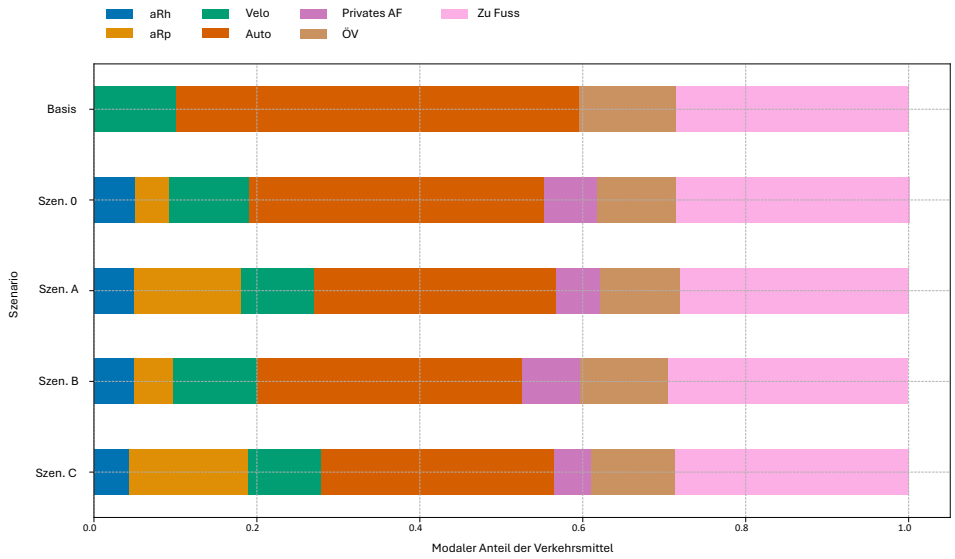


Fig. V *Verkehrsmittelanteile nach Anzahl Wegen im Fallbeispiel Chur*

Die drei getesteten Massnahmenpakete zeigen in allen drei untersuchten Regionen ähnliche Wirkungen. Der aRP-Besetzungsgrad steigt deutlich, allerdings auf Kosten einer höhe-

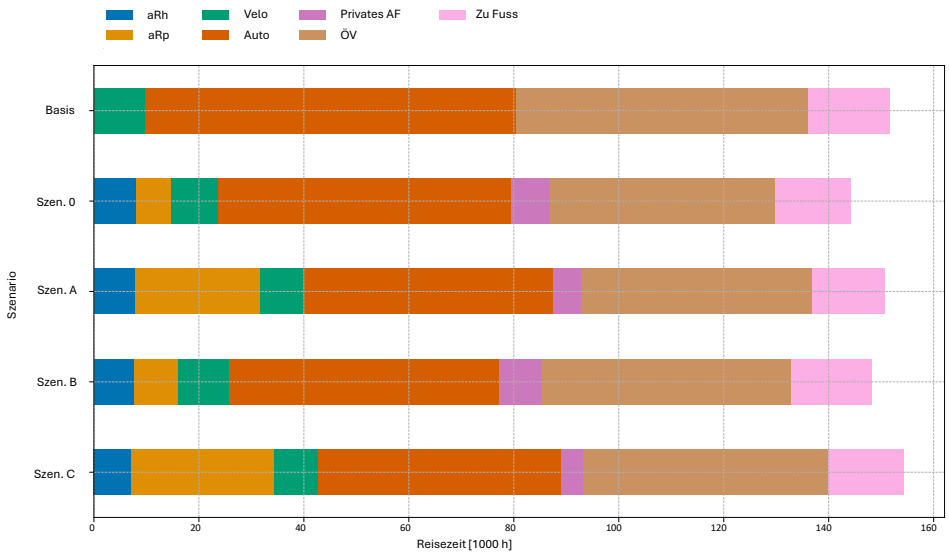


Fig. VI *Reisezeit nach Verkehrsmittel im Fallbeispiel Chur (Ohne Wartezeit für aRP und aRH)*

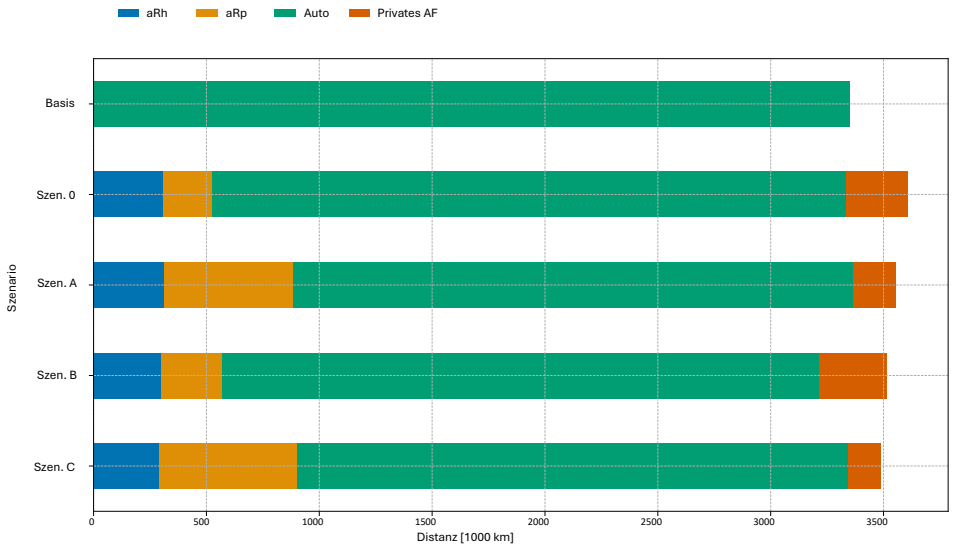


Fig. VII *Gesamtfahrleistung (Fhzkm) im Fallbeispiel Chur*

ren Gesamtfahrleistung, wobei der Anstieg in Zürich am stärksten ausfällt.

Unter Berücksichtigung der Annahme, dass selbstfahrende Fahrzeuge bei der Fahrt 17% weniger Straßenraum benötigen und dadurch die vorhandene Netzkapazität effizienter nutzen, zeigt sich in den Basisszenarien aller Regionen eine erhöhte Netzauslastung. Dieser Effekt ist in der Region Chur am geringsten ausgeprägt. Hier bewirken die im Szenario vorgesehenen Maßnahmen, dass die Netzauslastung im Vergleich zum Basisszenario ohne autonome Fahrzeuge kaum verändert und im Fall von Szenario 3 sogar leicht abnimmt.

In den Regionen Freiburg und Zürich hingegen steigt die Netzauslastung in den Szenarien um 7% bzw. 18%. In Freiburg führen die unterschiedlichen Massnahmenpakete zu einer leichten Verringerung der Netzauslastung, die jedoch weiterhin über dem Niveau des Szenarios ohne autonome Fahrzeuge bleibt. In Zürich hingegen bewirken insbesondere die Pull-Massnahmen, dass die Netzauslastung um etwa 26% zunimmt. Dies ist darauf zurückzuführen, dass Reisende hier häufiger auf autonome Ride-Pooling- (aRP) oder autonome

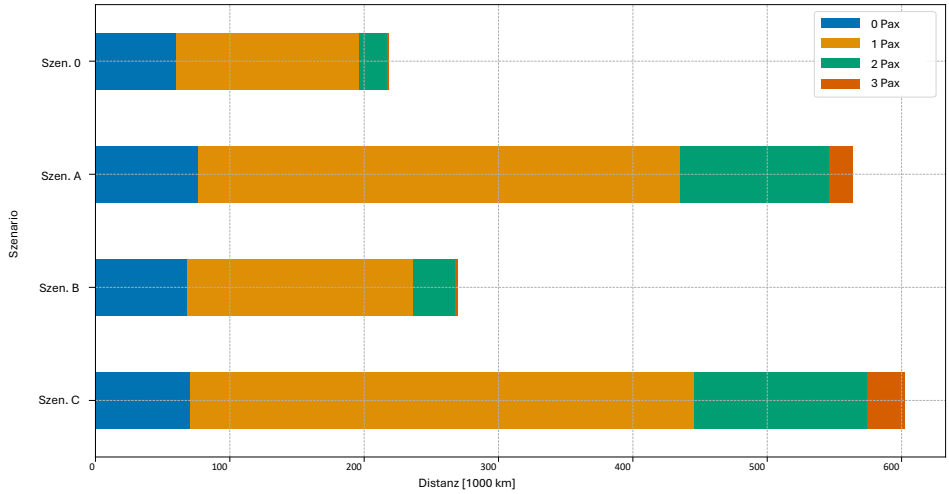


Fig. VIII *Gesamtfahrleistung (Fhzkm) nach Besetzungsgrad für aRP im Fallbeispiel Chur*

Ride-Hailing-Dienste (aRH) zurückgreifen, anstatt den öffentlichen Verkehr zu nutzen.

Die Ergebnisse zeigen, dass die getesteten Massnahmen in weniger dicht besiedelten Agglomerationen zielführend sind und zu einer Verbesserung der Erreichbarkeit beitragen, ohne zugleich die Netzauslastung zu erhöhen. In dicht besiedelten Agglomerationen hingegen sind im Kontext von autonomen Fahrzeugen andere Massnahmen erforderlich, um diese Ziele zu erreichen.

Aus der Sicht der Betreiber des konventionellen ÖV und von geteilten AF-Flotten steigern Pull-Massnahmen die Nachfrage insbesondere für aRP erheblich. Die höchsten Nettoeinnahmen für aRH- und aRP-Dienste werden erzielt, wenn sowohl Push- als auch Pull-Maßnahmen kombiniert werden.

Diskussion der Ergebnisse und weiterer Forschungsbedarf

Die Erfassung der Akzeptanz von aRP und aRH sowie die Modellierung des Reiseverhaltens im Allgemeinen, wenn autonome Fahrzeuge (AFs) breit verfügbar werden, sind mit verschiedenen Unsicherheiten verbunden. Besonders hervorzuheben ist, dass die Teilnehmenden der qualitativen Interviews sowie den Choice-Experimenten keine Erfahrung mit der Nutzung solcher Fahrzeuge hatte. Zudem ist die Modellierung autonomer Fahrzeuge und der damit verbundenen *on-demand*-Angeboten aufgrund ihrer Komplexität herausfordernd, da die Nachfrage und das Angebot von Fahrten in vielen Dimensionen miteinander verknüpft sind. In diesem Zusammenhang sehen wir den weiteren Forschungsbedarf wie folgt:

- Es wäre wertvoll, qualitative Interviews und Umfragen mit Teilnehmenden durchzuführen, die aus erster Hand Erfahrungen mit verschiedenen Formen autonomer Fahrzeuge gesammelt haben. Diese Teilnehmenden könnten in Zusammenarbeit mit Unternehmen rekrutiert werden, die solche Fahrzeuge bereits kommerziell anbieten oder im Rahmen von Pilotprojekten betreiben.

- In der *stated choice* Befragung wurden lediglich Wahlentscheide zwischen aRP, aRH, öffentlichen Verkehrsmitteln und privaten Autos untersucht. Je nach Tarifstruktur und angebotenen Abonnementen könnten diese neuen Verkehrsangebote jedoch auch wettbewerbsfähige Alternativen zum Radfahren und Zufussgehen darstellen. Zudem bieten der Fuss- und Veloverkehr Vorteile hinsichtlich der Senkung der Umweltbelastung und der Förderung der öffentlichen Gesundheit. Daher empfehlen wir, in zukünftigen Studien das Zusammenspiel zwischen diesen neuen Verkehrsmitteln und

dem Fuss- und Veloverkehr zu erforschen. Dabei sollte der Fokus darauf liegen, wie verkehrsplanerischer Massnahmen die Vorteile der jeweiligen Verkehrsmittel effektiv kombinieren und nutzen können.

- Die Fallstudien haben gezeigt, dass die Simulation des Reiseverhaltens mit grossen Flotten geteilter Fahrzeugen in komplexen Konfigurationen, die etwa auch das Angebote von intermodalen Fahrten umfassen, machbar ist. Die gewonnenen Erkenntnisse verdeutlichen sowohl die potenziellen Vorteile als auch die Herausforderungen, die autonome Fahrzeuge für das Verkehrssystem mit sich bringen. Es ist jedoch klar, dass diese Simulationsergebnisse einer detaillierteren Analyse bedürfen, um ein tieferes Verständnis darüber zu erlangen, wie autonome Fahrzeuge und insbesondere Fahrgemeinschaftsdienste dem Verkehrssystem, der Gesellschaft und der Umwelt zugutekommen könnten. Diese Erkenntnisse könnten auch in die iterative Verfeinerung und Weiterentwicklung der Simulationsszenarien einfliessen, was letztlich zu räumlich kontextbezogenen Empfehlungen für die Verkehrsplanung und -politik führen würde.

- Die Verfügbarkeit autonomer Fahrzeuge wird den Verkehr erheblich verändern und die Flächennutzung beeinflussen. Diese neuen Verkehrsmittel, also für aRP und aRH-Fahrdienste aber auch privat genutzte autonome Fahrzeuge, werden nicht nur die Verkehrsmittelwahl und den Fahrzeugbesitz beeinflussen, sondern auch die Zielwahl sowie die Art und Häufigkeit der ausgeübten Aktivitäten verändern. Um diese potenziellen Auswirkungen besser zu verstehen, ist es hilfreich, zu untersuchen, wie die Massenmotorisierung in der Vergangenheit verschiedene Aspekte des täglichen Lebens und der urbanen Umgebung verändert hat. Angesichts der Komplexität, alle relevanten Dimensionen zur Vorhersage zukünftiger Szenarien zu modellieren, könnte ein Backcasting-Ansatz von Nutzen sein. Durch die Beschreibung und Analyse verschiedener potenzieller Szenarien kann man deren Machbarkeit und Wünschbarkeit mittels geeigneter Verkehrsmodellen bewerten. Dieser Ansatz würde dazu beitragen, notwendige und wünschenswerte Massnahmen zu identifizieren, um den Fortschritt in Richtung eines bevorzugten Entwicklungspfads zu lenken.

Résumé

Vue d'ensemble et objectif

La numérisation transformera profondément la mobilité de demain, profitant à la fois aux services et aux véhicules. L'émergence des véhicules autonomes (VA) offre aux décideurs politiques, aux fabricants et aux consommateurs de nouvelles opportunités en matière d'autonomie, tout en nécessitant l'acceptation de certains risques. Les VA devraient augmenter la sécurité routière et permettant une utilisation plus efficace du réseau routier grâce à des distances de sécurité plus courtes. Parallèlement, les véhicules autonomes (VA) pourraient engendrer des kilomètres parcourus à vide et accroître la demande de déplacements en voiture. En plus de permettre une utilisation plus productive du temps de trajet (travail, lecture, etc.), les VA élargiront l'accès aux services de transport pour un public plus vaste. Toutefois, l'augmentation significative des volumes de trafic pourrait poser de sérieux problèmes, tels que les embouteillages, le bruit et la pollution, notamment dans les zones urbaines.

Le covoiturage, combiné à la technologie des véhicules autonomes (aRP), a le potentiel de réunir les avantages des transports publics (taux d'occupation des véhicules plus élevé) et des véhicules privés (trajets directs), permettant des gains substantiels en matière d'accessibilité, notamment dans les zones rurales et pendant les périodes de la journée où les services de transport public conventionnels ne peuvent pas être exploités efficacement. De plus, la transition de l'aRP vers un service de bus normal est progressive à mesure que le véhicule devient plus grand et que l'itinéraire devient plus régulier. En parallèle, il est probable que des flottes de véhicules autonomes exploitées commercialement offriront non seulement des services de covoiturage, mais également des services de transport à la demande (aRH), où les voyageurs sont pris en charge à un point d'origine unique et transportés directement à leur destination, de manière similaire à un taxi.

Ni l'acceptation ni le fonctionnement de l'aRP ne sont suffisamment bien compris. D'un point de vue de la planification à long terme, la compréhension des facteurs influençant le choix des déplacements utilisant l'aRP et les outils permettant de modéliser l'offre et la demande de l'aRP sont incomplètes et sont donc abordées dans cette recherche qui poursuit les objectifs suivants :

1. L'étude de la disposition à utiliser le covoiturage en Suisse ainsi que l'identification des facteurs déterminants pour le covoiturage avec et sans conducteur.

2. Quantifier les comportements de transport associés aux services de transport à la demande et de covoiturage fournis par les flottes de véhicules autonomes en concevant et en réalisant une nouvelle enquête de préférence déclarée.

3. Développer des algorithmes de planification et de dispatching optimaux qui permettent des lieux d'embarquement et de débarquement dynamiques afin de réduire la durée total des trajets.

4. Intégrer les résultats de l'enquête dans un modèle de transport basé sur des agents pour la Suisse et associer le modèle de choix avec des caractéristiques opérationnelles telles que le type et les dimensions des véhicules, la tarification, le temps d'attente, le temps d'accès et de trajet, ainsi que l'occupation des véhicules.

Étude qualitative

Une approche qualitative a été adoptée pour examiner les motivations et les obstacles influençant l'utilisation de l'aRP. L'objectif principal était d'identifier les facteurs déterminants pour son adoption. Un objectif secondaire consistait à évaluer des supports d'information, ultérieurement utilisés sous forme de vidéos explicatives dans une enquête par choix déclarés. Des entretiens qualitatifs semi-structurés ont été réalisés afin de mettre en lumière les attitudes et perceptions implicites, en recourant à des techniques de narration et des

techniques projectives pour approfondir la compréhension de ces aspects.

L'évaluation des entretiens a suivi un processus en deux étapes, conformément à la méthode d'analyse structurée du contenu. Dans un premier temps, deux collaborateurs indépendants ont codé les entretiens en s'appuyant sur des déterminants définis dans le cadre théorique. Dans un second temps, des codes supplémentaires ont été intégrés lorsque cela s'avérait nécessaire.

Les résultats des entretiens qualitatifs confirment les résultats des recherches précédentes sur les facteurs psychologiques pertinents déterminant l'acceptation du covoiturage. Ils peuvent être structurés selon le modèle d'acceptation de la technologie UTAUT (Unified Theory of Acceptance and Use of Technology). Les entretiens qualitatifs révèlent de nombreux facteurs pertinents concernant l'anticipation des performances (utilité perçue) qui influencent l'acceptation de l'aRP. Parmis ces facteurs figurent la sécurité de la technologie concernée, le temps d'attente et de trajet, les considérations environnementales, la fiabilité, la flexibilité, la disponibilité ou encore le confort. Il est à noter qu'aucun de ces facteurs n'est perçu distinctement comme un obstacle ou un moteur. Par exemple, la sécurité suscite des perceptions controversées : D'une Part l'aRP est perçu à la fois comme une technologie peu sûre associée à des risques, mais d'autre part, elle est des fois également perçue comme un mode de transport plus sécurisé que les voitures conventionnelles conduites par des humains. Ainsi, tous les facteurs d'influence peuvent être mis en relation aussi bien avec des motivations qu'avec des barrières à l'utilisation de l'aRP.

Pour certains facteurs (temps, flexibilité, disponibilité, confort et considérations environnementales), la classification en tant qu'obstacle ou moteur dépend de l'évaluation du covoiturage par rapport à la voiture privée ou aux transports publics. Par exemple, une voiture privée est perçue comme étant plus fiable que le covoiturage dans des véhicules autonomes (la disponibilité est donc perçue comme un obstacle) ; mais le covoiturage dans des véhicules autonomes est perçu comme étant plus flexible que les transports publics (la disponibilité est donc perçue comme un moteur). Pour les facteurs temps, flexibilité, disponibilité et confort, cette comparaison conduit à une évaluation favorable du covoiturage par rapport aux transports publics et à une perception défavorable par rapport à la voiture privée. Un autre facteur pertinent est la fiabilité. Notre étude souligne l'importance de la fiabilité, en particulier dans le contexte suisse, où les transports publics sont ponctuels.

En ce qui concerne l'effort attendu, les facteurs et les arguments qui en découlent sont moins controversés. Des facteurs tels que la planification et les informations fourni par l'application sont clairement perçus comme des moteurs. Ce sont également les facteurs les plus fréquemment mentionnés. Les préoccupations liées à la facilité d'utilisation perçue semblent moins importantes que les avantages perçus.

En ce qui concerne les coûts perçus, nous observons les mêmes mécanismes que ceux décrits pour certains des facteurs de performance : le covoiturage dans des véhicules autonomes est perçu comme plus cher que les transports publics et comme moins cher qu'une voiture privée.

Enfin, les aspects sociaux ont été discutés tant au niveau de la sécurité que de la socialisation. De manière surprenante, la sécurité n'a été évoquée que par quelques participants. Dans le cadre d'un système de transport inclusif et accessible, il est important de prendre en compte les aspects liés à la sécurité de l'espace public au sein d'un VA.

Enquête sur les préférences déclarées

Afin de comprendre et quantifier l'impact de l'aRH et de l'aRP sur le comportement des voyageurs, une enquête sur les préférences déclarées a été réalisée. L'échantillon a été tiré àl'aide d'un panel d'une société d'étude de marché selon des quotas pour s'assurer que les répondants représentent correctement la population cible, c'est-à-dire tous les résidents âgés de plus de 18 ans vivant dans une ville ou une agglomération urbaine suisse et qui se rendent régulièrement à une activité nécessitant un déplacement de plus de 2 kilomètres. Des quotas représentatifs ont établis pour la disponibilité des voitures, les groupes

d'âge, la situation professionnelle, le sexe, la langue et le type d'espace de la commune de résidence. Les personnes disposant d'un abonnement général (AG) ou régionale ont été suréchantillonnées afin de tester de manière plus fiable si les préferences des personnes utilisant fréquemment les transports publics diffèrent de celles des autres personnes en termes d'aRP et d'aRH.

L'enquête se compose de deux questionnaires en ligne que les répondants remplissent en deux vagues afin de permettre une expérience de type « Pivot-Design-Mode-Choice ». Le premier questionnaire recueille des données sur les trajets domicile-travail et de loisirs effectués régulièrement ainsi que des informations sur la possession d'outils de mobilité. Le second questionnaire comprenait deux expériences de choix de mode qui incluaient le ride-hailing et le ride-pooling comme nouveaux moyens de transport. En fonction de la disponibilité des liaisons de transport public entre le point de départ et la destination du déplacement déclaré, les alternatives de ride-pooling et de ride-hailing ont été définies comme des trajets directs ou intermodaux.

Entre les deux expériences de choix de mode, les répondants ont été invités à indiquer s'ils envisageraient d'adapter leur possession d'une voiture dans un contexte où les VA pourraient être possédes en privé et mis à disposition des grands opérateurs de flottes pour fournir des services de ride-hailing et ride-pooling. Pour garantir une compréhension commune de la façon dont fonctionne le covoiturage et comment il peut être éxploité avec des véhicules autonomes, nous avons produit des vidéos explicatives que les répondants ont visionnées avant de répondre aux expériences de choix de mode. Après l'expérience de choix de mode, les personnes interrogées ont indiqué si elles étaient prêtes à acheter des abonnements pour des services de covoiturage et ont exprimé leurs attitudes vis-à-vis de ces services.

L'un des principaux défis de l'approche de conception pivot était de s'assurer, sur la base des trajets rapportés, que les VA soient représentés dans les scénarios de décision en tant qu'alternatives pertinentes pour les itinéraires mono et intermodaux. En outre, la conception expérimentale devait garantir que les scénarios de décision présentaient des comparaisons relevantes entre les différentes alternatives tout en reflétant des ratios réalistes de temps de trajet et de coût.

La Fig. I illustre les parts des trois modes de transport alternatifs dans toutes les scénarios de décision. Elle différencie les cas où la voiture ou les transports publics ont été utilisés pour le trajet rapporté et si l'alternative du véhicule autonome a été spécifiée comme une option monomodale ou intermodale.

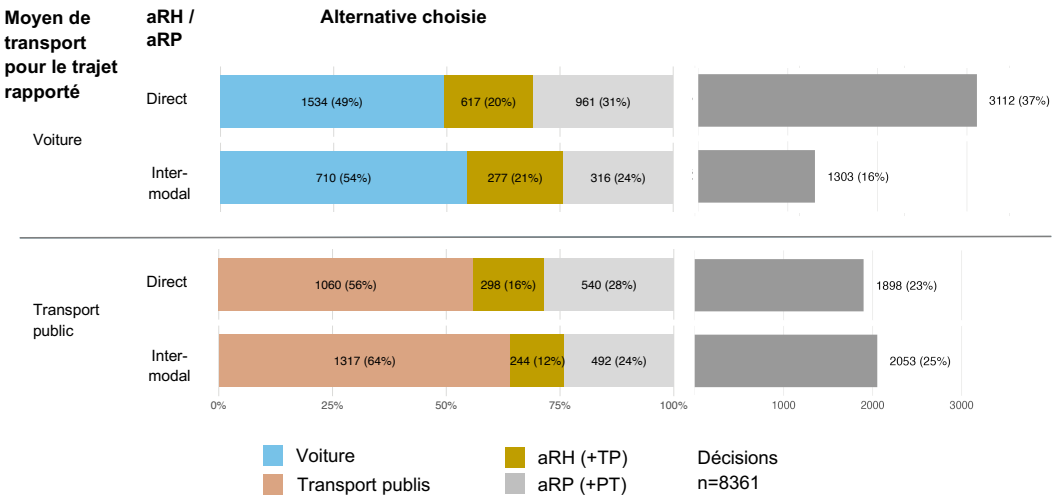


Fig. I *Proportions des moyens de transport choisis selon le motif du déplacement et le moyen de transport choisi pour le trajet rapporté*

Dans environ 50 à 65 % des cas, le mode de transport utilisé pour le voyage de référence a été retenu. Les alternatives aRH et aRP ont été sélectionnées dans 12 à 31 % des cas. Cela montre que la stratégie de conception de l'expérience a fonctionné comme prévu et que l'échantillon permet d'estimer des modèles de choix significatifs indépendants du mode de référence et du type de trajet aRH et aRP. Grâce à une sélection minutieuse de l'échantillon, un nombre suffisamment important d'observations a également été obtenu pour chaque type d'expérience de décision.

Les résultats du modèle de choix du mode montrent que la durée du trajet est évalué plus négativement pour l'aRP et l'aRH que pour les transports publics et les voitures privées. Les gains de temps de déplacement offerts par ces modes par rapport aux transports publics, combinés à leur coût réduit par rapport aux voitures privées, leur permettent d'attirer des parts de marché des deux modes existants. Cela suggère que les avantages de l'aRP et de l'aRH, en termes d'efficacité et de rentabilité, les positionnent comme des alternatives compétitives capables de capter des usagers des transports publics et des voitures privées.

Les constantes négatives spécifiques aux alternatives aRP et aRH capturent la moyenne de tous les effets non observés et pourraient donc être interprétées comme une réticence générale des personnes interrogées à choisir ces nouveaux modes, ce qui affecte directement leurs parts de marché anticipées. La constante est moins fort pour le covoiturage que pour le transport en commun et chez les personnes qui sont plus ouvertes aux innovations en matière de mobilité que la population en générale. On peut raisonnablement s'attendre à ce que cette réticence diminue généralement au fil du temps, à mesure que les utilisateurs se familiariseront avec ces nouveaux moyens de transport.

La Fig. II montre les coûts horaires unitaires (CH) selon la distance de trajet et le moyen de transport (voiture, transports publics, et aRP et aRH, en tant que déplacements directs et intermodaux). Pour tous les modes, les coûts horaires unitaires augmentent avec la distance du voyage en raisong d'une spécification de paramètre d'élasticité en fonction de la distance. Les pentes pour la voiture et les transports publics confirment les conclusions d'études antérieures qui montrent des coûts horaires unitaires plus élevés pour les déplacements pendulaires que pour les déplacements de loisirs et des différences croissantes entre les coûts horaires unitaires pour les déplacements pendulaires et les déplacements de loisirs en transports publics pour les trajets plus longs par rapport à la voiture.

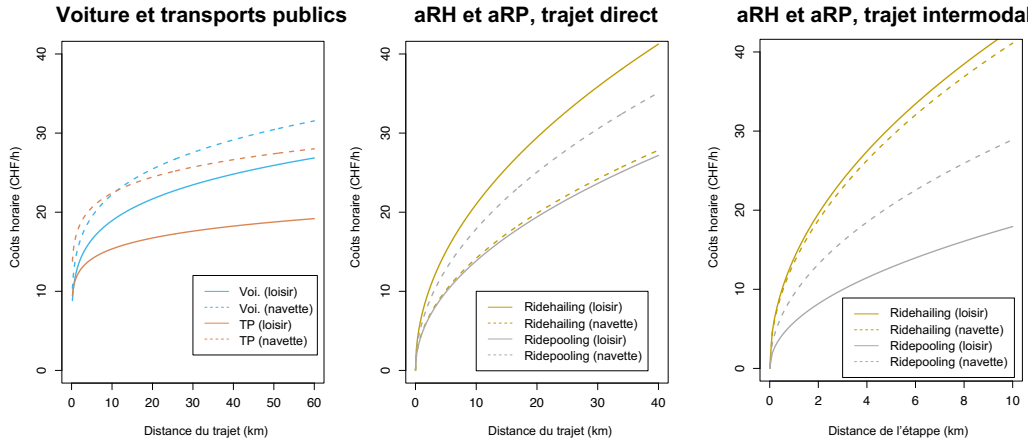


Fig. II *Coûts horaires unitaires selon le motif de déplacement et le moyen de transport*

Les courbes des coûts horaires unitaires pour aRP et aRH en tant que moyens de transport directs montrent une augmentation plus prononcée pour les longues distances de voyage par rapport à la voiture et aux transports publics. Cela suggère que le confort de voyage avec ces moyens de transport est perçu comme moins avantageux lors de longs trajets. Cette appréciation est intuitivement compréhensible : Dans les transports publics, différents types de véhicules sont généralement utilisés pour différentes longueurs de trajet, alors que

les personnes interrogées ont probablement supposé que le même type de véhicule était utilisé pour les aRP et les aRH, quelle que soit la distance.

Pour l'aRP, les coûts horaires unitaires sont plus élevés pour les trajets utilitaires que pour les trajets de loisir. Cette constatation est conforme aux résultats de cette étude et d'études antérieures concernant la voiture et les transports publics. Il est à noter que la valeur du temps a été estimée plus faible pour les trajets domicile-travail que pour les trajets de loisirs. Une explication possible pourrait être que le fait de travailler pendant le trajet dans une AV en tant que véhicule pendulaire a été perçu comme une possibilité réaliste et que, par conséquent, le temps de trajet est moins fortement perçu. Ce résultat devrait toutefois être examiné plus en détail dans de futures études.

Le graphique montre que les réductions de temps de trajet sur les étapes intermodales vers ou depuis la gare sont en général plus fortement évaluées que les réductions de temps de trajet dans les transports publics. Ceci est particulièrement vrai pour les aRH. Les personnes interrogées pourraient préférer des temps de trajet plus courts, car cela pourrait être considéré comme réduisant la probabilité de manquer la correspondance avec le segment de train suivant.

Certains aspects de l'expérience de voyage avec l'aRP et l'aRH, qui se distinguent des modes existants, n'ont pas été entièrement pris en compte par les variables décrivant ces alternatives, mais peuvent expliquer en partie la réticence observée. Par exemple, l'utilisation de l'aRP et de l'aRH nécessite généralement de faire des réservations via une application, ce qui alourdit la charge de planification et d'exécution d'un voyage. En outre, la demande et l'offre d'aRH et d'aRP fluctuent en fonction de l'heure de la journée et du lieu, créant un aspect d'incertitude de planification qui ne peut être que partiellement abordé dans les enquêtes sur les préférences déclarées. En outre, les opérateurs de flotte sont susceptibles de mettre en œuvre une tarification dynamique pour gérer ces fluctuations, ce qui augmenterait encore le travail de planification pour les clients.

L'expérience sur la possession d'outils de mobilité montre une réticence générale à renoncer à une voiture personnelle, même si des flottes de véhicules autonomes partagés pourraient permettre une offre de mobilité complète sans véhicule personnel. La Fig. III montre quelles sont les proportions de personnes interrogées qui disposent actuellement d'une voiture dans leur ménage et qui renonceraient à en posséder une ou qui achèteraient un VA privé si celui-ci était proposé à l'achat à différents prix supplémentaires par rapport aux voitures traditionnelles.

Comme attendu, le pourcentage de répondants prêts à acheter un véhicule autonome privé diminue à mesure que le supplément de prix augmente, atteignant son niveau le plus bas pour la majoration de 9'000 CHF, où seuls environ 10 % des personnes interrogées se disent intéressées. Fait intéressant, l'intérêt maximal a été observé pour un supplément de 6'000 CHF, avec 31 % des répondants favorables à l'achat, tandis qu'il était légèrement inférieur, à 26 %, pour une prime de 3'000 CHF.

Étant donné la taille relativement réduite de l'échantillon, ces différences pourraient s'expliquer par des variations statistiques. Cependant, elles pourraient également refléter des attentes divergentes des répondants concernant la faisabilité technologique des véhicules autonomes privés en fonction du niveau du prix supplementaire. Cette hypothèse pourrait aussi éclairer pourquoi la proportion de répondants prêts à renoncer à la possession d'une voiture augmente parallèlement à l'augmentation du prix supplementaire.

À l'inverse, les répondants se sont montrés très enclins à acheter une carte de réduction pour les aRP, en particulier ceux qui utilisent rarement les transports publics et qui ne disposent pas d'abonnement ou possèdent uniquement un demi-tarif (voir illustration IV). Bien qu'une partie de cet intérêt puisse être attribuée à des effets de cadrage, ces résultats mettent en lumière le potentiel commercial significatif des cartes de réduction, tant pour les aRP que pour les aRH.

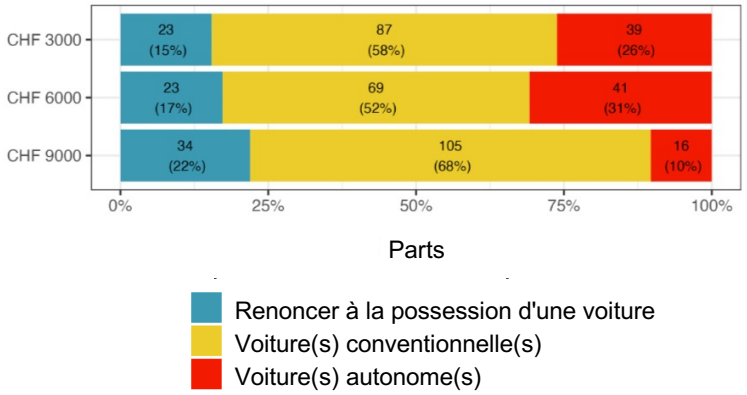


Fig. III *Intention d'adapter la possession d'une voiture en fonction des différents prix supplémentaires pour une voiture autonome*

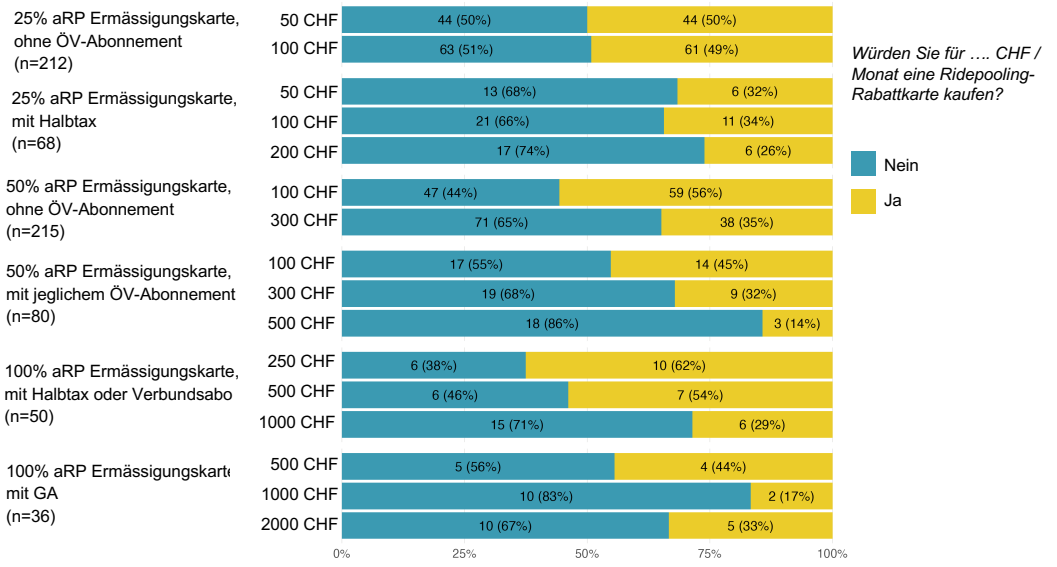


Fig. IV *Intention d'acheter un abonnement aRP, selon la possession d'un abonnement de transports publics et le niveau de prix.*

Optimisation operationelle de la flotte de covoiturage

Un cadre de simulation en temps réel a été développé, qui permet de prendre en compte les conditions de trafic variables lors de l'optimisation de l'allocation de la flotte de covoiturage à la demande fluctuante. Grâce à ce cadre, il a été démontré, en utilisant l'optimisation en ligne avec des algorithmes de résolution spécifiques, que 97% des courses de taxi actuellement enregistrées à Manhattan (New York, États-Unis) pourraient être effectuées avec seulement 2000 véhicules de covoiturage pouvant transporter jusqu'à cinq passagers chacun, au lieu des 13000 taxis actuels. Ces 2 000 taxis peuvent atteindre un temps d'attente moyen de moins de 2 minutes et un délai moyen à l'intérieur du véhicule de moins de 7 minutes. Cela montre qu'il existe un potentiel important d'amélioration des conditions de circulation avec un impact limité sur la durée des trajets si une ville décide de limiter le ride-hailing au profit du ride-pooling. Cependant, il s'est avéré que l'intégration de ce nouvel algorithme dans la simulation de transport multi-agents (MATSim) serait une tâche laborieuse qui pourrait augmenter de manière significative le temps de calcul. En même temps, l'impact sur la demande de transport par cet efficacité opérationnelle accrue fournie par la nouvelle optimisation en ligne est considéré comme limité par rapport aux algorithmes déjà mis en œuvre dans MATSim. Nous avons donc décidé de ne pas utiliser le nouvel algorithme pour les études de cas.

Études de cas

Une approche fondée sur une simulation de transport multi-agents (MATSim) a été utilisée pour evaluer les impacts potentiels des véhicules autonomes dans trois régions urbaines en Suisse : Coire, Fribourg et Zurich. Pour ce faire, la demande a été extraite du modèle national, ce qui permet de maintenir le trafic de transit. Un modèle de transport basé sur des agents, MATSim, a été combiné avec le modèle de choix de mode estimé à partir des données de l'enquête sur le préferences déclarées pour permettre aux individus modélisées de faire des compromis entre la voiture privée (autonome), le vélo, la marche, les transports publics et les services aRH et aRP. De plus, un modèle de possesssion des instruments de mobilité a été appliqué à la population pour anticiper le changement dans la possession des véhicules, compte tenu de la disponibilité généralisée des services autonomes partagés. Bien qu'il soit envisageable que les véhicules autonomes modifient également l'offre de transports publics réguliers, les études de cas excluent de tels changements.

Pour chaque région, le scénario de base représentant la demande et l'offre de transport actuelles a été calibré pour correspondre aux parts modales observées dans chaque région. Ensuite, une taille de flotte appropriée pour les services aRH et aRP a été appliquée sur la base des résultats d'une recherche par quadrillage, qui assure la rentabilité tout en maintenant un niveau élevé de demande et de satisfaction des utilisateurs. Enfin, les tarifs des services aRH et aRP sont conçus de manière à imiter les tarifs des voitures et des transports publics, respectivement. En effet, aRH est considéré comme un service privé et exploité pour attirer une forte demande, tandis qu'aRP fait partie des opérations de transport public.

Pour chaque région étudiée, cinq scénarios ont été simulés : l'état actuel du système, l'introduction des VA, et trois scénarios avec des mesures politiques visant à attirer et à pousser les individus vers un service aRP plus durable (Tab. I). Les trois scénarios politiques comprenaient des mesures d'attraction, telles que des subventions pour les services aRP en fonction de la qualité des transports publics au point d'origine ou à la destination, et des mesures d'incitation sous la forme d'une taxe basée sur la distance (Coire et Fribourg) et d'une péage de cordon (Zurich).

Du point de vue du système de transport global, les résultats montrent que l'introduction des services aRP et aRH réduit la durée totale des trajets, augmente la part des moyens de transport motorisés non publics et accroît la distance totale parcourue par les véhicules (voir les Fig. V, Fig. VI et Fig. VII, par exemple pour la région de Coire). C'est à Coire et à Fribourg que la part modale de la voiture diminue le plus grâce à l'offre d'aRH et d'aRP, tandis qu'à Zurich, les transports publics sont les plus affectés. Le taux d'occupation des véhicules aRP reste relativement faible, la majorité des trajets étant effectués soit sans

Tab. I *Aperçu des scénarios*

	Zurich	Coire	Fribourg
Scénario A : Attraction	Subvention pour les services aRP en fonction de la qualité des transports publics (Classification plus faible du point de départ où d'arrivé) : A : 0% ; B : 20% ; C : 40% ; D : 60% ; aucun : 80%		
Scénario B : Incitation	Péage de cordon (Péage à la frontière communale de la ville) pour les véhicules non-partagées : 6 CHF	taxe additionelle basée sur la distance puur les véhicules non-partagées : +0.2 CHF/km ; aRH : +0.25 CHF/km	
Scénario C : Attraction et Incitation	Combination de A et B		
Population	10%	100%	100%
Flotte aRP	1680	1200	2400
Flotte aRH	1200	800	1800

passagers, soit avec un seul passager. Cela souligne la nécessité de mettre en place des mesures politiques pour améliorer l'efficacité de ces services.

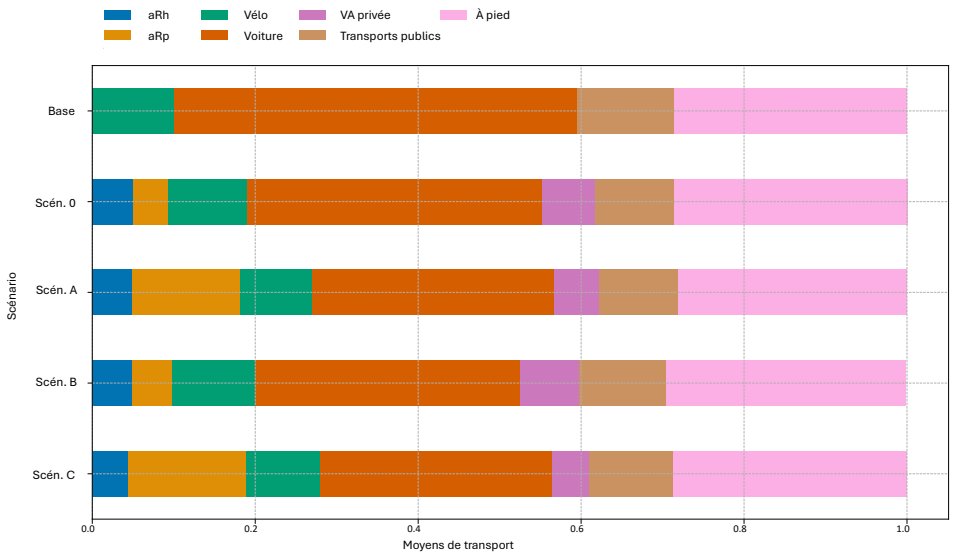


Fig. V *Moyens de transport utilisés selo nombre de trajets dans l'exemple de cas de Coire*

Les trois paquets de mesures de planification des transports testées ont des effets similaires dans les trois régions étudiées. Le taux d'occupation dans les véhicules aRP augmente nettement, mais au détriment d'une augmentation de la distance totale parcourue, l'augmentation étant la plus forte à Zurich.

En supposant que les véhicules autonomes nécessitent 17 % d'espace routier en moins (selon le taux de pénétration indiqué dans les études de cas) et exploitent plus efficacement la capacité disponible du réseau, les scénarios de base pour toutes les régions montrent une augmentation de l'utilisation du réseau. Cet effet est toutefois le moins marqué dans la région de Coire. Dans cette région, les mesures envisagées dans le scénario entraînent des changements minimes dans l'utilisation du réseau par rapport au scénario de base

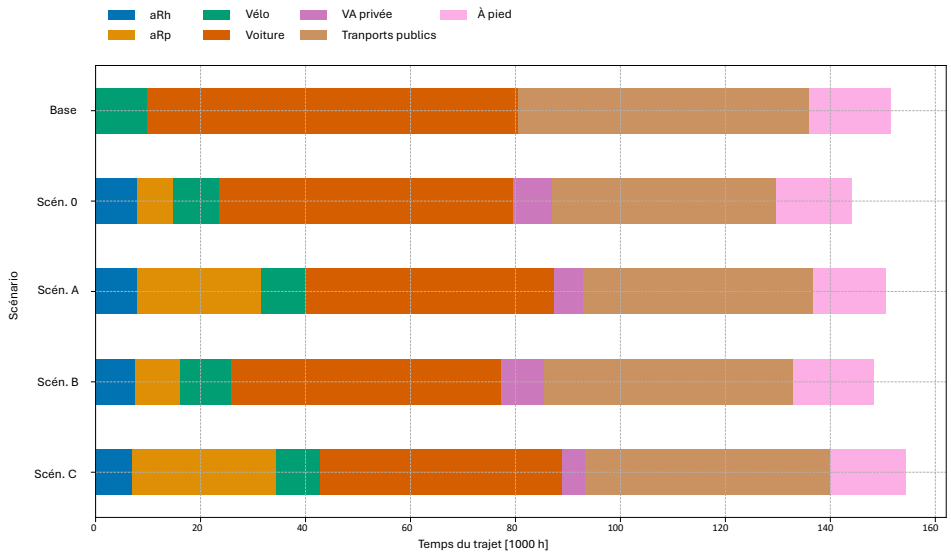


Fig. VI *Temps de trajet par moyens de transport à Coire (sans le temps d'attente pour l'aRP et l'aRH)*

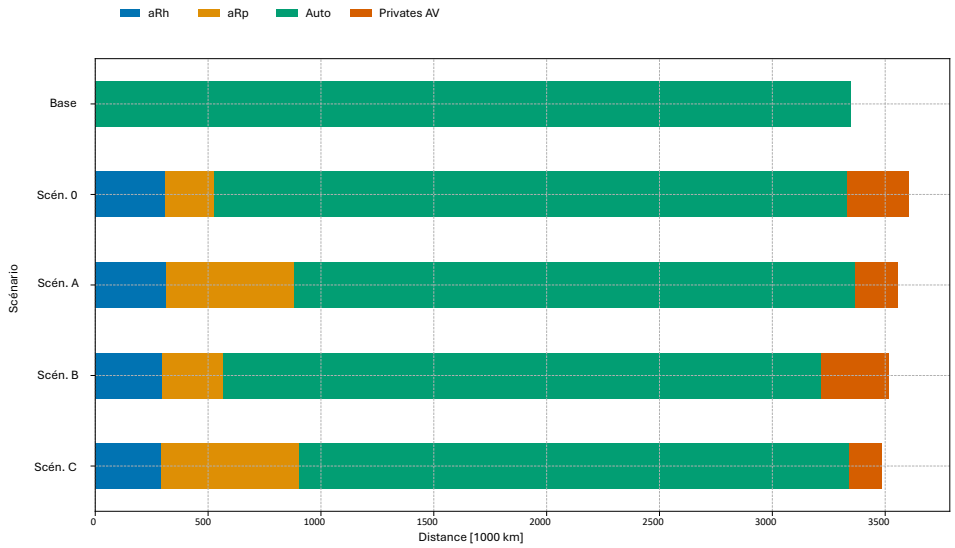


Fig. VII *Distance totale des véhicules à Coire*

sans véhicules autonomes. En effet, dans le scénario 3, l'utilisation du réseau diminue légèrement.

Dans les régions de Fribourg et de Zurich, l'utilisation du réseau augmente respectivement de 7% et de 18 % selon les scénarios. À Fribourg, les différentes mesures mises en place entraînent une légère diminution de l'utilisation du réseau, bien qu'elle reste supérieure à celle observée dans le scénario sans véhicules autonomes. À Zurich, en revanche, les mesures incitatives provoquent une augmentation de 26 % de l'utilisation du réseau. Cela s'explique principalement par le fait que les voyageurs dans cette région optent plus fréquemment pour des services de covoiturage autonome (aRP) ou de navette autonome (aRH) plutôt que pour les transports publics.

Les résultats indiquent que les mesures testées sont efficaces dans les zones moins densément peuplées, améliorant l'accessibilité sans augmenter l'utilisation du réseau. Toutefois, dans les régions urbaines densément peuplées, des mesures différentes sont nécessaires

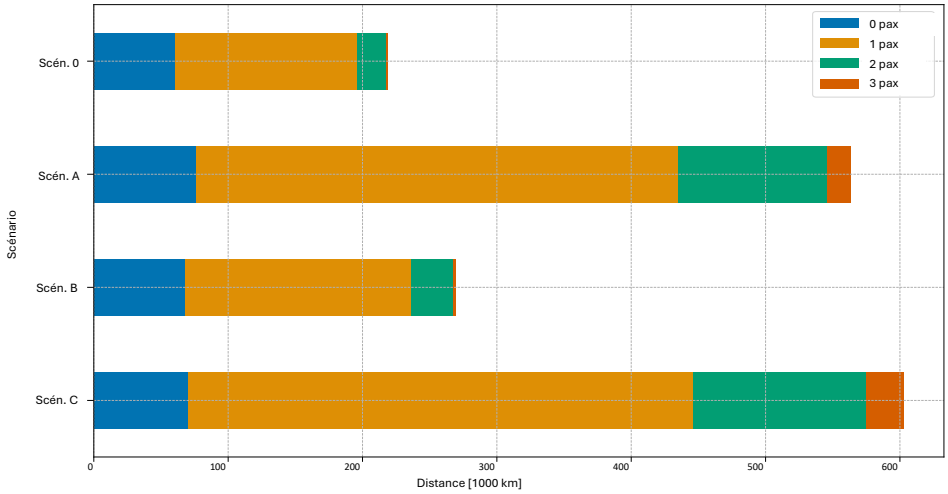


Fig. VIII *Distance totale des véhicules aRP selon le taux de l'occupation à Coire*

pour obtenir des résultats similaires dans le contexte des véhicules autonomes.

Du point de vue des opérateurs d'aRP et d'aRH, les mesures de politique d'attraction augmentent considérablement la demande, en particulier pour l'aRP. Le revenu net le plus élevé pour les services aRH et aRP est obtenu lorsque les politiques « push » et « pull » sont appliquées.

Limites et recherches futures

L'évaluation de l'acceptation de l'aRP et de l'aRH et la modélisation du comportement des voyageurs en général, si les VA deviennent largement disponibles, impliquent diverses incertitudes. Notamment, aucun des participants aux entretiens qualitatifs ou aux expériences de choix n'avait eu l'occasion de voyager avec de tels véhicules. En outre, la modélisation des véhicules autonomes et des services de transport qui leur sont associés est intrinsèquement complexe, car elle a un impact sur la demande et l'offre de transport dans de nombreuses dimensions interconnectées. Dans ce contexte, nous recommandons les directions suivantes pour la recherche en future :

- Il serait utile de mener des entretiens qualitatifs et des enquêtes sur les préferances déclarés avec des participants qui ont une expérience directe des déplacements à bord de diverses formes de véhicules autonomes. Les participants pourraient être recrutés en collaboration avec des entreprises qui exploitent ces véhicules.

- Dans l'enquête sur les préferences déclarés, seuls les compromis entre le covoiturage et le transport à la demande avec les transports publics et les véhicules motorisés privés ont été testés. Toutefois, en fonction de la structure tarifaire et des cartes de transport potentielles, ces nouveaux modes pourraient également offrir des alternatives compétitives au vélo et à la marche à pied. En outre, les modes de transport actifs présentent des avantages en termes de réduction de l'impact environnemental et de santé publique. Par conséquent, nous recommandons que les études futures explorent l'interaction entre ces nouveaux modes et les options de transport actif, en mettant l'accent sur la façon dont les mesures de politique des transports peuvent efficacement intégrer et tirer parti de leurs avantages respectifs.

- Les études de cas ont montré que la simulation du comportement de déplacement avec de grandes flottes de véhicules autonomes partagés dans des configurations complexes, telles que les trajets intermodaux, est faisable. Les informations recueillies mettent en évidence à la fois les avantages potentiels et les défis que les véhicules au-

tonomes présentent pour le système de transport. Cependant, il est évident que ces résultats de simulation nécessitent une analyse plus approfondie pour comprendre comment les véhicules autonomes, et en particulier les services de covoiturage, pourraient bénéficier au système de transport, à la société et à l'environnement. Ces informations pourraient également alimenter des ajustements itératifs et un développement supplémentaire des scénarios de simulation, ce qui permettrait finalement de formuler des recommandations politiques adaptées aux contextes spatiaux.

- La disponibilité des véhicules autonomes transformera considérablement les transports et influencera l'aménagement du territoire. Ces nouvelles options de transport, y compris les véhicules autonomes partagés et privés, n'affecteront pas seulement le choix du mode de transport et la possession de véhicules, mais aussi le choix des destinations et les types et la fréquence des activités menées. Pour mieux comprendre cet impact potentiel, il est utile d'examiner comment la motorisation de masse a historiquement changé divers aspects de la vie quotidienne et de l'environnement bâti. Étant donné la complexité de la modélisation de toutes les dimensions pertinentes pour prédire les scénarios futurs, une approche rétrospective pourrait s'avérer précieuse. En décrivant divers scénarios potentiels, on peut évaluer leur faisabilité et leur opportunité à l'aide des modèles de transport appropriés. Cette approche aiderait à identifier les mesures nécessaires et souhaitables pour orienter le développement vers une direction privilégiée.

1 Introduction

1.1 Background

Digitisation will significantly change future mobility. Services, as well as vehicles, will increasingly benefit from this digitisation. The advent of autonomous vehicles (AVs) provides policy-makers, manufacturers and consumers use of autonomous opportunities while they have to accept their risks. AVs are expected to increase traffic safety and allow for more efficient use of the road network due to shorter headways. At the same time, AVs could also generate empty vehicle kilometres traveled and increase the demand for car travel. Not only can the time for driving be spent otherwise (e.g., working, reading etc.), AV will also increase the access to transport services for a broader audience. The likely significant increase in traffic volume can pose major problems (e.g., congestion, noise, pollution etc.), especially in urban regions.

Ride-pooling (RP), i.e., the usage of vehicles with 4 to 8 seats for shared taxi services, is seen as a potential solution to lessen the undesirable impact of AV. Pooling services allow different customers to sequentially share parts of their trip, while optimizing the overall route of travel and minimizing detours for each individual passenger. So far, such services have only been tested with conventional vehicles. In this case, the driver's salary makes up a considerable part of the operating costs. Partially for this reason, RP services have attracted limited demand. Data on ride-hailing usage in New York and Boston shows that only about 15% to 20% of all ride-hailing trips were pooled (Schneider, 2022a,b) before the service was ceased due to the COVID-19 pandemic in 2020. MOIA, a transport service in Hamburg, Germany, only offers RP trips. It operated a fleet of 250 vehicles in 2019 and served on average about 6 000 trips per day. With an average occupancy rate of 1.33, the service is only responsible for about 0.11% of all trips and remained a niche product (MOIA, 2021b).

Ride-pooling, combined with AV technology (aRP), has the potential to combine the advantages of public transport (higher vehicle occupancy) and private vehicles (direct trips) and hence allows for substantial accessibility gains, especially in rural areas and during times of the day for which conventional public transport services cannot be efficiently operated. In addition, the transition from RP into a normal bus service is gradual as the vehicle becomes larger and the time table/route becomes more regular. At the same time, it is likely that commercially operated AV fleets will offer not only ride-pooling but also ride-hailing (aRH) services, where travelers are picked up from a single point of origin and transported directly to their destination, much like a taxi today.

Neither the acceptance nor the operation of RP are sufficiently well understood. From a long-term planning perspective, the understanding of the factors influencing the choice of travel using RP and tools to model demand and supply of RP are incomplete and need to be improved.

Results of revealed preference (RP) and stated preference (SP) surveys on pooled versus private ride-hailing demonstrate that the willingness-to-share (WTS) depends on age, gender, trip purpose, personal attitudes, travel time, waiting time and number of passengers (e.g. Kang *et al.*, 2021a; Hörl *et al.*, 2020a; Alonso-González *et al.*, 2020). The only existing survey in Switzerland, to our knowledge, did not include important behavioural aspects with regards to pooling such as distance to pick-up / drop-off points, travel and waiting time, reliability and number of other passengers in the vehicle (Hörl *et al.*, 2019b).

Agent-based models are being utilized extensively to forecast the potential demand for single-occupancy or pooled shared AV fleets, the main reason being the capability to capture operational decisions of service operators and capture dynamics between supply and demand. Previous forecasting studies have looked at the impacts of different AV service designs, private AV penetration levels, service costs, ridepooling algorithms, dispatching algorithms, rebalancing algorithms, service area size, parking constraints, and AV efficiency.

Most of these impacts have been looked at in isolation. Pairing behavioural models, based on survey data, with agent-based models to forecast AV demand and with automatic price adjustment, to our knowledge, was only done in SVI 2016/001 (Hörl *et al.*, 2019b); the simulated scenarios did not feature ridepooling as an option. It is necessary to extend the current forecasting based on agent-based models with pooling algorithms and test their effectiveness on a large scale.

Recently, there has been an increasing interest in investigating the dynamic version of the dial-a-ride problem (DARP). Early solutions of DARP have mainly utilized heuristic methods (Wilson and Urban Systems Laboratory, 1971). Psaraftis (1980) introduced the first model with a dynamic programming approach for both the static and dynamic DARP. In the past 40 years, there has been a steady growth in methods to solve DARP (e.g. Cordeau and Laporte, 2007; Ho *et al.*, 2018).

1.2 Research objectives

This research pursues the following objectives:

1. Investigating the willingness-to-share (i.e., ride-pooling) for Switzerland, discovering the relevant drivers and barriers of ridepooling with and without driver.

2. Quantifying travel behavior associated with ride-hailing and ride-pooling services provided by autonomous vehicle fleets by designing and implementing a new stated preference survey.

3. Incorporating survey results into an agent-based transport demand model of Switzerland and pairing the choice model with operational characteristics, e.g., vehicle type and size, pricing, waiting time, access and travel time and vehicle occupancy.

4. Developing optimal planning/dispatching algorithms that can be used in conjunction with MATSim and separately, that allow for dynamic pick-up and drop-off locations to improve overall travel times.

1.3 Overview of the research project and the report

The project follows a mixed-method approach. Fig. 1 shows how the different work packages ensure up- and downstream integration of the different research methods.

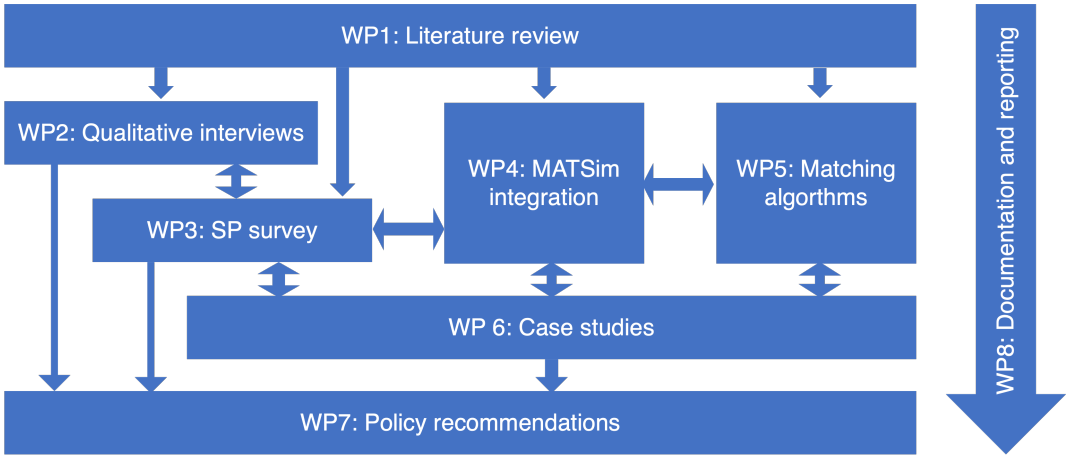


Fig. 1 *Overview of work packages*

These work packages are documented in the following chapters:

Chapter 2 presents the *literature review* conducted as part of work package 1. It summarises national and international literature and covers travel behaviour, simulation of ridepooling and autonomous vehicles and optimisation methods.
Chapter 3 aims to identify individual's most important drivers and barriers regarding the us-

age of ridepooling services. It does so by means of *qualitative interviews* conducted as part of work package 2.
Chapter 4 outlines the development, implementation and execution of a *stated preference survey* conducted as part of work package 3. This survey aims to identify the behavioral, supply-side and socio-economic factors that determine the use of ridepooling and ride-hailing. Special attention is paid to the fact that respondents are likely not to be familiar with ridepooling and ride-hailing services. To this end, visual material is developed to explain these services.

Chapter 5 details the integration of aRP and aRH within the MATSim framework to support both mono- and intermodal trips (WP4). Chapter 6 evaluates the efficiency gains achieved through an improved matching algorithm for ride-pooling (WP5). Chapter 7 summarises the implementation of the case studies and the results they produced (WP5). The policy recommendations in Chapter 9 are derived from all preceding work packages and form the basis for the synthesis and conclusions presented in Chapter 10.2.

2 Literature

This section reviews the scientific literature on ride-pooling covering psychological aspects, existing surveys on travel behaviour with ride-pooling options as well as simulations studies and research on optimisation of ridepooling operations.

2.1 Psychological factors influencing the adoption of ridepooling

This section presents an overview of the literature on psychological factors that influence the adoption of ridepooling in autonomous vehicles (aRP). aRP is a new form of mobility which is currently tested in pilot projects (e.g. Hagenzieker *et al.*, 2021). The factors influencing the acceptance of AVs have already been researched in numerous studies and summarized in literature reviews (Becker and Axhausen, 2017a; Golbabaei *et al.*, 2020). The following study is based on the assumption that the adoption of aRP can only be fully understood, if there is a deeper understanding of the underlying psychological factors such as drivers and barriers from a user perspective. Research on psychological factors influencing the intention to use aRP is limited to a few qualitative and quantitative studies (e.g., Zubin *et al.*, 2020; Sanguinetti *et al.*, 2019; Nordhoff *et al.*, 2018). In the following chapter the relevant literature for ridepooling with a driver (RP) and aRP is summarized, a model to cluster the relevant factors for aRP is introduced and the identified factors in the literature are clustered accordingly. The objective of this section is to identify relevant psychological factors that influence the adoption of aRP as derived from the existing literature.

2.1.1 Methods

The relevant literature regarding RP and aRP was identified by means of a literature search on Sciencedirect.com and Web of Science. The key words *autonomous*, *automated*, *carpooling*, *ridesharing*, *ridepooling* and *ridehailing* were combined with the Boolean operators AND/OR. Further, the search was limited to the key words in the abstracts of the articles. Subsequently, the search results were examined for their relevance. Studies that did not include psychological factors or human factors were excluded from the review. In the following chapter, the current state of research is presented. This narrative review includes three review papers and 22 empirical studies.

2.1.2 Psychological factors influencing the adoption of ridepooling

RP is an on-demand mobility service where travelers share a ride with other passengers during the whole or a certain part of the trip. This service differs from carpooling, a service where private people offer a shared ride (Sonneberg *et al.*, 2019). Previous studies have investigated factors that influence the intention to use ridepooling and carpooling. The most frequently investigated factors are cost/savings (Correia and Viegas, 2011; Nielsen *et al.*, 2015), trust (Amirkiaee and Evangelopoulos, 2018; Correia and Viegas, 2011; Créno and Cahour, 2014), safety (Nielsen *et al.*, 2015; Créno and Cahour, 2014) and socializing (Nielsen *et al.*, 2015; Amirkiaee and Evangelopoulos, 2018; Adelé and Dionisio, 2020; Créno and Cahour, 2014). Other factors of importance are flexibility (Nielsen *et al.*, 2015; Correia and Viegas, 2011), norms (Amirkiaee and Evangelopoulos, 2018), time (Ciari and Axhausen, 2012), environmental issues (Delhomme and Gheorghiu, 2016), comfort (Adelé and Dionisio, 2020; Créno and Cahour, 2014), privacy (Radke *et al.*, 2011), security (Nielsen *et al.*, 2015; Radke *et al.*, 2011) and hedonistic motivation (Adelé and Dionisio, 2020). The majority of these factors are also relevant in aRP and are therefore defined in more detail in the next chapter.

2.1.3 Psychological factors influencing the adoption of aRP

The literature reviews of Zubin *et al.* (2020) and Sanguinetti *et al.* (2019) serve as starting points to investigate the role of psychological factors in choosing aRP. They conducted literature reviews and summarized the underlying factors that determine the adoption of shared autonomous vehicles (SAVs). Zubin *et al.* (2020) clustered the resulting factors in the following categories: sociodemographics of potential users (age, gender, income and education level), travel behavior (travel purpose and mode choice), personality (trust and sharing with strangers) and operational characteristics (potential areas of usage, impact on traffic con-

gestion, travel time and travel costs, presence of personnel in the vehicle and service type as well as driving context). In a narrative literature review Sanguinetti *et al.* (2019) focused on potential risks and benefits of the pooled SAV experience and suggested design features and supports to promote aRP. They identified compromised personal space, security, control, and convenience as potential risks and benefits of pooled SAVs related to restoration and social capital, which could be supported by themed interiors; entertainment in the vehicle; augmented reality windshields; flexible seating allowing riders to face each other; accommodations for food and drink; ensuring broad access; and making SAVs a canvas for local art. Nordhoff *et al.* (2019) proposed a multi-level model to predict AV acceptance (MAVA), based on the theoretical framework, i.a. UTAUT (e.g., Venkatesh *et al.*, 2003, 2012) and a systematic literature review. MAVA proposes a four-stage decision-making process that considers acceptance as a result of this process. This model incorporates seven main acceptance classes with 28 acceptance factors. The factors identified in these studies and additional qualitative and quantitative literature are summarized in section 2.1.5.

2.1.4 Framework of psychological factors influencing acceptance of aRP

In order to structure the psychological factors influencing the acceptance of aRP found in the literature, an extended and adapted version of the unified theory of acceptance and use of technology (UTAUT2) is used (Venkatesh *et al.*, 2012). The UTAUT2 is an established theory to explain the adoption of technology from a user perspective and has been previously applied in studies to explain the adoption of AVs (Yuen *et al.*, 2020; Madigan *et al.*, 2017; Nordhoff *et al.*, 2019). UTAUT2 proposes that user behavior (i.e., the adoption of new technology) can be explained by the user's behavioral intention with regard to this behavior (e.g., adoption of aRP). The behavioral intention is explained by several constructs.

The following adapted version of the UTAUT2 contains seven of the initial constructs of the UTAUT2: (1) performance expectations (i.e., usefulness of aRP including safety, benefits for the environment, time-savings, cost-savings); (2) effort expectations (i.e., ease of use including uncomplicated planing and booking, effortless interaction with vehicle); (3) social influence (i.e., importance of technology usage to others) and (4) facilitating conditions (i.e., available resources). And three additional constructs: (5) Hedonic motivation (i.e., fun or pleasure derived from using the technology); (6) price value (i.e., monetary costs and pricing structure); (7) habit (i.e., performed behavior based on learning processes and previous experiences) (Venkatesh *et al.*, 2012). Additionally the construct social aspects was added to the adapted version of the UTAUT2 since additional factors have been identified in the literature that can be summarized under this construct. Further the model proposes moderating effects of gender, age and previous experience on these relationships. Fig. 2 visualises the adapted version of the UTAUT2 containing all constructs influencing behavioural intention/user behaviour and thus the acceptance of aRP.

In the following section the relevant constructs and the factors determining the acceptance aRP within each construct are explained.

2.1.5 Constructs and factors influencing the adoption of aRP

The factors identified in the literature are structured according to the constructs of UTAUT2 (see Tab. 1).

The construct of *performance expectations* comprises the largest number of factors influencing the adoption of aRP. Thereby, the factors safety and comfort of the vehicle stand out as the factors most frequently investigated. *Safety* is thereby defined to what extent a passenger feels safe with regard to the technology of the AV, speed or safety measures such as an emergency button or an external control center (Zubin *et al.*, 2020; Nordhoff *et al.*, 2018, 2020). *Comfort of the vehicle* includes aspects like atmosphere, vehicle exterior and interior, disability friendliness, personal space provided by seat arrangements and cleanliness (Etminani-Ghasrodashti *et al.*, 2021; Schuß *et al.*, 2021). *Time* (as in waiting time, pick-up time or total journey time) and *availability*, *reliability*, *flexibility* were also investigated by some studies (e.g., Etminani-Ghasrodashti *et al.*, 2021; Schuß *et al.*, 2021). Availability is defined as the access during different business hours and to recreational destinations, but also the capacity of service (Etminani-Ghasrodashti *et al.*, 2021). The perception of

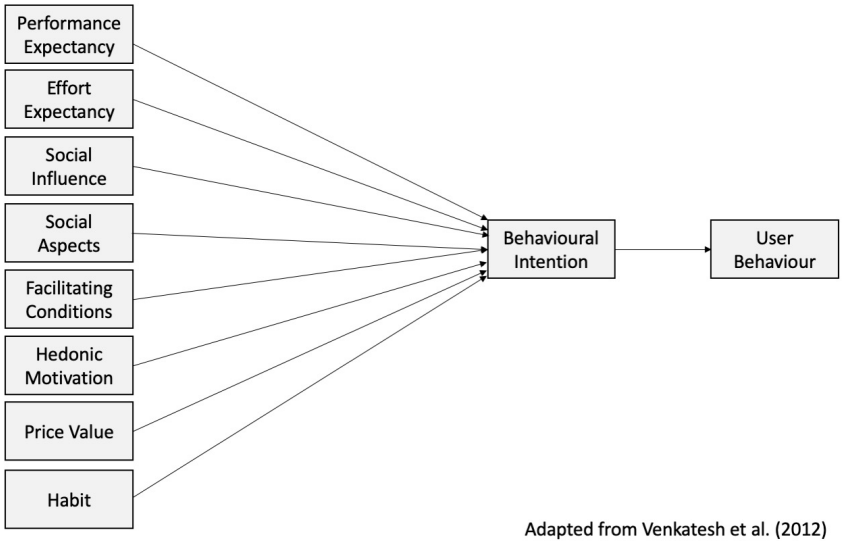


Fig. 2 *Framework of constructs explaining the acceptance of new technologies*

the *reliability* of aRP is influenced by the predictability of travel time, waiting time, punctuality and exact information about pick-up and drop-off locations in advance of the trip (Etminani-Ghasrodashti *et al.*, 2021). The factor flexibility includes the flexibility of changing routes and stops, the adjustment of stops, pickup and destination, flexible booking options and spontaneous availability of a ride (Schuß *et al.*, 2021). Additional factors are *trip purpose*, *social equity*, *environmental considerations* and *privacy*. Trip purpose can be related to work, shopping, education, home, leisure or other activities (Hamadneh and Esztergár-Kiss, 2022). Social equity refers to the availability of mobility for people who are less mobile (Paddeu *et al.*, 2020). Environmental considerations comprises assumptions about the impact of aRP on the environment (e.g., less traffic, electric vehicles, shared vehicles, reduced need for parking, better air quality, fewer emissions (Paddeu *et al.*, 2020). Privacy contains concerns about the use of personal information by companies, such as user's locations and facial recognition (Gurumurthy and Kockelman, 2020), but also the potential risks related to disclosing personal information such as home and work locations to co-riders (Sanguinetti *et al.*, 2019). *Activity during journey*, e.g., reading, writing, talking, using social media, gaming, eating/drinking or doing nothing (Hamadneh and Esztergár-Kiss, 2022) and *parking spaces* are the least investigated factors in aRP.

Effort expectancy is likewise a construct that unites a large number of factors. It comprises factors concerning the ease of using aRP: the process of *planning the trip*, *information provided on the app*, *interaction with AV* (e.g., information about travel, information of shuttle behaviour, auditory shuttle information (Nordhoff *et al.*, 2018), the recognition of groups by the AV or a voice that welcomes the passenger (Schuß *et al.*, 2021), *perceived control*, *liability* (the question of who is liable and responsible when AVs fail) and *payment*.

The following constructs are represented unidimensional in research on aRP: social influence (i.e., norms with regards to whether using aRP is accepted by meaningful others), facilitating conditions (knowledge and available resources to use aRP), hedonic motivation (the fun or pleasure derived from using aRP (Venkatesh *et al.*, 2012; Merat *et al.*, 2017), price value which includes perceived travel cost, e.g., student free cost, registration cost, unified cost and perceived cost saving, e.g., reduced fares, prices (Paddeu *et al.*, 2020), habit, age and previous experience with RP, AV or aRP.

The literature research led to an additional construct with three factors for *social aspects* in aRP. Security which is described as safety concerns related to other passengers in a shared driverless vehicle (Dolins *et al.*, 2021), comfort/discomfort regarding social situation

describes the psychological or social comfort / discomfort caused by close interpersonal space between passengers, (Merat *et al.*, 2017) and socializing.

Tab. 1 *Psychological factors influencing the adoption of ridepooling*

Construct	Description	Psychological factors	References
Performance expectancy	Extent to which aRP provides benefits (i.e., perceived usefulness)	Usefulness (general)	(Nordhoff *et al.*, 2018)
		Safety	(Barbour *et al.*, 2019; Dolins *et al.*, 2021; Etminani-Ghasrodashti *et al.*, 2021; Fan *et al.*, 2022; Irannezhad and Mahadevan, 2022a; Nordhoff *et al.*, 2018, 2020, 2021; Paddeu *et al.*, 2020; Sanguinetti *et al.*, 2019; Paddeu *et al.*, 2020; Schuß *et al.*, 2021; Zubin *et al.*, 2020)
		Comfort of the vehicle	(Dolins *et al.*, 2021; Etminani-Ghasrodashti *et al.*, 2021; Fan *et al.*, 2022; Nordhoff *et al.*, 2018; Sanguinetti *et al.*, 2019; Schuß *et al.*, 2021; Stoiber *et al.*, 2019; Susilawati and Lim, 2021; Zubin *et al.*, 2020)
		Social equity	(Etminani-Ghasrodashti *et al.*, 2021; Fan *et al.*, 2022; Paddeu *et al.*, 2020; Zubin *et al.*, 2020)
		Time	(Dolins *et al.*, 2021; Nordhoff *et al.*, 2018; Kyriakidis *et al.*, 2015; Sanguinetti *et al.*, 2019; Schuß *et al.*, 2021; Stoiber *et al.*, 2019; Susilawati and Lim, 2021; Zubin *et al.*, 2020)
		Environmental considerations	(Nordhoff *et al.*, 2018; Kyriakidis *et al.*, 2015; Paddeu *et al.*, 2020; Zubin *et al.*, 2020)
		Reliability	(Barbour *et al.*, 2019; Etminani-Ghasrodashti *et al.*, 2021; Irannezhad and Mahadevan, 2022a; Nordhoff *et al.*, 2021; Sanguinetti *et al.*, 2019; Stoiber *et al.*, 2019; Susilawati and Lim, 2021)
		Flexibility	(Etminani-Ghasrodashti *et al.*, 2021; Irannezhad and Mahadevan, 2022a; König and Grippenkoven, 2020; Schuß *et al.*, 2021; Stoiber *et al.*, 2019; Susilawati and Lim, 2021)
		Availability	(Etminani-Ghasrodashti *et al.*, 2021; Irannezhad and Mahadevan, 2022a; Nordhoff *et al.*, 2020; Paddeu *et al.*, 2020; Schuß *et al.*, 2021)
		Privacy	(Fan *et al.*, 2022; Sanguinetti *et al.*, 2019)

		Trip purpose	(Barbour *et al.*, 2019; Hamadneh and Esztergár-Kiss, 2022; Irannezhad and Mahadevan, 2022a; Paddeu *et al.*, 2020; Zubin *et al.*, 2020)
		Parking space	(Barbour *et al.*, 2019; Stoiber *et al.*, 2019)
		Activity during journey	(Hamadneh and Esztergár-Kiss, 2022)
Effort expectancy	The degree of ease users associate with aRP (i.e., ease of use)	Interaction with vehicle	(Nordhoff *et al.*, 2018, 2020, 2021; Sanguinetti *et al.*, 2019; Schuß *et al.*, 2021)
		Perceived control	(Sanguinetti *et al.*, 2019)
		Planning	(Etminani-Ghasrodashti *et al.*, 2021)
		Payment	(Etminani-Ghasrodashti *et al.*, 2021; Fan *et al.*, 2022)
Social influence	Extent to which users perceive that important others (e.g., family or friends) believe they should use aRP	Norm	(Nordhoff *et al.*, 2018)
Social aspects	Response to interactions and presence of other people	Security	(Dolins *et al.*, 2021; Fan *et al.*, 2022; Nordhoff *et al.*, 2018; Sanguinetti *et al.*, 2019; Stoiber *et al.*, 2019; Zubin *et al.*, 2020)
		Comfort / discomfort social situation	(Fan *et al.*, 2022; Nordhoff *et al.*, 2018, 2021; Sanguinetti *et al.*, 2019; Stoiber *et al.*, 2019; Zubin *et al.*, 2020)
		Socializing	(Sanguinetti *et al.*, 2019)
Price value	Cognitive tradeoff between perceived benefits and costs of using aRP	Cost	(Barbour *et al.*, 2019; Etminani-Ghasrodashti *et al.*, 2021; Fan *et al.*, 2022; Irannezhad and Mahadevan, 2022a; König and Grippenkoven, 2020; Paddeu *et al.*, 2020; Stoiber *et al.*, 2019; Zubin *et al.*, 2020)
Facilitating conditions	Users' perceptions of resources and support available to use aRP		(Venkatesh *et al.*, 2012)

Hedonic motivation	Fun or pleasure derived from using aRP	Hedonic motivation	(Nordhoff *et al.*, 2018)
Habit	Extent to which people perform behaviors automatically due to learning processes or previous experiences		(Barbour *et al.*, 2019; Irannezhad and Mahadevan, 2022a; Nordhoff *et al.*, 2018, 2020)

2.1.6 Conclusions

In sum, research on psychological factors influencing the adoption of aRP is still at an early stage. Approaches to investigate these factors are heterogeneous, resulting in a large range of possible factors that are proposed and/or have been found to influence adoption behaviors. In this research a framework (adapted from UTAUT2) with eight constructs is proposed to structure these factors. For some of these factors there is no consensus to whether they are perceived as drivers or barriers for the respective behavior. For example, some studies find safety as a major barrier (i.e., lack of trust in technology) whereas other studies observe that users perceive AVs to be safer than conventional means of transportation. These contradictory findings might be explained by the influence of the specific type of aRP used in the studies, as well as other contextual factors. In conclusion, whether a factor serves as a driver or a barrier can only be determined for a specific user group in a specific context.

2.2 Travel behaviour with ridepooling

2.2.1 Introduction

This section presents an overview of the travel behaviour research literature on ridepoolin and ride hailing with conventional and autonomous vehicles and serves two objectives. The first objective is to obtain an overview how research has addressed key challenges to quantify travel behaviour for modes of transport that are not yet available (e.g., AV, aRP, aRH) or only limited available (e.g. ridepoolin, ride hailing). The second objective is to obtain an indication of behavioral parameters related to (a)RH and (a)RP (e.g. waiting time, travel time, willingness-to-pool).

To address the first objective we have evaluated how previous research has dealt with the presentation of information on unfamiliar transport and services (e.g. RH / RP).

The second objective is addressed by comparing reported values of travel time savings for ride hailing and ridepoolin to similar attributes of other modes. Furthermore, further relevant parameter ratios are reported that describe the (un-)willingness to pool or the willingness to pay for a human driver. In addition, we compare ridership predictions for RH and RP based on model results from stated preference surveys with observed ridership to derive insights about potential challenges when forecasting demand for such services based on surveys.

This section continues with an overview of research methods that have been applied to describe travel behaviour with (a)RH and (a)RP in section 2.2.2. Given that we are interested to forecast demand for such services using agent-based simulation our literature review focuses on quantitative approaches. The process how we selected the studies presented in this literature review are described in section 2.2.3. Section 2.2.5, presents the findings of four studies on travel behaviour with ride hailing and ridepoolin according to the review focus outlined above. Our review of studies on automated ridehailing (aRH) and automated ridepoolin services (aRP) is presented in section 2.2.6.

2.2.2 Methods

Three methodological approaches can be recognized to quantify travel behaviour that include ridepoolin, ride hailing and autonomous vehicles as mode alternative.
First, qualitative approaches are mainly applied to analyse consumer attitudes and perceptions of ride hailing, ridepoolin and autonomous vehicles. Key issues include trust in the technology, opinions on booking routines and other practical aspects related to those modes of travel.
Second, quantitative approaches are used to derive behavioural parameters based on revealed and stated preference surveys which can be applied to expand the functionality of travel demand models to include ride hailing and ridepoolin as additional modes.
Third, to forecast the potential demand for ride hailing and ridepoolin services, transport simulation models are used to generalise the findings of behavioural models and to quantify the share of those new modes in competition with existing modes.

This review focuses on the second approach. Data used to model travel behaviour, including ride hailing and ridepoolin, usually specify service-specific variables that include various dimensions of the generalised cost, the context of the trip (e.g. trip purpose, time of day), sociodemographic variables (e.g. mobility tool ownership, age, gender and income) and personal attitudes. Since researchers have very limited access to revealed preference data on travel behaviour with RH and RP, most data are collected through stated preference surveys, where respondents are asked about hypothetical ride hailing and ridepoolin offers in stated choice experiments to derive trade-offs in comparison with conventional modes.
Since we assumed that at least in their early stages, ride hailing, ridepoolin and autonomous vehicles will have a small modal share and will predominantly be used by specific groups of individuals, we also review the literature on determining which the groups of people are likely to use such services and technology. Since we will not model the ownership of autonomous vehicles or new forms of vehicle lease or rent models, we will ignore the corresponding literature on modelling those aspects. The same applies to models describing the purchase of public transport travel cards or mobility as a service bundling schemes.

2.2.3 Study selection process

Since aRH and aRP services do not yet exist – with the exception of some pilot projects – consumers' preferences towards these modes can only be captured by SP surveys. Apart from the SP study design, it is crucial to inform respondents about how these new modes will function. We will therefore also describe how existing studies deal with that aspect. However, since RH and RP serve the same function as aRH and aRP, and since there are only a few studies on aRH/aRP based on SC experiments, we also searched for RH and RP studies because some of their results are interesting for comparison with the ones found in aRH and aRP studies.

We started our research with Google Scholar and Scopus using the following key words: shared automated vehicle demand literature review. From the results, we selected the following three overview studies: A overview of studies in the field of MaaS was compiled by Gkartzonikas and Gkritza (2019), covering studies from 2012 to 2019. It is important to note that – following Becker and Axhausen (2017b) – 2012 is the year with the earliest surveys on automated vehicles. Gkartzonikas and Gkritzab's key contribution was a table where they listed 53 stated-preference (SP) and choice studies on autonomous vehicles. However, only one of these studies – Krueger *et al.* (2016b) fulfilled our criteria. When applying our criteria plus a publication date of 2016 and later, Becker and Axhausen (2017b) found no additional study. Even in 2019, Hörl *et al.* (2019b, p. 38) came to the same conclusion. In the following, besides drawing on Krueger *et al.* (2016b), we therefore refer to studies we found ourselves. No additional study that met the aforementioned criteria was found in Jing *et al.* (2020) either. Ultimately, we were able to identify three studies in the field of aRH and aRP.

In our search for studies on RH and RP, we were able to identify Kang *et al.* (2021b), which provides a comprehensive overview of studies. From these studies, we selected six that we will discuss.

2.2.4 Presentation of the studies

In the following sections, we discuss the selected studies, addressing the following aspects:

- Objective and scope of the study
- Sampling
- Experimental design
  - Alternatives, variables, and related attributes considered
  - Number of choice sets
  - Provision of information on aRH and aRP
- Modelling
- Discussion of the results with respect to our research

We conclude the presentation of each study by highlighting and discussing the results.

We start by presenting the studies on RH and RP and then present the studies on aRH and aRP.

2.2.5 Studies on conventional ride hailing and ridepoolin services

In this section, we start with Irannezhad and Mahadevan (2022b) – the latest study on conventional ride hailing services (RH), such as UBER and Lyft, and on conventional shared ridepoolin services (shared RH), provided by cars (e.g. UBER-Pool) and minibuses (e.g. MOIA). We then continue with five studies that compare RH with shared RH, namely Tirachini and del Río (2019), Hou *et al.* (2020), Lavieri and Bhat (2019a), Lavieri and Bhat (2019b) and Alonso-González *et al.* (2021).

Uptake of PP and aRH/aRP in metropolitan and regional areas in Australia

The study by Irannezhad and Mahadevan (2022b) covers not only RH, but also forecasts of shared RH, aRH and aRP demand in Australia. A special focus was whether ride hailing – which has become ubiquitous in most Australian metropolitan areas – would prevail in regional areas, especially after the emergence of new RP or aRH/aRP services. Research was also undertaken to determine whether different observed and latent characteristics influence the adoption of RP, aRH and aRP.

The sample consisted of adults aged 18 years and over who are familiar with RH platforms. The respondents were selected from the Australian states of South Australia, Queensland, Tasmania and Western Australia. In mid-2019, when the survey was conducted, the shared RH service “Uber Pool” was not yet in service in those states. Over 750 individuals completed the survey (406 from metropolitan areas and 371 from regional areas). The questionnaire included two stated intention experiments in which the respondents indicated how likely they were to use RP and aRH for different trip purposes on a five-point Likert scale. Since most respondents were not familiar with RP, the following short text explained basic attributes of the service: “Sharing of vehicle with other travellers who want to go in a similar direction. Virtual pick-up points at both sides of the road make sure that the walking distance will be less than 300 metres. Price discounts up to 50% compared to ride hailing.” However, no information about waiting times and longer travel times was defined. Based on the information available in the paper, no information about self-driving vehicles was provided in the questionnaire, except that it would be generally available and common to hire. Acceptance of ridepoolin was investigated by asking the respondents whether they would share a ride hailing trip with one or two people if the discount was 25% and 50%, respectively.

The study employed two separate hybrid ordered logit models with latent variables to examine the observed and latent determinants of the frequency of ride hailing use in metropolitan

and regional areas. The researchers applied separate models for regional and metropolitan areas and for each trip purpose.

The most interesting and relevant results for our study are as follows: First, in the case of regional work-related trips, both a 25% discount if sharing the ride with one other passenger and a 50% discount if sharing the ride with two passengers were more attractive to the respondents compared to RH, where the latter was even more attractive than the first. Second, the stated intention of current RH users to use aRH showed that around 40% of metropolitan residents and more than 50 % of regional residents would not choose the AV service, even with price discounts of up to 50%. This might be related to the very limited amount of information on AV technology was provided to the respondents. Third, frequent PT users are more likely to use ride hailing frequently in both regional and metropolitan areas. Fourth, in terms of the likelihood of pooling, the results showed that regional infrequent PT travellers and metropolitan residents with tech-centric and anti-driving attitudes are more likely to adopt pooled services for all four trip purposes. Note that since the survey is based on RH users, the model cannot be used to forecast actual modal shares.

Study on RH in Santiago de Chile

Tirachini and del Río (2019) examined the use of RH in Santiago de Chile utilizing anintercept (face-to-face) revealed preference survey. The survey, conducted in 2017, included a discussion on the substitution and complementarity of RH with existing PT, explaining the probability of using RP versus RH, and explaining the frequency of the use of RH/RP.

To explain the variables – vehicle occupancy rate (in passengers per vehicle) and monthly frequency of ride hailing use – ordinal logit, ordinal probit, and generalised ordinal logit models were employed. The latter maps the distinction between 1 vs. (2, 3, 4 or more), (1, 2) vs. (3, 4 or more), and (1, 2, 3) vs. 4 or more pax/veh in the case of vehicle occupancy. Attitudinal variables, built environment attributes and trip-level characteristics (other than trip purpose) were not considered.

The sample (n=1529) consisted entirely of current RH/RP users (Uber, Cabify). The results indicate that RH is less likely to be shared with other passengers for leisure trips and by individuals with a high income. The results also reveal that the monthly frequency of ride hailing use is higher among more affluent and younger travellers. Furthermore, it was found that car availability was not statistically significant to explain the frequency of ride hailing use based on age, which they say contrasts with previous RH studies. Results indicated that for every RH user who combines the journey with public transport, there are 11 riders who substitute PT for RH, and that the modes most substituted for RH/RP are PT (37.2%) and traditional taxis (39.2%), whereas only 15.9% substituted car trips. Interestingly, only 5.4% were trips that would not have been made otherwise. The sample statistics show that the income distribution peaks at middle-income users (863-1177 USD/month) and decreases sharply with incomes higher than USD 1803. This might suggest that higher-income people prefer to have their own car and are therefore less likely to use RH. Most RH/RP trips were made between 8 pm and 6 am, and only 20% were made between 6 am and 5 pm.

The main reasons respondents gave for using RH/RP were that it was comfortable and safe/secure (28.9%), cheaper than other alternatives (14.4%) and faster (9.0%). Other reasons included ease of payment (6.9%), fare transparency (6.8%) and the consumption of alcohol (6.1%). It was found by the authors was that the average vehicle occupancy rate was 1.5 pax/veh – a value similar to those in Denver found by Henao and Marshall (2018), namely 1.3 pax/veh (deadheading kilometres excluded) and 0.8 pax/veh when all kilometres were considered (deadheading included).

Tirachini and del Río (2019) did not provide any figures on the overall mode share of RH or RP trips. However, given that each respondent takes approx. 4.2 RH or RP trips (frequency of use in the previous month) on average, the modal share of RH or RP might be less than 5% even among RH users, assuming an average total number of around three trips per month. It is worth noting that RH/RP was illegal in Chile up to the time of writing the

publication, but poor law enforcement coupled with strong user support allowed RH use to flourish.

The most relevant results for our study are as follows: First, the use of RH/RP decreases – above a certain level – with income, which might be explained by the ability to afford and therefore own a car. Second, the three most frequently mentioned reasons for using RH/RP were that RH/RP were more comfortable and safe/secure (28.9%), cheaper (14.4%) and faster (9.0%) than the alternatives. Third, vehicle occupancy is low, at around 1.5 pax/veh. Fourth, about half of the trips were made between 8 pm and 6 am, which could be due to the lack of PT services during that period. Fifth, the total modal share of RH or RP in Santiago in 2017 was very low; even among RH users, it was below 5%.

Willingness to pool RH trips in Chicago

Hou *et al.* (2020) used newly available data from Chicago transportation network companies such as Uber, Lyft and Via to examine RH trips between pairs of Chicago census tracts. The dependent variable in their study was the number of the individuals' RP trips as the proportion of the total number of RH/RP trips – which they call the willingness to pool ratio – between any two tracts (within each 15-minute time bin). The Chicago transportation network companies' network data was combined with supplementary area-level demographic and weather data. The independent variables included trip-specific attributes, temporal and weather characteristics, and area demographic and density attributes. Airport drop-offs, drop-offs at locations with high median household income, and weekend trips were most likely to be pursued using the RH mode rather than the RP mode. They used a multiple linear regression model to explain the willingness to pool ratio variable. They found that for a 10% fare difference between regular and pooled trips from a location (with all else remaining the same), the WTPO ratio increases by 0.82%. The nature of the data used precluded the use of individual-level explanatory variables. They also find, that all else being equal, if a ride hailing trip is requested during nighttime, the WTPO ratio decreases by 2.12%. They state that safety or an increased value of time at late hours could be possible explanations for this effect.

Report on the RP Moia project in Hamburg

The Report from Kagerbauer *et al.* (2021) which is on the Moia RP project that takes place in Hamburg will be thematized after the 24th February 2022. Note, that this report does not contain results from the evaluation of the SC experiment by use of MNL models yet; According to Kagerbauer *et al.* (2021) this is work in progress and a corresponding publication is planned for this year.

Publications on ride hailing and willingness to share in the Dallas-Fort Worth Metropolitan Area

Lavieri and Bhat (2019a) examine the choice of private versus pooled RH using an online survey of residents of the Dallas-Fort Worth Metropolitan Area.

The data was collected by an online survey. All respondents were residents of the Dallas-Fort Worth Metropolitan Area. The respondents were recruited through mailing lists held by multiple entities (local transportation planning organisations, universities, private transportation sector companies, non-profit organisations, and online social media), yielding a final clean convenience sample of 1607 respondents. The survey was conducted in the fall of 2017. In terms of ride hailing experience, about 56.4% of the sample (n=906) reported using ride hailing services at least once in their lifetimes, although only about 10.0% of the sample (n=157) reported experience with the pooled version of the service. A suite of socio-demographic and psycho-social attitudinal/life style characteristics, as well as a macro-representation of residential location (urban versus suburban versus rural residence), is considered in their revealed preference analysis.

The definition of ride hailing given to respondents was "ride hailing services use websites and mobile apps to pair passengers with drivers who provide passengers with transportation

in the driver's non-commercial vehicle. Examples are Uber and Lyft." Individuals who stated that they had previously used this type of service were further presented with the following definition of ridepoolin: "In the carpooling option of ride-sourcing, additional passengers with similar routes get picked up and dropped off in the middle of the customer's ride. Customers receive discounted rates when they choose this option". Based on the responses to these questions, and as applicable, the respondents were asked to indicate their frequency of use, in the past 30 days, of private and pooled ride hailing services.

A multivariate approach – a so-called Generalised Heterogeneous Data Model (GHDM) developed by Bhat (2015) – which allows for the joint estimation of multiple outcomes of different types (continuous, ordinal, count and nominal) was used. Their analysis is based on individuals who have ride-hailed in the past, and information on private versus pooled RH is sought in the context of the most recent RH trip.

According to their results, the main deterrents to pooled RH adoption are low residential location density and people's privacy concerns. In addition, tech-savviness, being young, and a high education status are associated with a higher pooling propensity. The study does not consider trip-level attributes.

Lavieri and Bhat (2019b) examine pooling adoption in the context of individuals' acceptance of increased travel times associated with the pick-up/drop-off of other passengers, travel costs, and their approval of strangers sharing the same vehicle. This study is perhaps the first study to consider the full comprehensive set of individual-level variables, attitudinal/lifestyle preferences, built environment (albeit in the form of a coarse urban versus suburban residence distinction), and trip-level attributes.

They use joint revealed preference and stated preference survey data obtained by the same web-based survey of commuters in the Dallas-Fort Worth Metropolitan Area (DFW) of the U.S. as in Lavieri and Bhat (2019a). In addition, they exploit data from an SC experiment that was designed as follows: One alternative was always RH, the other RP, and the case of automated services aRH and aRP. Five trip attributes characterised each scenario: (1) travel time (which was associated with a specific distance for fare calculation purposes), (2) fare structure, (3) cost amount reduction resulting from pooling, (4) additional travel time associated with pooling, and (5) the number of additional passengers. The levels for the travel time attributes (the first and the fourth attributes above) were defined with the objective of keeping the scenarios realistic, while also providing an instrument to engender adequate time variability in the attribute values across scenarios. For the second attribute, fare structure, a three-level scheme was used. The first level assumed that there would be no change in the non-pooled fare structure compared to today. The other two levels (reflecting an autonomous vehicle future) assumed that service fees would no longer be necessary (because of the absence of human drivers) and that there would be a certain percentage reduction in the distance-based fare. For the third attribute, the corresponding reduced cost was 20%, 40% and 60% relative to the aRH rate. The number of additional passengers was one, two and three. In all, there were 243 possible combinations between the attribute levels. From these combinations, 27 different scenarios were chosen with a focus on isolating the main effects and retaining orthogonality. Each individual was randomly assigned to respond to six scenarios, split evenly between commute and leisure trip purposes.

A multivariate approach is used to simultaneously model each respondents' current RH experience and their future intentions regarding the use of aRH and aRP services for commute and leisure trip purposes (aRH services are essentially private RH services without a human driver, while aRP services are essentially RP services without a human driver). To accommodate individual variability in the valuation of privacy and time, Lavieri and Bhat use the attitudinal/lifestyle constructs of privacy-sensitivity, time-sensitivity, and interest in productive use of travel time.

Privacy-sensitivity yet again features as one of the key deterrents to RP. The results also reveal that users are less sensitive to the presence of strangers when on a commute trip compared to a leisure-activity trip. The value of time (VoT) sample average estimate is USD

26.5 per hour for work travel and USD 23.2 per hour for leisure travel. Individuals are willing to pay (UWTPO)[1], on average, about USD 0.50 (equivalent to 1.10 min) travel time savings) not to have an additional passenger for commute travel; this willingness to pay not to have an additional passenger increases to USD 0.90 (equivalent to 2.33 min), on average, for leisure travel. Both these values appear to be independent of travel time. The effects of trip-level attributes on the willingness to share trips is obtained based on an aRP system in the future rather than on a human-driven RH system. Note that the level of familiarity with RH is not considered as an element of the modelling process, which can bias trip-level effects.

Willingness to share rides in pooled on-demand services of Dutch urban individuals

Alonso-González *et al.* (2021) used a pure SP approach to investigate travel behaviour with pooled RH. This study has many similarities to Lavieri and Bhat (2019b), although it was undertaken in a European context. The survey was based on 1077 respondents – 1006 (93%) were considered valid after data cleaning – who were individuals aged 18 years and older with a mobile phone living in highly urbanised areas in the Netherlands. The stated choice experiment always consisted of two labelled alternatives: One RH and one RP. When the survey was conducted, no large-scale RP service was available in the Netherlands. The respondents needed to be informed about the functioning of RP, the process of booking and using an RP service. Before conducting the SC experiment, therefore, this information was provided using a map showing text bubbles associated with the places where the three following steps take place: Step 1: Book your ride with your smartphone; Step 2: Walk to the pick-up point; Step 3: The ride.

The complete SC design results in six blocks with four scenarios each. For the attribute levels, they considered two set of values, depending on the length of the respondent's reference trip ($\leq$ 12 km or > 12 km). Each alternative was describes by the following variables and related attribute levels: Expected travel time with RH (10, 15, 18 for short trips | 20, 25, 28 min. for other trips), additional travel time for RP (3, 6, 9 | 4, 7, 12 min), cost RP (2, 4, 6 | EUR 3, 5, 7), extra cost for RH (0.5, 2.2, 3 | EUR 0.6, 2.2, 3), number of additional passengers (1, 2, 4 | EUR 1, 2, 4). To increase realism, RH is considered to always have shorter travel times (non-existent high occupancy vehicle lanes in our context) and to be more expensive than the RP option. The experimental design of the SP experiment is an orthogonal fractional factorial design with blocking. Despite the rather large variation of attribute levels, around 30% of the respondents exhibited a non-trading behaviour. 50% of non-traders chose the RH alternative in all of the scenarios shown, and the other 50% chose the pooled alternative only. A mixed logit model with random coefficients and a latent class choice model was used to analyse the data. Also, the modelling included a combination of covariate and latent segmentation effects, while Lavieri and Bhat (2019b) introduced socio-demographic effects based on a combination of covariate effects and psycho-social mediation effects. Remarkably, despite differences in survey methodology, model specification and geographic context, similar VoT (around USD 25 per hour) and a UWTPO (USD 0.50 – 0.90 per additional passenger) were derived as in the study by Lavieri and Bhat (2019b). However, the study by Alonso-González *et al.* (2020) did not include attitudinal considerations.

2.2.6 Studies on automated ride hailing (aRH) and automated ridepooling services (aRP)

Preferences for shared autonomous vehicles in the major metropolitan areas of Australia

The objective of Krueger *et al.* (2016a) was to advance future research about the travel behaviour impacts of shared autonomous vehicle, u., by identifying the characteristics of users who are likely to adopt shared autonomous vehicles (i.e., aRH and aRP) and by eliciting willingness to pay measures for service attributes. The respondents were residents of the major metropolitan areas of Australia, namely Adelaide, Brisbane, Melbourne, Perth and Sydney. They were recruited by an online panel administered by Qualtrics. In addition, age and income quotas were fixed, although there was some imbalance compared to the

[1] UWTPO stands for the unwillingness to pay for pooling a ride.

population density, which was corrected for by weighting.[2] To improve the quality of the data, three attention filters were included in the survey.[3] The final sample size was 435.

The stated choice experiment followed a pivot design, and respondents were first asked to indicate details for a trip they had recently undertaken. These details were the trip purpose, duration, distance, cost, the means of transport and the waiting time. To check the plausibility of the trip details, subjects were asked to provide addresses of the origin and the destination of their trip, where known, or crude approximations, where unknown. The choice experiment included three modes, the first being the current mode used for a trip the respondent had described in the first stage of the survey – car, public transportation, walking and cycling. The two other alternatives were aRH and aRP. Apart from the mode, the alternatives were defined by waiting time, travel time and cost. The attributes of the mode alternatives corresponded to a recent trip the respondents had reported (origin, destination, distance, travel and waiting times, purpose, mode of transport, cost) prior to the choice experiment (trip length quartiles: 4, 10 and 20 km; 12, 25 and 45 min).

Given two attributes with three levels each and a one-level attribute, a complete factorial experimental design requires nine profiles for each alternative. Applying the minimal overlap principle (Huber and Zwerina, 1996), nine choice sets were created, each with two hypothetical alternatives. For each respondent, five choice sets were randomly selected from the set of nine. In addition, the researchers collected information on sociodemographics and mobility-related characteristics and behaviour. They also used Likert-type attitudinal indicators to obtain measurements for modal preferences.

Before the choice experiments were presented, the respondents were given information on the nature of the aRH service in the form of a Prezi slide show: the researchers emphasised that aRH would be part of a fleet of shared vehicles, which would be easily available on request. They also highlighted the idea that aRH could be imagined as driverless taxi services. Furthermore, the respondents were informed that smartphones would be used to request an aRH or aRP trip and the vehicle would arrive after a specified waiting time. On arrival at the destination, there would be no need to park the vehicle or pay parking fees, because the vehicle would continue its journey to pick up the next passenger. The respondents were also informed about the nature of the ridepooling option: in the information material, it was made clear that ridepooling would involve riding with other passengers inside the same vehicle for part of the trip.

To evaluate the data, various mixed logit models were used. These models varied in their use of the actual or log-transformed cost values; the omission of the panel structure of the data or the use of fixed or random effects relating to the distribution of in-vehicle travel time. For the latter, Kreuger et al. also applied different distribution assumptions (log-normal vs. triangular).

Separate coefficients for waiting time and in-vehicle time for each alternative were estimated. To cover inertia effects, constants and interaction terms on travel costs were included for the observed mode. Besides sociodemographic variables such as age, gender, age, income, presence of children, car availability and car sharing membership, the respondents were categorised into five different groups: uni-modal car users (25.8% of the total population), pedestrian car users (24.7%), passive bi-modals (11.2%), pedestrian tri-modals (25.7%) and true multi-modals (12.6%). The contribution of such information to explain choice behaviour was tested with interactions terms. The final model includes 57 parameters, of which most were statistically significant.

The most interesting findings were:[4] First, the disutility of in-vehicle travel time (IVTT) in aRP is on average twice as high as for aRH; when the chosen mode in the declared trip

[2] In particular, there was undersampling in the 30-49 age group and low income group.

[3] These filters were designed as follows: Two of these attention filters required respondents to select a specific response for a Likert item, one asked respondents to input a word in a text box. Only complete and valid responses were included in the analysis.

[4] Note that for all results, apart from the fifth result in this section, we computed the values from the parameters of Model 1 in Tab. 5 on p. 350.

was driving a car and using PT, the ratio of IVTT to aRP and aRH amounted to even 3.6 and 13.5, respectively. If we take willingness to pay (WTP) as a basis, rather than preferences, the figures are even multiplied by a factor of four. This is because Krueger et al. used alternative specific parameters for travel cost for the individual alternatives, of which the one referring to the baseline alternative is four times larger than the one of the other two alternatives. Second, there was an average a priori preference for aRH compared to aRP that translated to a UWTPO of AUD 14 (approx. CHF 9). Third, the disutility of waiting time (WT) was about 7.5 times higher than IVTT in the case of aRH, and even more than eleven times higher in the case of aRP. In the case of PT as a main mode, the disutility of WT was 11.5 times smaller than IVTT. Fourth, if the trip purpose was shopping, leisure, or a medical or dental appointment, the preference for both aRH and aRP was lower than when the purpose was for education or work.

The most surprising result is certainly the very high disutility of waiting time in comparison to in-vehicle travel time for aRH and aRP, especially when compared to results from the other surveys, which do not, however, include (a)RH and (a)RP options. Based on a stated preference survey with more than 4500 respondents in Switzerland, Weis *et al.* (2021b) report a parameter ratio between WT and total travel time of 1.2. Arentze and Molin (2013b) report parameter ratios for WT and IVTT between 1.23 and 1.5, depending on trip distance, based on a mode choice experiment conducted with more than 2700 respondents in the Netherlands. Earlier studies such as Wardman *et al.* (2016) for the UK and Bovy and Hoogendoorn-Lanser (2005) for the Netherlands find similar ratios: 1.8 and 1.6 for the access time versus IVTT ratio, and 1.5 and 2.2 for the WT versus IVTT ratio. Since there is no obvious reason for this difference, the values found by Krueger et al. must be viewed with caution. However, there is an indication that some additional information on the trip features, for instance on the reliability of the AV service in terms of punctuality, might help to reduce potential variable bias and may also help to improve the accuracy of the estimated parameters. In addition, the inconvenience of the pick-up point for aRH could have an effect: it may be less safe, and there might not be any shelter from the wind and rain. This impact is also suggested by the difference between willingness to pay for waiting and access time found by Wardman *et al.* (2016) and Bovy and Hoogendoorn-Lanser (2005).[5]

Assessing the potential for demand adaptive hybrid transit in Chicago

Another result that supports the argument regarding the importance of the place of waiting and the information on it in an SP experiment is the one found by Frei *et al.* (2017), who conducted an SP survey based on 121 Chicago residents, about half of whom responded in summer and the other half in winter. They found a ratio between waiting time and in-vehicle travel time of a non-autonomous shared service that was even less than one (0.54), even though this was declared as waiting time due to a delay in the service. One key reason for this low value could be that respondents were told that they could wait at home, since that was the collection point, which is of course very convenient compared to waiting at a station or a pick-up point. Another interesting finding is that respondents who carried a gym bag to work had a negative preference component towards the shared service that equated to a penalty of USD 3.65; interestingly, but not surprisingly, this penalty was even higher for public transport (USD 5.77). Another interesting factor they examined was the impact of the weather on mode choice: If the weather was bad (cold and rainy), willingness to pay for the shared service increased by USD 1.34 in summer and USD 3.48 in winter, since being collected from home made this service very attractive compared to public transport. It follows from these two results that it is very important to specify weather conditions and the type of luggage users need to carry in this context. A panel mixed logit model was used to evaluate the data. The results were compared to a standard multinomial logit (MNL). Most willingness-to-pay values, apart from the alternative specific effects, varied little between the two methods. A total of 64 parameters were estimated. Despite the

[5] This interpretation is also consistent with the finding of Arentze and Molin (2013a) that a transfer with 10 minutes' time to change trains is equivalent to a 22-minute extra in-vehicle time. In other words, the transfer itself causes a penalty of roughly 12 minutes when considering a 65 km trip. In contrast, Wardman *et al.* (2016) determined a penalty of 18 minutes for the UK, and Bovy and Hoogendoorn-Lanser (2005) found even smaller penalties equating to 5 and 10 minutes of train-in-vehicle time.

rather small number of respondents, the vast majority of these parameters were statistically significant. However, the sample was not representative, since respondents were recruited via the Northwestern University Transportation Center's Facebook and Twitter links (the survey links were subsequently shared throughout these social networks) and the Chicago Metropolitan Agency for Planning's weekly newsletter. This is shown by the fact that the sample consisted almost only of people with a university degree, and that people aged 25-34 and those commuting by public transport and other means other than by driving a car were strongly over-represented. Therefore, the results must be interpreted with care and cannot be generalised. The authors offered the respondents the option of solving a number of additional choice sets, but the results showed that this led to a sample selection bias.[6]

On the influence of Choice Experiment Designs on Eliciting Preferences for AVs of New Yorkers

Bansal and Daziano (2018) conducted an SP experiment to analyse choice behaviour with ride hailing and ridepooling as additional modes for a reported trip that was conducted by public transport or by car. Using a Boolean variable "automation", RH and RP were also presented as aRH and aRH.

They recruited 303 New York residents living in households that owned at least one car. The respondents completed a vehicle ownership survey and a mode choice SP survey. However, the vehicle ownership experiment was not included in the main study, because the participants felt that the choice context of "giving up vehicle ownership" was too constraining. Based on a check for response quality and consistency, data from about a third of the respondents was omitted from further analysis.

The mode choice experiment included three labelled alternatives: current travel mode, RH ("low-emission UBER ") and pooled RH ("low-emission UBERPool"). As the current travel mode, they used the most frequent trip, which served as a reference. At the beginning of the questionnaire, information about all alternatives and technologies was provided in form of text and visuals. The alternatives of the mode choice experiment were defined with the following variables: access and wait time, in-vehicle travel time, trip cost (excluding parking fees), parking fees, CO_2 emissions, automation (yes/no). Based on a population-based pivot-efficient design approach implemented with NGene, the experiment design included six blocks, each with seven choice situations per respondent. Because respondents do not generally consider all experimental attributes while making decisions, as evidenced by the growing attribute-non-attendance literature, the information about those attributes identified by the respondent as relevant in the decision-making was collected.

Using a multinominal logit model to analyse the collected data, they found a ratio of 3.02 between "out-of-vehicle time" and "in-vehicle time". In addition, they ascertained that respondents would ask for an average rebate of USD 3.2 for an automated trip compared to a trip with a driver. The parameter for CO2 emissions was not significant. Unfortunately, the paper does not include a table with parameter estimates or any information concerning the UWTPO.

Unlike in most other studies, the information provided on marginal cost to drive the own vehicle was based on both variable and fixed costs, resulting in a value of USD 0.45 per km. Since most people only value marginal cost in mode choice decisions, this might result in a bias towards travel modes other than using a car.

The authors conclude that the willingness to pay measures were sensitive to population

[6] The survey design allowed respondents to choose to respond to 0, 6 or 12 additional choice sets, after having responded to six choice sets. The results show that the respondents who chose to respond to additional choice sets had an additional willingness to pay of around USD 1.3 for both the shared service and public transport. This finding shows that this option is useful for gaining additional information in the dataset, but it clearly leads to a bias and should not therefore be used: in this case, respondents who had an over-average preference for public transport and shared services were selected by this option. They may have wanted to provide these additional responses in order to express their liking for these two options.

weighting and to demographic weights and attribute-non-attendance information.[7] This is the finding most relevant to us, apart from having some willingness to pay measures above as orientation for our survey, despite the pretest having a smaller sample size. The authors state that this sensitivity may also diminish with an increase in sample size. It is therefore important to use a dataset where the weighting of respondents is accurate and where information is collected on attribute-non-attendance.

Forecasting induced traffic by automated vehicles in Zurich (CH)

In a study commissioned by the Swiss Federal Roads Office (FEDRO), Hörl *et al.* (2019b) conducted an SP survey among Swiss respondents to derive behavioural parameters on mode choice decisions for a future situation with autonomous vehicles. The survey included two mode choice experiments. The first experiment included public transport, car, aRH, aRP and aRH in combination with rail as mode alternatives. After the first experiment, the respondents were asked whether they would adapt their existing set of mobility tools given the availability of aRH and aRP. The second mode choice experiment included privately owned autonomous vehicles as an additional mode alternative.

All respondents are from the Swiss Canton of Zurich. They were recruited by sending 4000 letters using the authority's official register of residents. The incentive payment to the respondents was CHF 20. To complete the questionnaire, around 90 min were needed. The respondents were reminded by email if their response was not returned within three weeks of the stated deadline. The numbers of responses for stages one, two and three were 359, 309 and 295. The respondents' information on their mobility tools were checked and corrected after contacting them if necessary. To evaluate the key data of the survey – the SC experiment – it was possible to use the answers provided by 267 respondents, who produced 4739 responses.

In the first stage of their questionnaire, Hörl et al. asked respondents about their age, income, gender, household size, household type, level of education, type of work, and working hours per week. The authors also asked about all household members' mobility tools (cars and public transport subscriptions) and the availability of car parking at their place of residence. In addition, they asked respondents to describe two journeys that they undertake on a regular basis (origin, destination, day of the week, time of day, availability of parking space at the destination, the number of people who make this journey together).

In the second part, the authors explained what aRHs are; also, a link to a video presenting the Mercedes F105, a concept car to demonstrate what a fully autonomous car could look like, was provided by a QR code.

The third part included two types of stated choice experiments. The mode choice experiment captured the currently available means of transport as well as aRH, aRP and aRH specially dedicated for accessing PT access points. The choice alternatives included the following variables: total travel time, travel time using the main mode, travel time to access rail (either by bus or aRH), waiting time, access and egress time (only for bus feeder), the number of transfers, service frequency and journey costs. The experiment employed a pivot design approach with attribute levels generated based on a trip reported by the respondent. The variable attributes were based on information retrieved from Google Maps API for the chosen and all other considered travel modes; they were then adapted according to an efficient experiment design strategy.

The baseline for aRH travel times was equal to that of cars; aRHs with ride sharing was 30% above the baseline. The cost of public transport was computed based on the Swiss public transport tariff system, conditional on the public transport travel card available to the respondent. Car costs were assumed to be CHF 0.263 per km, based on calculations by the Swiss Touring Club (TCS). The base cost levels were CHF 0.55 per km for aRH and CHF 0.30 per km for aRP; the base waiting time was 3.5 min for aRH and 4 min for aRP.

[7] Note that the authors plan to collect a larger sample (N=1000) to validate these hypotheses, and to test the impact of using various modelling specifications on the results.

In the experimental design, the attribute levels were change +/- 33% from their base levels. The order of the alternatives was changed among respondents but kept constant for the same respondent. Four additional sets of information were given for each choice situation: Weather conditions (nice, bad), length of service of previous aRHs, public transport subscriptions, and trip purpose. The alternative of using a car and a bike was only presented if the households owned these mobility tools. If the reference trip contained a train leg, an alternative that included an aRH as access to the train station was added. The survey included also attitudinal questions.

The respondents were asked to answer a total of 24 choice sets. A standard MNL and a hybrid choice model were estimated for the mode choice experiment. Based on the hybrid choice model, the value of travel time saving (VTTS) aRH (around CHF 0.40 per min) did not differ much in comparison to a private car, aRP and private AV; the VTTS for aRH was only about 10% lower than the one of aRP. This is surprising, since travel time could be used for other activities instead of driving. In view of this aspect, the resulting VTTS for travel time in public transport (CHF 0.30 per min) is consistent. The disutility of waiting time and access time was estimated to be 1.25 times and 1.7 times higher than in-vehicle travel time by PT. The disutility of a transfer was in the range of 5 minutes' in-vehicle time. The comparably low value may be due to the small risk of missing connections, good facilities at public transport hubs, and spacious well-sheltered environments in Swiss public transport hubs.

The VTTS for aRH was also derived by a standard MNL model. The resulting values were quite different to the values found. It showed that for ride hailing, travel time is valued twice as much compared to aRH without ride sharing, private AV, and private cars. Note that Hörl et al. use the latter for forecasting individual demands in MATSIM, where they simulate the actual travel flow. The authors justify their choice by the unsuitability of mixed logit and hybrid logit models for forecasting individual demands, see Hörl *et al.* (2019b) (p. 91).

2.2.7 Conclusion

Sample of respondents

In most cases, the author chose to use a sample of current RH users. Given the low modal share of RH/RP use even among current RH/RP users and the fact that RH/RP users are rarely found in high income categories, we believe this is a good strategy. For the case of Switzerland, we believe it is even more justifiable to sample either people who are already using RH/RP or people how are likely to use RH/RP for the following three additional reasons. First, the average income in Switzerland is much higher than that of the respondents of most of the surveys discussed above. Second, in Switzerland, the level of PT service that will compete with aRH/aRP is much higher than the level of service provided in the place of residence of the respondents from most of the surveys discussed above. However, since there are only very few existing RH/RP users in Switzerland, we cannot simply select such users. Instead, it could be meaningful to select our respondents by identifying them via the properties of early adopters determined by earlier surveys on aRH/aRP, which are being tech-savvy and young. We do so, since we believe – as it might have been the case of smartphones fifteen years ago – that the preferences of these people could be representative for the preferences of average people in future when the aRH/aRP services will actually be available.

Survey design

In most of the studies analysed, the information provided to respondents on the new modes (aRH/aRP) was rather limited and its presentation was rather basic, or even too simplistic. However, we believe that the aspect of information provision is very important to obtain realistic results from the use of SC experiments. We thus imagine it as a good idea to present an introductory video that presents automated modes in a very concise and comprehensive way, taking great care to avoid information that could lead to bias, such as displaying fancy AVs. Most of the studies were conducted using a SC experiment. With the exception of the studies that researched the frequency of using various services and applied ordinal

logit models, all studies involved the use of a discrete-choice experiment. To describe travel behavior with aRH aRP based on SC is a suitable approach for our project since it allows to derive behavioral parameters that can be used in MATSim. Moreover, we believe that this type of choice experiment will give us the option of using the majority of proven methods to evaluate the data and make forecasts. All studies use SC designs with a maximum of three alternatives and only a few attributes (six at the most); in some cases, one was always the stated mode. Some studies also only examined UWTPO using SC designs with just two options – one non-shared and one shared option – and presenting a maximum of three attributes.

Using a pivot-design approach and limiting the choice set to only the chosen alternative a new (a)RH/(a)RP options has the following advantages: First, it limits the cognitive burden of respondents as it excludes alternatives that they have already decided against. Second, web-based survey are more cost-efficient than paper-based questionnaires and thus are suggested to be used in our case. This implies that many people answer using mobile devices. Therefore, choice set with only few alternatives are better suited to be answered with a mobile device with their limited screen size.

We also suggest asking the respondents which attributes they considered, and how important they considered these attributes to be when choosing the best alternative. Moreover, we will ask about soft factors explaining preferences for aRP/aRH. This would give us a better understanding of the respondents' reasons for opting for these modes, and in particular for deciding against them. So far, only Maghraoui (2019) has done this. He found that the respondents who opted for aRP reported a different levels for all attributes compared to the respondents who opted against aRP and thus for their current mode. This held inparticualar if the respondent were segmented according their current mode: Respondents with the current mode PT, Bike and Walk who opted against aRP valued costs much more than the ones who opted for it. In contrast, for respondents with the current mode PrT this difference was low.

Model

All studies based on discrete-choice SC experiments use various types of MNL models. In the remainder of this section, we will therefore only address MNL models. The results of the studies explored showed that the results of interest to us may strongly depend on the type of MNL model applied. For this reason, we intend to use various types of MNL models to check the resulting range of parameters. However, since our models will ultimately be used to forecast individual decisions in Matsim we must adapt our model to its restrictions, which is to use a basic MNL model that allows for alternative specific attributes and sociodemographic only. However, we will check for potential bias compared to the results for MNL model variants that could be considered "best practice", which are believed to explain the actual respondents' behavior the best.

The studies used not only the mode attributes, but also the following additional attributes: 1) a small number of basic sociodemographic attributes; 2) the trip purpose; 3) the respondents' mobility tools; 4) whether or not the respondents carried a bag with them; and 5) the time of the day.

Besides using the types of variables mentioned above, we intend to add the following variables: First, a number of variables on soft factors that express preferences for various modes, e.g. possible reservations against sharing aRH or aRP. Second, variables on the type, weight and number of luggage items. However, we will only be able to use them in models that are ultimately only be used to test for potential biases of the basic MNL model used for Matsim. In the studies we observed that high discounts (20 .. 60%) for the pooling options price were used. We suggest this might be useful in our case too in order to get sufficient variation in this attribute and thus being able to calibrate the cost parameters that is of key interest.

Travel behaviour

Tirachini and del Río (2019) found for Santiago de Chile that half of the trips were made between 8 pm and 6 am. This supports the view that RH/RP is rather a substitute for PT and PrT since the use of RH/RP at these times could be due to a lack of PT services at night. Their data also shows that RH/RP services lose their attraction above a certain income level and almost diminishes at incomes above USD 3400.

The fact that low average occupancy rates were found (1.3 .. 1.5 pax/veh) for RH/RP services implies that the shared alternatives must be made even more attractive than RH and aRH. This is particularly true for the latter, since UWTP was found to be around 10..15 times higher for aRP vs. aRH than for RP vs. RH.

Results for the unwillingness to pay also differ strongly for ride hailing services between being picked up at home or at a collection point.

All these findings are relevant to us for the following two reasons: First, they highlight the importance of making the RH/RP and aRH/aRP alternatives in the SC experiment even more attractive than in the other studies in order to get a sufficient number of responses that choose these modes; note that is necessary to be able to calibrate the parameters of interest. Second, it shows, that those aspects (time of the day / availability of public transport, broad range of price discounts and other incentives for pooling options, different forms of pick-up and drop-off) need to be considered when explaining the demand for ride hailing services.

2.3 Simulating travel demand with ridepooling

2.3.1 Introduction

This section presents an overview of the literature on simulation of transport demand for on-demand transport services. The aim of this literature review is threefold:

- evaluate the differences of modelling on-demand mobility between aggregated and agent-based transport models
- present previous findings of simulation studies of potential impacts of on-demand mobility and specifically of pooled services
- present previous findings of research projects in Switzerland on on-demand mobility

To achieve the aims above we first present how on-demand mobility can be modelled using PTV Visum, which is the most frequently used transport modelling software in Europe and in Switzerland. Using PTV Visum as an example we present trade-offs between aggregated and agent-based models that rely on complete activity schedules of individuals. This is completed with the presentation of most used agent-based models in transportation.

The second aim is achieved by conducting extensive literature search for most recent agent-based simulation studies of on-demand transport services with a specific focus on ride-pooling. We aimed to find a broad range of papers that are using different simulation frameworks and focusing on different geographical regions.

The third objective is achieved by presenting the findings of two comprehensive projects focusing on automated mobility on-demand in Switzerland - Hörl *et al.* (2019b); Axhausen *et al.* (2020)

The literature review is concluded with the summary of our findings, which will guide the choice of methodology and case studies.

2.3.2 Trip-based vs. agent-based transportation models

Traditional transport simulation models describe travel demand with aggregated, trip- or tour-based models. PTV Visum[8] is in Switzerland the most frequently used software to implement such aggregated models. Besides computing average link loads over the course of a day or during the peak hour, it also offers dynamic traffic assignment to compute traffic volume in time slices across the day of for multi-modal transport networks.

MaaS Modeller is an extension of Visum that allows the simulation of ride-hailing and ride-pooling. While Visum and its MaaS Modeller extension have been used successfully in various studies (for a recent study, look at Bürstlein *et al.* (2021)), there are several limitations:

- MaaS Modeller cannot dynamically simulate trip requests, so it requires planning in time windows
- MaaS Modeller cannot model heterogeneous fleets (but such a feature is planned to be added in future versions of the model)
- MaaS Modeller does not allow extending or replacing the algorithms used, i.e., dispatching, matching, routing, which reduces the possibility for experimentation
- MaaS Modeller is limited to trip-based model which limits the extent of possible analysis of the impacts of policies on individuals as performed trips cannot be linked back to an individual. However, recent versions of PTV Visum allow for activity-based travel demand modelling, but it is unclear to the authors to which extent Visum and the MaaS Modeller allow to consider attributes of individuals and the context of trips within activity schedules when modelling travel behaviour.

[8] https://www.ptvgroup.com/en/solutions/products/ptv-visum/

Recently, MaaS Modeller was integrated in the software PTV Visum 2022, which allows to include the simulation of ridesharing with the MaaS modeller as part the computation to identify equilibrium conditions of travel demand. To this end, skim matrices such as travel and waiting time that are used in the mode choice model of Visum are provided as averages in space and time. As these are usually noisy, Visum smooths these values over space and iterations. However, the exact procedure is not clear and to our knowledge cannot be replaced.

The main methodology used to examine the impacts of shared on-demand mobility in most studies was agent-based simulation. The main driver of the methodological choice is the specific nature of shared-mobility due to its dynamic (temporally and spatially) supply and demand relationship and heterogeneity in terms of travel behavior (e.g., often small and specific share of population has the willingness to use and pay for such services). The ability of agent-based models to provide a more detailed representation of persons, vehicles and their interaction was the key in propelling this methodology to the forefront of automated mobility-on-demand modeling. In a most recent literature review of agent-based models for automated vehicles, published by Li *et al.* (2021), the authors report that most of the studies employ well established agent-based models (MATSim (Horni *et al.*, 2016) in 46%, SimMobility (Azevedo *et al.*, 2017) in 12% and POLARIS (Auld *et al.*, 2016) in 4% of reviewed papers).

Other frameworks like AnyLogic (Borshchev, 2015), and NetLogo (Tisue and Wilensky, 2004) are used in less than 10% of the studies. Some researchers also develop new agent-based models usually focusing on a specific research question (i.e., Djavadian *et al.* (2021), who looked at the potential of automated mobility on-demand service to replace private vehicle mobility in Toronto).

Learning is one of the fundamental features of a powerful agent-based model Bonabeau (2002). This is usually a feature of equilibrium models like MATSim, POLARIS, and SimMobility. Platforms like AnyLogic or NetLogo are usually not used to model equilibria (for a recent paper, see Inturri *et al.* (2021)). In what follows we, therefore, focus on reviewing aforementioned agent-based transportation models using MATSim, POLARIS, and SimMobility.

2.3.3 Agent-based transportation models

SimMobility is a framework primarily developed by MIT and is comprised of three components focusing on different temporal scales (Adnan *et al.*, 2016). *Short-term* is a microscopic traffic simulation model. *Mid-term* model uses a mesoscopic traffic simulation to investigate an individual's daily activity planning and mobility behavior. It includes mode, departure time, and destination choice dimensions. It uses a dynamic traffic assignment as previously developed for DynaMIT. *Long-term* model is used to capture land use and economic activity with the focus on accessibility. The three models can be used independently or jointly where each can feed information to the others. The mid-term model is most frequently used. It is available as open-source through a GitHub repository[9] and is entirely developed in C++.

POLARIS is a framework primarily developed by Argonne National Laboratory and is very similar in structure to the mid-term model of SimMobility (Auld *et al.*, 2016). It contains an activity-based model based on ADAPTS (Auld and Mohammadian, 2012) responsible for scheduling simulated individuals' activities. Traffic simulation is on the mesoscopic level de Souza *et al.* (2019). The simulation involves microscopic simulation on the node (intersection) level and macroscopic on the link (road) level. It currently does not provide a feedback loop between the activity-based and network simulation models. It is promoted as open-source. However, one needs to file a request and sign a contract with the Argonne National laboratory to gain access. It is developed in C++ with additional libraries for visualization and analysis developed in JavaScript and Python.

[9] https://github.com/smart-fm/simmobility-prod

MATSim is an open-source agent-based modeling framework developed in Java (Horni *et al.*, 2016).[10] MATSim simulates the daily sequence of activities connected by trips of individuals. During the mesoscopic traffic simulation, individuals interact with transport supply and other transportation network users. Through the repetition of a single-day simulation, individuals learn and adapt based on their experiences using the concept of daily plan scoring. In theory, the joint evaluation of activities and trips allows agents to adapt their plans in any dimension by changing routes, modes, departure times, activity duration, or sequence (in practice, this is mostly limited to route, mode and departure time). This is where MATSim's methodologically differs from other models introduced in this review. Due to the difficulty in estimating the scoring function Feil (2010) and integration of preferences for future mobility services (see Hörl *et al.* (2018)), Hörl *et al.* (2018) developed an extension to MATSim (now available as one of the core modules[11]), which allows integration of behavioral models in the MATSim iterative loop. This converts MATSim to an agent-based model methodologically similar to SimMobility and POLARIS.

2.3.4 Relevant literature on DRT using agent-based simulation

Many studies have shown that shared automated vehicles can have a tremendous disruptive effect on mobility behavior and transportation systems. Early research focused on the impacts of single-occupancy shared on-demand services. While the magnitude of the effects can vary based on region, population density, or network structure, in general, the findings show a high potential to reduce the vehicle fleet, and the number of parking spaces at the expense of increased vehicle kilometers traveled (VKT). This has led to several studies on ride-pooling as a potential solution to the increase of VKT (Bischoff *et al.*, 2017a; Gurumurthy and Kockelman, 2018; Gurumurthy *et al.*, 2019a; Vosooghi *et al.*, 2019a; Ruch *et al.*, 2021; Oh *et al.*, 2020; Zwick *et al.*, 2021a; Kagho *et al.*, 2021; Gurumurthy *et al.*, 2021).

Bischoff *et al.* (2017a) evaluate the potential for ride-sharing using taxi demand data in the city of Berlin. They use MATSim and its DRT extension to perform their study. They implement an insertion heuristic that inserts a new request's pickup and drop-off stops in the vehicle schedule that provides the smallest increase in the additional vehicle work time. The authors report that with ride-sharing, VKT can be reduced by up to 20%. Even though they show the occupancy rates in a figure, it is challenging to compute the average occupancy rate of the vehicles. However, they note that increasing the capacity of vehicles from three to four seats does not change the occupancy levels substantially.

Gurumurthy and Kockelman (2018) use 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 implement their simulation framework in MATLAB and allow users to ride-pool based on similar origin, destination, and departure times or en-route pickups that do not substantially alter current onboard passengers' travel times. They find that almost 60% of all trips could be shared with less than 5 min of added travel or waiting time.

Gurumurthy *et al.* (2019a) use MATSim and its demand-responsive transit extension to evaluate the impacts of ride-sharing for shared automated vehicles in Austin, Texas. They assume that solo travelers are priced at $0.5 per trip, $0.4 per mile and $0.1 per minute (estimates of Simoni *et al.* (2019), and shared ride cost half as much as a solo ride. The authors assume no behavioral preferences difference between single and pooled rides and they simulate a 5% population sample. The findings 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. Unfortunately, the authors do not report which MATSim, and DRT extension version they used nor which pooling algorithm they utilized. The only hint suggests that the trips are matched close to their origin into pooled rides[12].

[10] www.matsim.org

[11] https://github.com/matsim-org/matsim-libs/tree/master/contribs/discrete_mode_choice

[12] Given the publication time it is likely that the algorithm used was presented in Bischoff *et al.* (2017a).

Vosooghi *et al.* (2019a) investigate the potential impacts of shared automated vehicles service in the Rouen Normandie metropolitan area in France. The authors perform simulation studies using MATSim and its DRT extension. While they also do not note the MATSim version used, they highlight that the pooling heuristic used is described in Bischoff *et al.* (2017a). The authors assume 0.5 EUR/km as cost for single rides and 0.3 EUR/km for pooled rides. The authors use results from Al Maghraoui (2019) to model users taste variations and willingness to use ride-hailing services. Finally, due to computational reasons only 10% of the population is simulated. In all their simulations, more than 60% of the time, vehicles are only carrying one passenger. The authors also note that a 4-seater vehicle should be enough to serve most pooling demand. As their simulation model allows for mode-choice, all scenarios exhibit an increase in VKT when all motorized modes of transport are considered. On the other hand, scenarios with ride-sharing compensate for some of the added VKT, but only slightly.

Ruch *et al.* (2021) developed a ride-sharing extension of the framework called AMoDeus Ruch *et al.* (2018) that can be used to quantify the performance of shared automated fleets using static demand. The AMoDeus framework uses MATSim for the network assignment and is open-source. In Ruch *et al.* (2021) the authors show the performance of four most frequently used ride-pooling algorithms Ma *et al.* (2013a); Alonso-Mora *et al.* (2017a); Bischoff *et al.* (2017a); Fagnant and Kockelman (2018a). They find that the algorithm proposed by Alonso-Mora *et al.* (2017a) performs best in terms of VKT increase. They investigate two scenarios: an urban area demand represented by the San Francisco taxi demand and a rural scenario represented by the rail demand in a rural area in Switzerland. The findings show that the vehicle is only used by a single traveller in more than 40% of the trips in the urban case, whereas in the rural case, the share increases to 68%. The authors conclude that the increased discomfort of sharing rides could potentially be hard to justify with the increased efficiency of the shared service. They also point out that vehicles with 4-6 should be enough to support the occasional ride-pooling trips.

Zwick *et al.* (2021a) employ agent-based methodology to investigate the potential demand for shared automated vehicles in Munich using MATSim. Unlike previously reviewed studies, the authors here test two types of services, door-to-door and stop-based service, in cases of static replacement of car trips and under mode-choice[13]. The authors note that downsampling their population (i.e., to reduce computation time) would lead to artifacts in pooling behavior, therefore, they always simulate 100% population samples. In general, the results suggest that a stop-based service exhibits higher pooling and, therefore, lower VKT than a door-to-door service. In the mode-choice scenarios, due to lower demand, the pooling potential is also reduced. In all scenarios, the authors find that vehicles with up to five seats can be beneficial. Moreover, in the case of stop-based service, even the six-seaters are fully occupied for 10% of the total driven distance.

Kagho *et al.* (2021) investigate the impacts of demand-responsive service in Wayne County, USA. The authors use MATSim, its discrete mode-choice, and DRT extensions to perform the study (version is not documented). Due to a lack of survey data, the authors make educated assumptions regarding the DRT parameters values in the mode-choice model. The addition of DRT would increase the VKT of the DRT users by up to 66%, even though the system-wide VKT would increase only by about 0.07%. Pooling potential is relatively small, with almost all trips having fewer than three passengers. The highest average occupancy rate in all simulated scenarios was 1.12.

Gurumurthy *et al.* (2021) look at the potential impacts of geofencing on a system of shared automated vehicles in Chicago, Illinois. The authors use POLARIS (version not documented) with the ride-pooling heuristic presented in Gurumurthy *et al.* (2020) and look at system-wide impacts of SAVs based on the service area size and pooling availability. They note that while ride-pooling can save some of the VKT, the geofencing accounts for the most VKT saved due to restricting the service to high-density neighborhoods. They also note that pooling had a larger effect when larger areas were considered.

[13] Based on the value of time assumptions.

The only two studies known to the authors that directly integrate estimated behavioral mode-choice models within an agent-based simulation for automated on-demand services are studies by (Oh *et al.*, 2020) and Hörl *et al.* (2021) (Vosooghi *et al.* (2019b) integrate their models within the MATSim scoring environment).

Oh *et al.* (2020) use SimMobility and combine the 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. To investigate the pooling potential, the authors develop a pooling algorithm that resembles the one implemented by Bischoff *et al.* (2017a). The authors assume the cost of single rides to be in the range of 75% - 125% of current taxi costs, and that pooled-rides have a 25% discount. The results using a 100% population 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.* (2021) conducted a similar study in Zurich by combining a mode-choice model focusing on automated mobility with an agent-based simulation. However, the authors go one step further and, in an iterative process, adjust the price of service based on the demand. The studies conducted only include single-occupancy vehicles and focus on the city of Zurich and its surroundings. Findings based on a 10% population sample suggest that users are willing to accept the waiting time of around 4 minutes with the price of 0.75 CHF/km. On the other hand, the introduced services' impacts are generally negative with the modal shift from more sustainable modes and increased congestion in residential areas. In total, the increase in the vehicle-driven distance goes up to 100% in specific simulated scenarios. Therefore, the authors suggest that shared on-demand automated service needs to be regulated to avoid negative environmental impacts.

In the Swiss context, two notable projects investigating the impacts of shared automated vehicles (SAVs) have so far provided the most insights about the potential of SAVs: ASTRA 2018/002 Axhausen *et al.* (2020) and SVI 2016/001 Hörl *et al.* (2018). Both projects rely on the cost covering estimates of automated vehicle fleets in Switzerland presented in Bösch *et al.* (2018). The simulation results of the SVI 2016/01 project, were extended and published in Hörl *et al.* (2021), which do not consider pooling, even though the SP travel survey conducted within the project considered pooling as one of the alternatives. The SVI 2018/002 project touched upon the potential of ride-pooling while investigating the large-scale impacts of vehicle automation. While the estimated potential of ride-pooling was low, the authors suggest that one of the reasons was that the pooling algorithm was rather simplistic. It matches any new request with the closest vehicle with available space and which does not violate the specified detour constraints. If none of the vehicles are currently available, the request can be rejected or put on hold.

2.3.5 Conclusion

To summarize the reviewed papers we will first focus on the outcomes of the presented studies and second on the technical and methodological approach.

As can be seen from the above studies (see also summary in Table 2, the estimated potential of ride-pooling varies across regions. While some authors report high potential and even system-wide VKT reductions Gurumurthy and Kockelman (2018); Bischoff *et al.* (2017a), others report less promising results Ruch *et al.* (2021); Kagho *et al.* (2021). Considering that these studies are context- and methodology-specific, different outcomes are reasonable. Different assumptions on cost for ride-hailing and ridepooling as well as the lack of credible behavioral models on individuals' preferences for pooled services are further reasons which make it difficult to draw robust and generalizable insights from those studies.

Most studies only simulated ride-pooling in door-to-door mode, although Zwick *et al.* (2021a) show that stop-based service could lead to higher occupany-rates. Finally, almost no study (with the exception of Gurumurthy *et al.* (2019b) tests the impact of policy measures to increase the attractiveness of ridepooling, e.g., HOV lanes, occupancy-based road pricing

or subsidies (urban public transport only covers about 60-70% of its costs and is subsidies as it ensures mobility for everybody and helps to reduce congestion).

From the perspective of the methodological approach the following summarizes the main findings. All reviewed studies use pooling algorithms that have been previously developed within the framework that the authors utilize. In general, adding and testing self-made algorithms into existing frameworks (i.e., MATSim, Polaris, SimMobility) is not straightforward and requires considerable coding effort. However, a smart algorithm could lead to reduced cost (more efficient operation) and higher occupancy rate which make the service both more affordable and more sustainable. Therefore, an alternative, which we will explore in this project is to allow an agent-based simulation, in our case MATSim, to exchange information with an outside framework that is responsible for matching of potential riders and pooling them in vehicles. Providing an appropriate API will increase the flexibility of the MATSim framework, thus allowing easy benchmarking and comparison of algorithms.

Frequently equilibrium simulation studies reviewed above use population samples to conduct their investigations. The authors of these studies mostly cite high computational needs as the main reason for downsampling their populations. However, as Zwick *et al.* (2021a) note and as (Zwick *et al.*, 2021b; Kaddoura and Schlenther, 2021) show population samples could have non-linear effects on pooling and other service measures. Therefore, an investigation specific to our study areas should be be carried out to analyse the effects of population sampling, which can guide our decision when making tradeoffs between computation time and accuracy.

Tab. 2 *An overview of findings of ride-hailing studies using agent-based simulations.*

Paper	Region	Demand	Software	mode-choice	ride-pooling	VKT	shared-rides
Bischoff *et al.* (2017a)	Berlin, Germany	static	MATSim	no	yes	-20%	60%
Gurumurthy and Kockelman (2018)	Orlando, Florida	static	MATLAB	no	yes	-1%	60%
Gurumurthy *et al.* (2019a)	Austin, Texas	dynamic	MATSim	with assumptions	yes	+(2 - 4.5)%	na
Vosooghi *et al.* (2019a)	Rouen Normandie, France	dynamic	MATSim	with assumptions	yes	+ (13 - 27)%	40%
Ruch *et al.* (2021)	San Francisco and Switzerland	static	AMoDeus	no	yes		32 - 60%
Oh *et al.* (2020)	Singapore	dynamic	SimMobility	estimated	yes	+(11 - 42)%	$\sim 60\%$
Zwick *et al.* (2021a)	Munich, Germany	dynamic	MATSim	assumed	yes	+(3 - 8)%	na
Hörl *et al.* (2021)	Zurich, Switzerland	dynamic	MATSim	estimated	no	+xxx	-
Kagho *et al.* (2021)	Wayne County, USA	dynamic	MATSim	with assumptions	yes	+0.07%	10%
Gurumurthy *et al.* (2021)	Chicago, Illionis	dynamic	POLARIS	with assumptions	yes	increase	na

2.4 Optimising ridepooling operations - matching algorithm

2.4.1 Introduction

Optimization of ride sharing services has attracted a lot of research interest recently. This problem can be formulated mathematically in a similar way as the vehicle-routing problem (VRP) and the dynamic pick-up and delivery problems. The general definition for pick-up and delivery problems is how to optimally transport objects or people from an origin to a destination. Given that all the input data are available before the determination of the routes, the problem is classified as a static optimization problem, for instance the works done by Bongiovanni *et al.* (2019). On the other hand, in the dynamic version of the problem, some of the input data are communicated during the operational process (e.g. customer requests). Hence the solutions we are seeking are known as strategies to decide for the real-time operations as a new request is received. Another classification presented in Pillac *et al.* (2013) is based on whether the information received by a request is certainly known (deterministic) or still undetermined and subject to changes (stochastic). The classification of vehicle routing problems by information evolution and quality is presented in Tab. 3.

2.4.2 Relevant literature

The first approaches to optimise ridepooling operations have been devloped in the context of transportation for elderly and handicapped people (paratransit) and are known as the dial-a-ride problem (DARP). In Oxley (1980) a solution is proposed for a demand responsive service for individuals who are not able to use public transport. Early solutions of DARP have mainly utilised heuristic methods, e.g., the solution provided by MIT for the DARP service in Rochester, New York, USA by Wilson and Urban Systems Laboratory (1971). Later, Psaraftis (1980) introduced the first model with a dynamic programming approach for both the static and dynamic version of DARP. In the past 40 years, there has been a steady growth of different methods applied to solve DARP as the extensive reviews by Ho *et al.* (2018) and Cordeau and Laporte (2007) show.

The study in Ho *et al.* (2018) classifies the solutions proposed by different researchers for dynamic deterministic DARP into theoretical and experimental approaches. The theoretical solutions include (a) an online algorithm, which has proven to provide better results versus its offline counterpart, or (b) a methodology to compute a lower bound which is tighter compared to the previously introduced lower bounds (see e.g. Waisanen *et al.* (2008); Yang *et al.* (2004)). On the other hand, experimental approaches mostly develop simulation engines or other dynamic models. In these approaches, a new input (event) triggers the simulation engine or the model to make decisions in a short period of time. As stated in Ho *et al.* (2018), a passenger request is in most of the cases the simulation trigger (event) for rescheduling the vehicles' routes (e.g Berbeglia *et al.* (2012); Häll *et al.* (2015)). The aim of such approaches is to serve the new request in an optimal way. In most of the studied cases, there is a penalty when a request is rejected. The work by Ho *et al.* (2018) recommends to consider other triggers (events) for rescheduling as well, such as vehicle breakdowns and unexpected events, in order to have a more realistic representation of the dynamic deterministic DARP (see e.g. Beaudry *et al.* (2010)). Atasoy *et al.* (2015) have developed an approach which offers more options of on demand and personalized services with different pricing scheme instead of rejecting the request. Their model is built based on a choice model and consumer surplus is optimised as a proxy of passenger satisfaction.

Researchers have applied different methods to solve different types of DARPs. Some so-

Tab. 3 *Classification of vehicle routing problems by information evolution and quality Pillac et al. (2013)*

		Information quality	
		Deterministic input	Stochastic input
Information evolution	Input known beforehand	Static and deterministic	Static and stochastic
	Input changes over time	Dynamic and deterministic	Dynamic and stochastic

lution can be applied to more that one type of DARP as classified in Tab. 3, therefore we classify the methods based on the solutions rather than the type of the problem.

2.4.3 Exact methods

Exact algorithms for DARPs are primarily developed using the branch-and-bound concept (B&B). These algorithms are divided into three types: branch-and-cut (B&C), branch-and-price (B&P), and branch-and-price-and-cut (B&P&C). The development of exact methods for DARPs has a strong bias toward deterministic and static problems. Many stochastic programming problems are computationally intractable for realistic DARP instances, and exact methods may not be capable of providing timely solutions for dynamic DARPs. Furthermore, exact methods can provide the highest quality solutions, which is the most important concern during the planning phase (i.e., static problems). Another finding of the exact methods examined is that they are for single objective DARPs. to our best knowledge exact algorithms for multi-objective DARPs are less studied. The very first algorithms based on branch and cut was developed by Cordeau (2006) derived from the well-known inequalities for the Traveling Salesman Problem and Vehicle Routing Problem by applying several families of valid inequalities as cuts for the three-index mixed integer programming formulation. Some other inequalities were also applied in other studies based on the problem-specific features. (e.g. Ropke *et al.* (2007), Parragh (2011), Braekers *et al.* (2014), Liu *et al.* (2015)).

2.4.4 Heuristics and metaheuristics

Since DARP is an NP-hard problem, most of the proposed techniques include classical heuristics or metaheuristics that can be applied to large-scale problems. Implementation of construction heuristics can be beneficial when a feasible solution is required in a short period of time, e.g. in dynamic DARPs (see Wong *et al.* (2014); Marković *et al.* (2015)). Moreover, Wong *et al.* (2014) has evaluated different strategies by application of construction heuristics. Most of these heuristics are based on the concept of greedy insertion heuristics, in which the vehicle with the cheapest insertion criterion in their route is chosen to accommodate the request(see e.g. Jaw *et al.* (1986)). Finally, in Diana and Dessouky (2004) various insertion strategies have been studied.

Tabu Search (TS) is another well-known and commonly used metaheuristic to solve static DARPs. In TS a tabu list is created and the local search algorithm avoids revisiting previously evaluated solutions. As stated in Ho *et al.* (2018), the study in Cordeau and Laporte (2003) was among the first who applied the TS method to solve static DARPs. However, for a dynamic DARP a shorter response time is required; actually Attanasio *et al.* (2004) provided several parallel computation methods for implementing TS processes to solve dynamic DARPs. There are several other metaheuristics developed to solve different classifications of DARPs, e.g., simulated annealing, variable and large neighborhood search, genetic algorithms, and hybrid methods. Interested readers are referred to the review surveys Ho *et al.* (2018) and Cordeau and Laporte (2007) for a detailed summary of previous works.

Given all the above literature, we mainly focus in our work on real-time operations of ride sharing systems and aim to solve the matching problem (i.e. matching demand with supply), on the fly (i.e. as real-time requests arrive by the users in the operational center). Users are assumed to use an interface (e.g. smartphone app) to hail a taxi service, willing to share the vehicle with other passengers, and provide pick-up and drop-off time windows of their preference. The designed matching optimization algorithm needs to be fast enough (i.e. provide a response in a fraction of a second) and take into account different objective criteria, provided by the system's operator. Our main contribution is to give experimental solution for a dynamic deterministic ride sharing problem. As stated before in experimental solution, researchers benefit from simulation environments. Whereas in Chapter 2.3 the studies that benefit from MATSim are introduced, in the following, we specifically review their algorithms in more detail .

2.5 Matching Algorithm in agent based simulations

Ruch *et al.* (2020) have used MATSim as a simulation environment to which they linked

their AMoDeus framework through an API to investigate four different ride pooling algorithm in addition to a very basic method as a globally applicable reference that is not scenario-specific. This method was described by Ruch *et al.* (2018) as Global bipartite matching policy (GBM) and minimizes the Euclidean distance between the locations of open requests and available vehicles by using the Hungarian method to solve a bipartite matching problem. We review the other four algorithms in more details and study their features in the following.

High Capacity Shared Autonomous Mobility-on-Demand Algorithm: (HCRS) has been developed by Alonso-Mora *et al.* (2017b). Using integer linear programming, the concept of this well-formalized operational strategy for the ride-sharing mobility-on-demand problem is to explore all viable choices in a reasonably efficient manner. So-called journeys are composed of two elements: (1) the vehicle, which includes the set of passengers on board; and (2) the set of passengers from whom the vehicle is scheduled to pick up the vehicle. As a result of this constraint, journeys during the exploration phase are limited to a maximum wait time and a maximum increase in total travel time relative to the quickest route. In addition to passengers who have already boarded vehicles, these restrictions apply to all other passengers on the road. Once a route has been discovered, the cost of each conceivable trip is calculated as a sum of the total travel delay experienced by all passengers participating in the trip. A passenger may also be purposefully disregarded by the system, resulting in a significant financial loss for the company. An integer linear program is used to find the solution that minimizes the sum of the expenses of the selected trips. If there are both ignored requests and idling cars at the same time after each assignment, the algorithm will send the idling vehicles towards the direction of the ignored requests in order to minimize the total of Euclidean distances between these assignments once the assignment is completed.

T-Share Policy: The T-Share policy presented in Ma *et al.* (2013b) was one of the first contributions to investigate the efficiency gains that result from multiple travel parties sharing a single-use taxi. The algorithm makes the assumption that a unit-capacity mobility-demand system is in operation. Then it takes action on a collection of vehicles that are now conveying a single travel party and determines whether or not more travel parties may be accommodated on the vehicle in question. This procedure is carried out in two stages. When a client transportation request is received, an algorithm known as "dual side taxi searching" is utilized to identify a group of already occupied cars that may be able to accommodate the transit request by modifying the present timetable. This set has the minimum possible cardinality, which means that the iterative process stops as soon as it discovers a nonempty set, which is the case in this case. Next, for this set of potential taxis, an algorithm known as the "insertion feasibility check" determines which vehicle and schedule insertion permutation can handle the additional request with the least amount of additional mileage while still meeting the constraints of the latest pickup and the latest arrival of the passenger. When the T-share operating policy was expanded to allow for the addition of a travel party to a vehicle even when there are already many travel parties in the vehicle, it was considered a significant accomplishment.

Dynamic Ride Sharing Strategy: (DRSS) presented in Fagnant and Kockelman (2018b) offers an operational policy that is based on earlier work done for the single traveler per vehicle scenario by the same researchers. In this algorithm in each time step, a suitable vehicle is discovered and, if possible, assigned to a request for all unassigned travel parties. Ride-sharing assignments are sought with the utmost priority and are subject to the following five requirements: The total travel time of the planned parties may increase by a maximum of 20% above the original schedule. The remaining travel time of the scheduled parties must not rise by more than 40% compared to the original timetabled journey. When compared to the projected travel time of a straight drive, the total travel time of the unassigned party may increase by no more than the greater of 3 minutes and 20%. Pickup of the unassigned party must occur within the following five minutes. The total planned time to serve all travel parties must be less than the total planned time to serve the scheduled parties plus the total planned time to serve the unassigned party separately, unless otherwise specified. If a suitable ride sharing option cannot be discovered, the next highest priority is to allocate the nearest available car to a traveling party. Block-balance methods are used to rebalance idle vehicles, in which the local imbalance of free vehicles and demand between

nearby cells is used to calculate rebalancing directives.

Extended Supply Demand: (Ext-DS) This policy is a ridesharing-heuristic-based expansion of the single traveler per vehicle policy introduced in Bischoff *et al.* (2017b). For the purpose of unit-capacity assignment, an overstock and a shortage are defined by the presence of more available cars than open requests, or vice versa. Then, for each vehicle (or request), the set with the greater cardinality is iterated in random order and the nearest request (or vehicle) is assigned. Additionally, the ride-sharing extension searches for each car if there are open requests within a radius of no more than 0.62 miles and a divergence of no more than 5 degrees from the on-board passengers' destination. Additionally, the traveling car picks up on these demands.

Among all the introduced algorithms the High Capacity Shared Autonomous Mobility-on-Demand Algorithm: (HCRS) developed by Alonso-Mora *et al.* (2017b) has the best results in the MATSim environment based on the study presented in Ruch *et al.* (2020).

Conclusion This literature review presented the ride-sharing algorithm's mathematical problem as a combination of vehicle routing problem and dynamic pick up and delivery problem known as dial a ride problem (DARP). We introduced the classification of this type of problem as static or dynamic based on information evolution, deterministic or stochastic based on information quality. For all types of DARP, solutions are implementing either exact methods benefiting from the concept of branch and bound, or Heuristics and meta-heuristics methods, primarily benefiting from construction heuristics such as greedy insertion and tabu search. Although the solution to these kinds of problems is very similar in methodological aspects, the details of the problem itself depend highly on the features needed in each study. For instance, considering time windows for pick up or drop off, or if sharing is mandatory for all the requests or optional. Regarding all these details, each study is specifically designed to meet a predefined purpose, and not all results are easily comparable. Moreover as stated in chapter 2.3 there is a lack of studies focusing on behavioural models on individual preferences for pooled services as well.

Given the fact that the focus of the current project is on dynamic deterministic DARP, we reviewed the papers focusing on this type of problem utilizing the agent-based simulation. Among all the algorithms implemented in MATSim, the best-performed algorithm introduced by Ruch *et al.* (2020) is introduced by Alonso-Mora *et al.* (2017b), known as the High Capacity Shared Autonomous Mobility on Demand (HCRS) algorithm. However, in this study (Alonso-Mora *et al.*, 2017b) behavioral aspects are neglected, and also the objective function is only minimizing the operational expenses. Therefore, by achieving the knowledge of previous studies, we try to produce an algorithm that best meets the features we pursue in our project and produce an algorithm that performs efficiently stand-alone and can also be implemented in MATSim environment.

3 Qualitative interviews

3.1 Introduction

To identify drivers and barriers that determine the usage of aRP, we adopted an exploratory approach using semi-structured qualitative interviews. The use of qualitative interviews allows for an in-depth investigation of factors such as attitudes and behavioral tendencies (Brinkmann, 2014). The qualitative interviews served two objectives: The main objective was to identify the relevant factors of people's intention to use - or not use - aRP. In addition, the interviews served the purpose to pretest informational materials intended to use to mitigate concerns when using aRP of the stated-preference survey.

This section will first explain the methods used to achieve these objectives. Second, results are reported and discussed. Finally, conclusions for the following work packages are summarized.

3.2 Methods

3.2.1 Data collection procedures

To achieve the research objectives we conducted 19 semi-structured qualitative interviews. The interviews were structured in two parts: The first part served for the identification of drivers and barriers. The second part aimed to pre-test the informational materials (videos). Interviews were conducted in two waves. This iterative procedure allowed for an adjustment of the materials used for the second wave based on the results of the first wave. The main part of the interviews - the identification of relevant factors that influence people's intention to use aRP - was identical for both waves.

In the *first wave* there was an additional focus on drivers and barriers of using AVs in general. Further, the pretest of the informational materials (videos) addressed the general comprehensibility. The findings out of the pretest of the videos were then used to adjust the videos if required for the second wave.

In the *second wave*, the focus was only on the factors of using aRP, skipping questions regarding the use of AVs in general. Besides, we pretested the videos more thoroughly in order to analyse the effect of information that informs about AV and RP, and mitigates possible concerns about these new modes of transport. Nine interviews were conducted in the first wave; ten interviews were conducted in the second wave. The interviews in the first wave were conducted in February 2022; the interviews in the second wave approximately one month later in March 2022. The respective procedures of the two waves are listed in Tab. 4.

Each interview took between 45 to 60 minutes. The interviews were administered remote via a video communication application. The interviews were conducted by trained interviewers according to a pretested semi-structured interview-guideline. All interviews were recorded and transcribed.

Tab. 4 *Interview procedures for first and second wave*

Waves:	Procedure in first wave	Procedure in second wave
Sample size:	*n*=9	*n*=10
Introduction:	Description of the terms AV and RP	
Part 1 - Focus:	Factors influencing use of AVs	-
Part 1 - Main part:	Factors influencing use of aRP	
Part 2: Focus	Pretesting video - general comprehensibility	-
	-	Pretesting video - contextual information

3.2.2 Interview techniques

The present research adopted two specific interview techniques to overcome the challenges to identify implicit attitudes and perceptions: Narrative storytelling and projective interviewing technique.

Researching attitudes towards hypothetical scenarios in the future - such as using aRP - is a challenge that can be overcome by applying the interview techniques of as the narrative storytelling (Sools, 2020). Narrative storytelling enables tapping into more implicit aspects as it relies less on cognitive-rationalising aspects and rather allows the expression of emotional, complex or conflicting attitudes (Wattanasuwan *et al.*, 2009).

Projective techniques are another method that allows for a better understanding of underlying motives (Gröppel-Klein and Königstorfer, 2009). Projective techniques are a means to tap into implicit feelings, attitudes and motivations, that may otherwise be difficult to express or are influenced by social desirability. We thus used the third-person technique in order to gain more meaningful insights into the reactions to the videos. In this technique, participants are asked to imagine a third person and answer any questions with respect to this person's supposed motives, attitudes or behavior (Kirchmair, 2011).

3.2.3 Recruitment and sample

Participants were recruited using different channels. To ensure the participation of innovators with regards to ride-pooling, a part of the participants were recruited over the customer base of existing ride-pooling services in Switzerland. The major part of the participants were recruited over social media channels and a recruitment service provider. To ensure the inclusion of participants from the segments of early and late majority, participants were screened accordingly. To this end, the following screening questions was used:

In recent years, various new transport offers have emerged. Those include new drive technologies (electric cars, hydrogen cars), new sharing offers (e.g., Mobility) or new mobility services (e.g., taxi rides via app like Uber).

How strongly do you agree with the following statement? "Generally speaking, I am one of the first in my circle of friends and family to try out new mobility offers".

The respondents were asked to indicated agreement on a five level scale and only respondents who indicated the levels "quite much (ziemlich, 4)", "partly (teils-teils, 3)" and "little" (wenig, 2) were asked to participate in the qualitative interview. In this way, it was ensured that moderately innovative persons were recruited which are expected to provide more heterogeneous opinions as compared to recruiting only early adopters.

Participants were residents of the German-speaking part of Switzerland who were either mostly public transport users (*n*=11), or mostly private car user (*n*=8). A detailed overview of the participants' attributes is listed in Tab. 5. Participants were balanced in terms of

gender (male, *n*=9; female, *n*=10) and aged between 21 and 61 years; the mean being 36 years, the median being 33 years. The interviewees received a monetary incentive of 50 Swiss francs for their participation.

Tab. 5 *Description of sample*

Tag	Interview wave	Age	Sex	Previous experience with RP	Main modality type
P1	First	49	Female	Yes	Public Transport
P2	First	61	Male	No	Public Transport
P3	First	32	Female	No	Public Transport
P4	First	42	Female	No	Public Transport
P5	First	24	Male	Yes	Public Transport
P6	First	25	Female	Yes	Public Transport
P7	First	50	Male	No	Car
P8	First	41	Male	Yes	Public Transport
P9	First	25	Female	No	Public Transport
P10	Second	21	Female	No	Public Transport
P11	Second	22	Male	No	Car
P12	Second	26	Male	No	Public Transport
P13	Second	22	Male	Yes	Public Transport
P14	Second	23	Female	No	Car
P15	Second	59	Male	No	Car
P16	Second	33	Female	No	Car
P17	Second	54	Female	No	Car
P18	Second	44	Male	No	Car
P19	Second	46	Female	No	Car

3.2.4 Interview guide

The interviews were conducted following a semi-structured interview guide. The interview guides for the first and second wave are described in Tab. 6.

In the introduction, the concept of AV and RP was explained and the participants were asked whether they have previously heard of or used this mode of transport. In order to identify the factors influencing the use of AVs and aRP (Part 1), the technique of narrative storytelling was used: The participants were asked to imagine a fictitious journey with an AV or with aRP, respectively. Interviewees were asked to imagine the whole journey from the very beginning (the planning), to how they get to the vehicle, how the actual drive looks like up until to their arrival at their endpoint. The participants were then asked why they would use - or not use - an AV or aRP, respectively. With additional questions we could gain a more thorough understanding of the relevant factors.

In order to pretest the videos about AV and RP that were produced for the SP survey (Part 2), the participants in the first wave were asked general questions about comprehensibility. In the second wave, the questioning was conducted with the third-person strategy. Participants were asked to imagine a person who predominantly uses a private car and who gets information by watching the video about AV and RP, respectively. The participants were then allocated to one of two groups (AV or RP) and only answered detailed questions about the respective video. Since the questions concerned a specific part of the video, the respective section was recapped beforehand.

Tab. 6 *Interview guides for first and second wave*

Part	Procedure	Content		
		First wave	Second wave	
Introduction	Description of terms AV and RP	Definition of concept of AV and RP	-	
		Inquiry about previous experience		
Part 1 Focus	Factors influencing intention to use AV	Narrative storytelling about journey in AV	-	
		Follow-up questions about factors: trust, safety, cost, norms, flexibility, perceived control, time, environment, emotions		
Part 1 Main part	Factors influencing intention to us aRP	Narrative storytelling about journey with aRP		
		Follow-up questions about factors: trust, safety, security, socializing, cost, norms, flexibility, perceived control, time, environment, emotions		
Part 2 Focus	Pretest video AV and RP: General comprehensibility	Questions about general comprehensibility	-	
	Pretest video RP: Contextual information	-	Introduction to third-person strategy	
			Group RP	*Group AV*
			General question about comprehensibility	
			Specific questions about costs, reliability, availability, trust and comfort regarding social situations	-
	Pretest video AV: Contextual information	-	General question about comprehensibility	
			-	Specific questions about trust, safety, security, cost

3.2.5 Analysis

The transcribed interviews were analyzed according to the procedures of a structured content analysis. The narrative storytelling, including the questions about specific factors, was analyzed in a two-step procedure. In a first step, interview-transcripts were coded by two independent coders along the constructs and factors based on the findings from the literature review (see chapter 2.1, deductive coding). New codes where given to additional factors when necessary (inductive category development). The coding system for Step 1 is described in Tab. 7. Overall, the coding system comprises seven constructs and 23 psychological factors. In a second step, different arguments within a factor were classified either as a driver, barrier or as neutral. This resulted in a three-level structure of the coding system: (1) constructs, (2) factors and (3) arguments that describe either a driver, barrier or a neutral argument for using aRP.

The feedback about the videos was analyzed separately. A deductive coding system was derived from the factors addressed in the videos, such as cost, reliability, availability, and trust for the RP video; and trust, safety, security, and incentives for the video presenting aRP. For each factor the following additional subcodes were defined: understanding, importance and motivation to use the offering presented in the video in relation to the factor. Additional codes were defined, such as spontaneous reaction, intention to use RP from a personal perspective, overall understanding for each video and applicability of the videos. The interviews were coded along the determinants based on the previously defined coding system. The findings were summarized for each factor.

The interviews were analyzed using the software MAXQDA.

Tab. 7 *Coding system*

Construct	Factors	Description	References
Performance expectancy	Safety	To what extent a passenger feels safe in regard to the technology, speed or safety measures, e.g., an emergency button	Zubin *et al.* (2020); Nordhoff *et al.* (2018, 2020)
	Time	Statements about waiting time, travel time, walking time, etc.	Merat *et al.* (2017)
	Privacy	Concerns about the use of personal information, such as the user's locations and facial recognition	Gurumurthy and Kockelman (2020)
	Environmental considerations	Considerations about the impact of aRP on the environment (e.g., less cars, better air quality, less emissions	Paddeu *et al.* (2020)
	Comfort of the vehicle	Aspects like atmosphere, vehicle exterior and interior, disability friendliness, personal space due to seat arrangements and cleanliness	Etminani-Ghasrodashti *et al.* (2021); Schuß *et al.* (2021)
	Parking space	Statements about the need, availability and cost of parking spaces	Stoiber *et al.* (2019)
	Trip purpose	Work, shopping, education, home, leisure or others	Hamadneh and Esztergár-Kiss (2022)
	Reliability	Aspects of predictability of travel time, waiting time, punctuality and exact information about pick-up and drop-off locations in advance	Etminani-Ghasrodashti *et al.* (2021)

	Flexibility	The flexibility of changing routes and stops (pickup and destination), flexible booking options and spontaneous availability of a ride	Schuß *et al.* (2021)
	Availability	Access during different business hours and to recreational destinations, but also the capacity of service	Etminani-Ghasrodashti *et al.* (2021)
Effort expectancy	Perceived control	The feeling of having the ability to control something	Sanguinetti *et al.* (2019)
	Information on app	Information on real-time positioning of the AV and its near-future trajectory, pricing and payment. Possibility of direct booking and payment.	Merat *et al.* (2017)
	Payment	Includes the payment method, e.g., cash or credit card	Etminani-Ghasrodashti *et al.* (2021)
	Planning	Includes the process of planning a trip (short-term or long-term) and the tool that the consumer uses to plan a trip	own definition
	Liability	Statements about accidents, claims and corresponding liability	own definition
	Interaction with vehicle	Communication with automated vehicle	Nordhoff *et al.* (2020)
Social influence	Social norm	Extent to which users perceive that important others (e.g., family and friends) believe they should use the service	Venkatesh *et al.* (2012)
Facilitating conditions	Skills	Requirements for the users	own definition
Hedonic motivation	Hedonic motivation	The fun or pleasure derived from using the service	Venkatesh *et al.* (2012)
Price value	Cost	Travel cost and cost saving from the consumer's perspective	Paddeu *et al.* (2020)
Social aspects	Security	Safety concerns related to other passengers	Dolins *et al.* (2021)
	Comfort in social situation	Psychological or social comfort or discomfort caused by close interpersonal space between passengers	Merat *et al.* (2017)
	Socializing	Interaction between two or more passengers on a shared vehicle	Sanguinetti *et al.* (2019)

3.3 Results

The results of the qualitative interviews are reported along the framework of constructs explaining the acceptance of new technology.

The results of the pretest of the videos are not reported in detail here. The pretest led to two minor changes in the information in the video: 1) relevant costs comparison for car users and 2) clearer differentiation between RP and aRP. The results were directly incorporated

into the adaptation of the videos and are more thoroughly described in chapter **??**.

3.3.1 Performance expectancy

Performance expectancy consisted of ten different factors: safety, privacy, environmental considerations, comfort of the vehicle, parking space, trip purpose, reliability, flexibility and availability. The results are described along the most frequently mentioned factors in descending order.

Safety was both very frequently mentioned as a driver and as a barrier for using aRP: 18 participants mentioned a driver and 14 mentioned a barrier (see Tab. 8). Often the same person mentioned some concerns about autonomous driving while simultaneously being convinced that it is safe ("*I did ask myself, what if the vehicle short-circuits, a chip fails or a sensor isn't calibrated properly. However, it would generally lead to safer streets. I am convinced that technology is safer than humans.*", P04). When using aRP for the first few times, participants generally expect feeling insecure ("*I think I am going to feel insecure, to have these doubts whether you can trust it. Because always when there is something new, you are unsure whether this will work.*", P03). Whereas some were only sceptical about the technical functioning of the vehicle, others were afraid of accidents or technical failures and thus being stranded somewhere. A few participants stated that it is a new and unfamiliar mode of transport without it being perceived negatively. Most participants, however, showed high trust in autonomous driving. They often mentioned that autonomous driving is safer than human-operated vehicles ("*I would trust it more than human reliability. Humans make mistakes.*", P15). Participants also showed high trust in the safety standards a vehicle has to meet before being allowed to drive. A few people mentioned that they would use RP when they have information about its safety, e.g., information about accident rate.

Tab. 8 *Results for category:* Safety

Valence	Number of mentions	Arguments
Drivers	18x	Trust in technical functionalities
		Belief that AV are safer than human-operated vehicles
		Trust in safety tests
		Growing trust through repeated use
		Information about safety standards
		Other: Feeling safe due to presence of other passengers; Presence of driver during initial test drives
Neutral	5x	New and unfamiliar at the beginning
		Open questions about how vehicle works
Barriers	14x	Feelings of insecurity and uneasiness
		Sceptical about technical functionalities
		Fear of accidents
		Difficulty at handing over control
		Fear of technical issues
		General fear of AV
		Guilt in case of an accident

Environmental considerations was very frequently mentioned as a driver: 18 participants mentioned it as a driver and five participants mentioned it as a barrier (see Tab. 9). An important argument for aRP being environmentally friendly was that these vehicles make better use of their capacity ("*Why should a large bus drive into the smallest villages with only a handful of passengers?*", P02). Another frequently mentioned aspect was that aRP would use alternative propulsion technology, e.g., would be electric vehicles. Additionally,

the reduction of privately owned vehicles was often seen as an environmental driver for aRP. A barrier is the lower capacity of aRP compared to conventional public transport, which would also lead to an increase in traffic ("*The advantage of public transport is that a lot of people can use a bus, in a small [aRP] fewer people have space*", P01). aRPs not being operated at sufficient capacity was also seen as a problem. Other barriers were the negative impact of the propulsion technology, either the use of conventional combustion engines or the disadvantages of electric driving, e.g., battery or local pollution.

Tab. 9 *Results for category:* Environmental considerations

Valence	Number of mentions	Arguments
Drivers	18x	Higher use of capacity Alternative propulsion technologies Reduction of car ownership Decrease in traffic Clever routing Eco-friendly (general)
Neutral	1x	Other: Sustainability is not an important factor
Barriers	5x	Conventional public transport is more sustainable Other: Increased traffic; Use of conventional propulsion technologies; Negative effects of electric driving; Insufficient use of capacity

Availability was very frequently mentioned as a driver and also often mentioned as a barrier: 16 participants mentioned a driver and nine participants mentioned a barrier (see Tab. 10). aRP was often seen as a service that complements public transport, e.g., during off-peak hours or in rural areas where the public transport network is less dense ("*Where I live in the mountains - [using aRP] instead of a bus is actually quite cool. [...] Why should a large bus drive into the smallest villages with only a handful of passengers*", P02). Whereas some participants thought aRP was a good service for urban areas, other thought it less suitable as the existing public transport network was seen as sufficient. A sufficient number of vehicles was considered important to enable spontaneous and flexible use of the service, whereas an insufficient number was considered a barrier. Four car users and one public transport user considered the advantages of a private car: the private car was seen as more flexible than aRP and it allowed for leaving their belongings in the car ("*I would miss my car. For example for leisure activities, where I can just pack my car that sits in the garage. I can throw everything in it and leave. Ride-pooling can't offer me that.*", P18).

Tab. 10 *Results for category:* Availability

Valence	Number of mentions	Arguments
Drivers	16x	Service for off-peak hours
		Service for areas with insufficient public transport network
		Sufficient number of vehicles
		Service for urban areas
		Addition to public transport
		Extensive network to enable direct trips
		Weather-dependent service (e.g., snow)
		Suitable vehicles for transport needs (e.g., heavy luggage)
		Replacement for public transport
		Other: replacement for private car
Neutral	-	
Barriers	9x	Insufficient number of vehicles
		Private car is always available
		Service not suitable for urban areas
		No immediate availability
		No possibility of leaving your belonings (as in a private car)

Time was very frequently considered a driver and also frequently considered a barrier: 15 participants mentioned a driver and 13 participants mentioned a barrier (see Tab. 11). However, only eight participants deemed aRP to be faster due to direct trips or improved public transport connections. Some public transport users did not see any improvements in travel time as existing public transport was good enough. Some participants regarded aRP as slower, but deemed that either acceptable or would only use it for journeys where travel time is a less important factor, e.g., leisure trips. A few participants said that compared to public transport waiting time would be reduced. A frequently mentioned barrier was a longer travel time due to the pick-up of other passengers and respective detours ("*You have to expect longer waiting times [...], the car has to pick up other 6, 7 or 8 people and travel time will be longer*", P09). A few participants said the AV would be driving (too) slowly and others said there might be occasional delays due to technical issues.

Tab. 11 *Results for category:* Time

Valence	Number of mentions	Arguments
Drivers	15x	Shorter travel time due to direct journey
		Slightly longer travel time is ok
		Shorter waiting time
		Suitable for journeys where time factor is less important (e.g., leisure time)
		Time savings because current public transport is not ideal
		Other: Possibility of indicating a maximum travel time; aRP is similar fast to public transport
Neutral	-	
Barriers	13x	Longer journey due to detours
		Pickup- / dropoff-time is hard to estimate
		No time savings compared with public transport
		aRP vehicle drives slowly
		Occasional delays due to technical problems
		Other: Fixed departure times are stressful

Flexibility was very frequently mentioned as a driver and moderately frequently mentioned as a barrier: 15 participants mentioned a driver and ten participants mentioned a barrier (see Tab. 12). Most appreciated was the possibility of door-to-door transport. Also seen as enhancing flexibility were well-defined, well-accessible bus stops, shorter waiting times and not having a fixed timetable. Concerning booking an aRP, some participants appreciate spontaneous use, yet some did not deem this to be possible and again other participants preferred booking in advance. Whereas a few participants considered an aRP to choose a more direct journey with less stops ("*You can better connect destinations and the passengers*", P12), more people imagined that an aRP would be doing detours because it needs to drop off passengers at their individual destinations ("*Several people need to be [in an aRP]. And they all have their individual journeys and yet you have to bring the journeys down to a common denominator.*", P04). Some car users also generally consider to be more flexible with their private car than with an aRP.

Tab. 12 *Results for category:* Flexibility

Valence	Number of mentions	Arguments
Drivers	15x	Door-to-door transport
		Well-defined, easy to reach stops
		Spontaneous use
		Booking in advance
		Fewer stops / detours
		Short walk to vehicle or final destination is acceptable
		More flexibility without fixed timetable
		Other: Similarly flexible to private car; Possibility to drink and not drive themselves; Regular schedule; Combination with public transport; Stop in no-parking zone; Exclusive use for a group
Neutral	-	
Barriers	10x	Detours due to pick-up / drop-off of passengers
		More flexibility with private car
		No short-term booking and changing of journey
		Long distance to final destination
		Other: No sole use of vehicle possible

Trip purpose was frequently mentioned as a driver: 12 participants mentioned a driver and only one participant mentioned a barrier (see Tab. 13). aRP would most frequently be used for leisure trips ("*I would like [using it] for going on a hike or doing a day trip with a few [friends]*", P17). Some participants would also use it for work. Other situations that were mentioned were places that are hard to reach by conventional public transport. Very few would use aRP for grocery shopping. One person said that they would not spontaneously use aRP.

Tab. 13 *Results for category:* Trip purpose

Valence	Number of mentions	Arguments
. Drivers	12x	Leisure trips
		Work
		Places that are hard to reach by public transport
		Grocery shopping
		Other: Trips within town
Neutral	-	
Barriers	1x	Other: No spontaneous use

Reliability was both frequently considered a driver and a barrier: nine participants mentioned a driver, ten participants mentioned a barrier (see Tab. 14). However, when looking at the factors in detail, reliability of aRP is generally deemed low. Some participants would still use it for journeys where punctuality is less important, e.g., during leisure time ("*It would be [for] journeys [...] with more flexible times like dinner with friends*", P05). Car users as well as public transport user perceive RP as unreliable and thus not useful when one has to be on time, e.g., for an appointment, or catch a connecting service. A minority of the participants - three public transport users and two car users - deem RP to be reliable. A few

participants indicated that they need transparent information about scheduled pick-up and drop-off ("*Maybe at the beginning I do not trust [the information in] the app, [...] this will not be an issue if the information is transparent*", P13). One participant sees a private car as more reliable ("*Something can happen all the time, in a car you have less of a problem with that, as you can drive around [the accident]*", P16).

Tab. 14 *Results for category:* Reliability

Valence	Number of mentions	Arguments
Drivers	9x	Reliable
		Suitable for journeys without fixed appointments
		Information about scheduled pick-up / drop-off
Neutral	-	
Barriers	10x	Unreliable
		Trial needed to test reliability
		Other: Reliability depends on availability of vehicles; Car is more reliable than aRP

The *comfort of the vehicle* was moderately frequently mentioned as a driver and as a barrier: ten participants mentioned a driver, two mentioned a neutral factor and eight mentioned a barrier (see Tab. 15). They imagined a vehicle with enough space for luggage, comfortable seating and easy access for elderly or disabled people. Demands cover a wide range of aspects: the size and equipment of the vehicle, cleanliness, safety aspects, information or particular features in the vehicle. Some participants mentioned as a barrier the small passenger area and worried about bad air quality. Additionally, some people were worried about vandalism in the vehicle.

Tab. 15 *Results for category:* Comfort of the vehicle

Valence	Number of mentions	Arguments
Drivers	10x	Sufficient space for luggage
		Comfortable seating
		Easy access for elderly or disabled people
		Sufficient large vehicles for groups
		Safety requirements (e.g., seatbelts)
		Digital information board
		Cleanliness
		Charging possibility for mobile phone
		Other: Comfort depends on length of journey; Snack machine; Possibility to transport pets; Low windows for enjoying the view; Similar to comfort of private cars
Neutral	2x	Other: mix of seating and standing area; Identification of vehicle with number plate
Barriers	8x	Small passenger area
		Bad air quality
		Danger of vandalism
		Other: Doubts about vehicle performance; Size too large; Standing area

Privacy was infrequently mentioned as a driver and a barrier: two participants mentioned a driver and two mentioned a barrier (see Tab. 16). Some participants said they wished not to share personal data or were concerned about insufficient privacy. However, some were also confident, that their privacy was sufficiently protected.

Tab. 16 *Results for category:* Privacy

Valence	Number of mentions	Arguments
Drivers	2x	Good privacy
Neutral	-	
Barriers	2x	Other: General uneasiness about privacy; No disclosure of personal data desired

The issue of *parking spaces* was infrequently mentioned as a driver: three participants mentioned a driver and one person a barrier (see Tab. 17). To not have to search for a free parking space and to pay for it was seen as an advantage of using aRP. As a barrier was mentioned that the aRP might have problems finding a parking space as it is larger than a personal car.

Tab. 17 *Results for category:* Parking spaces

Valence	Number of mentions	Arguments
Drivers	4	No search and cost for parking space
Neutral	-	
Barriers	1x	Other: Difficulty for aRP of finding a large enough parking space

3.3.2 Effort expectancy

Effort expectancy consisted of six factors: perceived control, information on app, payment, planning, liability, and interaction with vehicle. The results are described along the most frequently mentioned factors in descending order.

Planning was very frequently mentioned as a driver: 15 participants mentioned a driver and two participants a barrier (see Tab. 18). Participants imagined to plan their journey easily online or via app ("*I think it needs to be something that is very easily accessible and available [...] It needs to be simple, really simple.*" (P11). While some participants explicitly want to plan ahead, others want to plan short-term. Some participants requested certain features like real time data for vehicles or the possibility to plan for a group with different pick-up places. Barriers to planning was the insecurity about pick-up / drop-off time and a car user said using an aRP needs more planning than using a private car.

Tab. 18 *Results for category:* Planning

Valence	Number of mentions	Arguments
Drivers	15x	Planning online or via app
		Possibility of short-term planning
		Possibility of planning ahead
		Easy planning
		Real-time data for vehicles
		Planning for group with different pick-up places
		Other: Multimodal planning; Booking of extras, e.g., luggage
Neutral	-	
Barriers	2x	Other: Insecurity in planning; Private car requires less planning

Information in the app was frequently considered a driver: 14 participants mentioned a driver (see Tab. 19). Most frequently requested are information for travel planning: the availability of vehicles, pick-up and drop-off time and travel time as well as information about the route of the aRP ("*I can plan that I would like to have [an aRP] and then it shows me that one is 10 km away and picks up two others and I know in 15 minutes it will be at my place. [...] and I get an estimated travel time to have a rough idea of how long it is going to take.*" (P09). Some participants also wished for information about other passengers, e.g., the amount of other people in the vehicle. Less often mentioned are information about the vehicle itself, e.g., about the size and interior.

Tab. 19 *Results for category:* Information in the app

Valence	Number of mentions	Arguments
Drivers	14x	Information about availability vehicles, pick-up- and drop-off time, travel time, route
		Information about other passengers
		Information about vehicle, e.g., interior
		Other: Environmental information; Connections to public transport
Neutral	-	
Barriers	-	

Payment was mentioned eleven times as a neutral factor (see Tab. 20). It covers participants' demands concerning the payment process. Most participants want the option of having a subscription.

Tab. 20 *Results for category:* Payment

Valence	Number of mentions	Arguments
Drivers	-	
Neutral	11x	Subscription-based (e.g., monthly, yearly) Payment via credit card or app No subscription needed, e.g., single tickets Other: Billing; Single tickets without subscription; No subscription needed
Barriers	-	

Interaction with vehicle was mentioned by six participants as a neutral factor. They generally imagined a smooth and digitised communication with the vehicle (see Tab. 21). They imagined both a mixture of technology as is common today in public transport, e.g., via app or pressing a button, and more automatised forms of interaction ("*It notices when [...] everyone is inside, maybe like at the post office, it notices when you've given up a parcel [due to the weight]. [...] then the journey starts*.", P06).

Tab. 21 *Results for category:* Interaction with vehicle

Valence	Number of mentions	Arguments
Drivers	-	
Neutral	6x	Automatic recognition through vehicle Direct communication with vehicle Communication with vehicle via app Other: Being greeted by vehicle
Barriers	-	

Liability is a new factor that emerged from the results of the interviews. It was infrequently mentioned as a barrier: Three participants mentioned a barrier and one person mentioned a driver (see Tab. 22). The issue of liability was only addressed by car users. They expressed feelings of uncertainty of who is in charge in case of a breakdown and having to wait by the roadside in such case.

Tab. 22 *Results for category:* Liability

Valence	Number of mentions	Arguments
Drivers	1x	Insurance included
Neutral	-	
Barriers	3x	Uncertainty about liability in case of an accident / breakdown Waiting by the roadside in case of an accident Other: No intervention themselves in case of a breakdown

Perceived control was infrequently mentioned as a barrier and only mentioned by two participants (see Tab. 23). They mentioned feeling unwell or afraid of handing over control to

an autonomous vehicle: "*Entirely autonomous [...] I find this somehow strange. It's strange when you have to give up control completely.*", P04).

Tab. 23 *Results for category:* Perceived control

Valence	Number of mentions	Arguments
Drivers	-	
Neutral	-	x
Barriers	2x	Difficulty to hand over control
		x

3.3.3 Social influence

For social influence there is only one relevant factor: Social norms. *Social norms* were both moderately frequently considered a driver and a barrier for using aRP: seven participants mentioned a driver and eight participants mentioned a barrier (see Tab. 24). Whereas some considered their social circle as being open-minded and expected positive reactions, others stated that their social environment is suspicious about new technologies and they would expect negative reactions ("*My family would be speechless and wonder how that works. It would be science fiction for them. They would be overwhelmed*", P10). Some participants reported that colleagues at work might react negatively as an aRP shows lower social status or that their social circle mostly consists of car user who would be skeptical of aRP.

Tab. 24 *Results for category:* Social norms

Valence	Number of mentions	Arguments
Drivers	7x	Positive reactions
		Other: (Positive) surprise
Neutral	2x	No reaction
Barriers	8x Mistrust about new technologies	
		Negative reaction from work colleagues
		Mistrust from car users

3.3.4 Facilitating conditions

Skills is a new factor that emerged from the results of the interviews. It was an infrequently mentioned barrier for using aRP: three participants mentioned the need for specific skills that can work as a barrier (see Tab. 25). These include technological skills and also addresses issues about accessibility: "*The other thing is the accessibility for people who don't have a smartphone or have trouble with these technologies. [...] I see the danger that people [...] who don't have access to mobile phones for financial reasons [are excluded].*" (P05)

Tab. 25 *Results for category:* Skills

Valence	Number of mentions	Arguments
Drivers	-	
Neutral	-	
Barriers	3x	Technical competencies Other: minimum age; language

3.3.5 Hedonic motivation

Hedonic motivation is a moderately frequently mentioned driver for using aRP: nine participants mentioned a driver and two participants mentioned a barrier (see Tab. 26). Often curiosity about trying new technologies is reported. aRP was also seen as an adventure and fun. Hedonic reasons against aRP were the feeling of unfamiliarity, especially at the beginning, and the fun of driving themselves: "*What keeps me driving is that I enjoy driving myself. I'm trying to figure out what's fun enough for me to stop driving. Maybe if it had a racing mode?*" (P15).

Tab. 26 *Results for category:* Hedonic motivation

Valence	Number of mentions	Arguments
Drivers	9x	Curiosity about new technology Adventure Fun Other: Relaxing, Entertainment during journey
Neutral	-	
Barriers	2x	Other: Feelings of unfamiliarity, fun of driving themselves

3.3.6 Price value

For the construct price value there is only one relevant factor: Costs. *Cost* is a frequently mentioned driver for using aRP: twelve saw it as a driver, four mentioned a neutral factor and five mentioned a barrier (see Table 27). Costs were often seen in the range of costs for public transport. It was also seen as generally cheap, cheaper than a car or at least cheaper than a taxi. Some participants see flexible fares as an option. High costs, however, were seen as a deterrent to using aRP. Which price exactly is considered too expensive, is subjective and is connected to perceptions of fairness as the following comment shows: "*[Pricing] needs to make sense. If I see, the company only wants to make money instead of [a pricing] that makes sense.*" (P08). Often the comparison to public transport pricing is made: "*It shouldn't be more expensive than an SBB [swiss railway company] ticket. Otherwise I could just go by train.*" (P10). However, a few participants also said they accepted prices slightly above public transport pricing.

Tab. 27 *Results for category:* Cost

Valence	Number of mentions	Arguments
Drivers	12x Similar in price to public transport	
		Cheap (general)
		Cheaper than private car
		Cheaper than taxi
		Other: Equal pricing for everyone; No extra costs for luggage
Neutral	4x	Flexible pricing
		Slightly more expensive than public transport is ok
Barriers	5x	High costs as a deterrent for using aRP
		Other: More expensive than public transport is not ok

3.3.7 Social aspects

Social aspects consisted of three factors: security, comfort in social situation and socializing. The results are described along the most frequently mentioned factors in descending order.

Socializing was a very frequently mentioned driver, but also a frequent barrier: 13 participants mentioned a driver, nine mentioned a barrier and four mentioned neutral factors (see Tab. 28). Equally often did participants say that they would like to socialize than they would not like to. Some liked this opportunity to get to know other people. An aRP was also seen as better for socializing because it is a smaller vehicle. On the other hand, some participants said that this may lead to awkward situations: "*It's less anonymous than it is on the train. [...] sooner or later you will [start talking] with the people. Ideally, they are pleasant. But you can't choose.*" (P18). Sometimes it was mentioned that the need for socializing depends on the mood, context and time of day. Thus, giving and reading the signs whether passengers are open to socializing were seen as important: "*[aRP] creates new social spaces [...] It takes a bit of intuition. If someone is sitting there in the morning grimly with their headphones on, you don't try to force a conversation.*" (P13).

Tab. 28 *Results for category:* Socializing

Valence	Number of mentions	Arguments
Drivers	13x	Willingness to socialize
		Possibility to meet new people
		Experience with aRP as conversation topic
		Smaller vehicle is better suited for having conversations
		(Non-verbal) communication about willingness to socialize
Neutral	3x	Willingness to socialize depends on the time of day
		Socializing is similar to public transport: some socialize, some don't
		Probability to meet new people is small
Barriers	9x	No need for socializing
		Awkward social situation
		Other: Awkward when not able to greet anyone while boarding

Comfort regarding social situation was a frequently mentioned driver for using aRP: eleven participants saw it as a driver, three saw it as a barrier and one person mentioned a neutral factor (see Tab. 29). Some public transport users as well as car users considered the presence of other passengers as not being a problem. When comparing aRP to public transport, it was deemed similar regarding the social situation ("*In public transport I also sit in a compartment with people I don't know. It makes no difference.*", P12). Some participants mentioned that the seating and seat arrangement influences feelings of privacy and comfort. However, others said that they would feel uncomfortable when being in a small shared space with unknown passengers.

Tab. 29 *Results for category:* Comfort regarding social situation

Valence	Number of mentions	Arguments
Drivers	11x	Presence of other passengers is not a problem
		Familiar because similar to public transport
		Design of interior influences comfort
		Feelings of familiarity when regularly meeting same passengers
Neutral	1x	Different social space
Barriers	3x	Sharing a small social space is uncomfortable
		Awkward when travelling all alone

Security was infrequently mentioned as a barrier as well as a driver: three participants saw it as a driver and two as a barrier (see Tab. 30). However, gender was a relevant aspect as only female participants mentioned the topic of security. The absence of a driver or security personnel is an issue for some, but does not necessarily deter them from using aRP ("*There is the security aspect, especially for women, [...], there should be a panic button or that you can see the other users in the app and you could report if something happened [...] But I would still use it, even at night*", P06). For one participant security concerns depend on the time of day and can be mitigated through the use of surveillance camera. Someone suggested having the possibility of female only trips.

Tab. 30 *Results for category:* Security

Valence	Number of mentions	Arguments
Drivers	3x	Not concerned about harassment Other: No harassment through driver; Possibility of female only trips
Neutral	-	
Barriers	2x	Absence of driver / security personnel Other: No camera surveillance; Feeling insecure at night

3.3.8 Discussion of findings

Concerning factors of performance expectancy, participants had mixed feelings about the safety of aRP and also mentioned initial concerns. Better eco-friendliness was mostly attributed to better use of the capacity of the vehicle and to alternative propulsion technologies, e.g., electric vehicles. Improvements in availability were seen because aRP would complement existing public transport services. Time was a controversial issue and many participants imagined journeys to be longer due to detours for picking up other passengers. Better flexibility was seen in the possibility of door-to-door transport, however, they were also concerned that the flexible routing decreases their own flexibility. Participants mentioned mostly leisure trips as trip purpose for using aRP. This is also due to the low perception of reliability. Comfort of the vehicle comprises notions about luggage space, comfortable seats and a disabled-friendly vehicle. Additionally, concerns about privacy are related to insufficient data protection, and not having to worry about parking was seen as an advantage of an aRP compared to a private car.

When looking at the factors of effort expectancy, participants imagined their planning to be easily done online or via app. To do so, participants wanted comprehensive information in the app to enable smooth planning. Payment should be low effort with the option of having a subscription. Also the interaction with the vehicle itself was considered smooth and digitised. For some car users, questions about liability in case of an accident or breakdown emerged. Rarely, the loss of perceived control due to autonomous driving caused feelings of uneasiness.

Because social influence depends on the respective social circle, the reactions participants expected from their friends and family ranged from very positive to feelings of distrust.

For the facilitating conditions, issues were raised around skills that are needed for using aRP. Especially technological skills were considered necessary.

Hedonic motivation is mostly reported around curiosity for aRP as a new technology. The fun of driving themselves, however, can deter car driver from using aRP.

The cost of aRP was perceived as low and high prices were seen a deterrent for using aRP. The pricing was often compared with conventional public transport.

When it comes to social aspects, the willingness to socialize differed between participants as well as between time of day, context and mood. Thus, giving and reading the signs whether passengers are open to socializing was seen as important. For public transport users and car users, comfort regarding social situation was not an issue and comparisons with conventional public transport were made. The seat arrangements also has an influence on feeling comfortable. Concerns about security were not a big issue. However, gender is relevant here insofar only female participants mentioned this topic, even when they stated it is not a concern of theirs.

3.4 Conclusion

In sum, results of the qualitative interviews confirm the relevant psychological factors determining the acceptance of aRP found in previous research.

As described in the existing literature the qualitative interviews reveal a large number of relevant factors with regards to performance expectancy (perceived usefulness) that determine the acceptance of aRP. With respect to *performance expectancy* most of the identified psychological factors appear to be of great relevance for the adoption of aRP, since they have been mentioned and discussed by a majority of the interviewees. Hence, to understand the adoption of aRP the following performance factors need to be considered:

- Safety: Safety with regards to technology
- Time: Waiting time and travel time
- Environmental considerations: Impact on the environment
- Reliability: Predictability
- Flexibility: Changing routes and stops
- Availability: Access regarding time and space
- Comfort regarding the vehicle

It is important to note, that none of these factors are distinctly perceived as a barrier or driver. Most noteworthy is the controversial perceptions of safety: aRP is perceived as an unsafe technology that is associated with risks, as much as it is perceived as a safer transportation mode as compared to conventional cars driven by humans. However, all of these factors have been associated with motivating arguments and demotivating arguments. For some factors (time, flexibility, availability, comfort and environmental considerations), the classification as barrier or driver depends on whether aRP is assessed relative to PrT or PT. E.g., PrT is perceived more available than aRP (hence availability is perceived as a barrier); but aRP is more available than PT (hence availability is perceived as a driver). For the factors time, flexibility, availability and comfort, this comparison often leads to a favourable perception of aRP in comparison with PT and an unfavorable perception of aRP in comparison with PrT. Another factor that was found to be of relevance is the factor of reliability. Our research underlines the importance of reliability particularly in this Swiss context. Moreover, it is important to note that environmental considerations have been found to drive the usage of aRP.

With regard to *effort expectancy*, the factors and the derived arguments are discussed much less controversial. Factors of ...

- Planning
- Information on the App

are clearly perceived as drivers. These are also the most frequently mentioned factors. Despite the large number of derived factors, the concerns with regard to the perceived ease of use appear to be smaller in comparison with the perceived benefits.

Social influence also perceived as drivers as much as barriers and led to some consideration by approximately half of the participants. Whereas facilitating conditions, defined as the perception of necessary competencies, led only to very few arguments. A small controversy arises with regard to the hedonic motivation and the question whether driving in PrT or using aRP is more fun. Some perceive driving (themselves) as a hedonic experience while others expect using aRP likewise to be an enjoyable experience, which is mostly attributed to its novelty.

Concerning perceived costs, we observe the same mechanisms as described for some of the performance factors: aRP is perceived as more expensive than PT, and as cheaper compared to PrT. Overall, participants perceived ...

- Costs of aRP

to be low and hence as a motivating factor.

Finally, *social aspects* have been discussed with regard to security as much with regard to socializing. Surprisingly, security has not been mentioned frequently. What is less surprising, is the fact that security is only of concern by female respondents. With regard to a fair and accessible transportation system - despite the small resonance in this study - it is important to consider the public space within aRP from the perspective of discrimination.

4 Stated preference discrete choice survey

4.1 Starting position

4.1.1 Objective

The objective of the stated preference discrete choice survey is to derive behavioural parameters which explain the attractiveness of RH/RP and aRH/aRP trips in relation to existing modes of transport and can be used in a MATSim transport demand simulation model.

4.1.2 Challenges

We identified the following nine challenges concerning the design of a stated preference survey that is suits the stated objectives.

1. Respondents have limited knowledge on RH and RP and even less on aRH and aRP

   Therefore, we need to provide clear and understandable information about these modes of transport.

2. People have limited or no experience how qualitative factors relating to (a)RH and (a)RP will influence their behaviour

   For the same reason as for the first challenge, namely because in most cases the respondents have no experience RH/RP or these modes are even unknown to them, and the modes aRH/aRP even do not exist yet, the resondents have problems to estimate how features of RH/RP and aRH/aRP would influence their preferences towards these services. This is particularly true for qualitative features as features related to safety and security.

3. High cognitive load to the respondents when deciding on the options RH/RP or aRH/aRP

   The third challenge we are facing is that deciding on whether or not choosing a RH/RP or on aRH/aRP might impose a high cognitive load to the respondents. The reason for that is because in most cases the respondents have no experience RH/RP or these modes are even unknown to them, and the modes aRH/aRP even do not exist yet. We thus took the following measures to reduce the mental load of the SC experiment: First, we will use a pivot design based on current trips to create realistic choice situations. Second, we will limit – and in some cases even omit – the adaptation of variables related to the reported trips. Third, we will start the SC experiment with simple choice sets and will increase their complexity with the subsequent choice sets since we believe that the respondents will be more considerate in responding on complex choice sets if they first could get some experience by answering simple ones.

4. Complexity of leisure trips

   In Switzerland, leisure trips play a big role, since they make up a high share on total person kilometers travelled. Such trips are mostly over a longer distance. The destination is often in a less densely populated region that is not connected to the main PT services which leads to more transfers. Therefore, RP/Rh and aRH/aRP will only play a feeder role for public transportation in dense areas which are the origin of such journeys in most cases. The fact that for many leisure trips luggage and equipment is carried along adds even more complexity. The challenge is to present choice situations that are simplified but still realistic and presented in a way that avoid biases caused by the respondent.

5. Daily travel choice is strongly influence by long term choices of the mobility tools

   The fifth challenge is that the daily travel choice are constrained, enabled by the mobility tools owned. For instance, a car owner does not easily sell his car, if this car can be used another couple of years. And such a person will then be very hesitant to

opt for a mode that is a substitute to using the car, as public transportation or RH/RP and aRH/aRP services. In contrast, if the same person would not own a car, as for instance because he would not buy a new car when scraping his current old car as a result of the introduction of aRH/aRP on a large scale, he would be be much more likely to use PT or RH/RP and aRH/aRP services. Since we are interested in forecasting the consumers demand in the long run, the latter case of the example of the car owner mentioned above is relevant to us. Because, this case is much rarer than the first case, and of that, we ask the respondent on fictive daily choice situations where they are reluctant to consider, if they would in this case at the same time sell their car, it is very challenging to create a model that maps the mode choice decision in a long term situation.

6. Limited number of respondents and survey duration due to the limited survey budget

   The sixth challenge is the limited survey budget which implies a limited number of respondents and a limited amount of incentives that can be offered. The latter implies that the survey duration may not exceed a certain limit. We thus must restrict the number of choice sets. Consequently, we focus on choices relative to today's chosen modes which means that we omit choice sets that contain choices between modes that are all different to the reported mode.

7. Low market share of RH/RP and aRH/aRP

   The challenge of the low market share of RH/RP and aRH/aRP are: If we present RH/RP and aRH/aRP with realistic prices the number of observations when respondents choose this option is very low; this is particularly true since because we have only a very limited number of respondents. Thus, it will be very difficult to calibrate the parameters. If in contrast, we present the RH/RP and aRH/aRP option with attractive and thus low prices, the following two problems arise: First, the respondents might not consider these options as realistic which might lead to biases. Second, we will calibrate the model around a point, which is not in the range of realistic prices. As a consequence, forecasting demand using realistic price scenarios would lead to biases.

8. Attitudes and soft factors level might bias stated choices

   Unobserved factors like attitudes and soft factors that are relevant for the decision between alternatives can bias the results. The challenge is to capture such variables in the survey and find a model specification that enables to include such information.

In the following subchapters 4.2, 4.3, 4.4, 4.5 we show how we address those challenges through the design and implementation of the survey.

4.2 Survey structure

The structure of the survey is illustrated in Fig. 3. The survey is composed of two web-based questionnaires which the respondents fill in two waves.

The first questionnaire, the screening survey, includes screening questions to identify respondents who fulfil the sampling criteria. In addition, information on a regularly conducted trip to work or education as well as a recent trip to a leisure activity are collected. Finally, information on mobility tool ownership of the respondent is collected. Based in this information, a personalised second questionnaire is generated which includes the pivot design discrete choice experiments.

The second questionnaire, the main survey, includes four parts. The first part features choice experiments with two alternatives: the chosen mode of the reported trip and a ridepooling option which is operated with conventional (non-autonomous) minibus. The idea is to get respondents accustomed to the concept of ridepooling without bothering them with information about autonomous vehicles. To ensure that all respondents have a meaning-

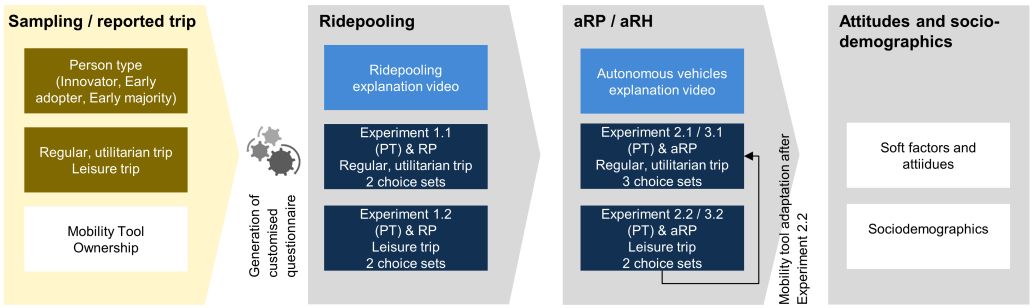


Fig. 3 *Survey structure*

ful understanding of ridepooling, each respondent is required to watch a short explanation video before the choice experiments (see Section 4.4.2 for more information and the links to the videos). The respondents indicate their mode preference in choice situations which are based on the reported trips in the first questionnaire. For both a utilitarian (work or education) or frequently repeated (i.e. at least once a week) trip and a leisure trip, they indicate their preferred mode of transport in two choice situations for each trip purpose. These choice situations always include two alternatives. Depending on the availability of pubic transport connections between the origin and the destination, the ridepooling alternative is either defined as a direct trip or intermodal trip in case such an option seems more attractive (see 4.5.4 for more details).

The second part features the choice experiments with autonomous ridehailing and ridepooling options. Again, each respondent watches a short explanation video first. The video describes how autonomous vehicles function in general and which type of new ridehailing and ridepooling services are expected to be offered with different types of autonomous vehicles. The choice situations are again constructed based on the characteristics of the utilitarian and leisure trip reported in the first questionnaire. Different than in the first part, the alternatives now include both ridehailing and ridepooling options in addition to the chosen mode of the reported trip. Again, the ridehailing and ridepooling options are either defined as a direct or intermodal trips depending in the availability and attractiveness of public transport legs for the given origin and destination pair. After these experiments, respondents were asked whether they would own a car or autonomous vehicle in a scenario where autonomous ridehailing and ridepooling services, as well as automated private-use cars, were available. Based on their responses, the mode of the first alternative in subsequent choice experiments was adjusted accordingly.

The type and number of the mode choice experiments of the third part is the same as in the second part. However, the respondents are asked whether or not they would own a car in a world where aRH/aRP services exist, and if so, if they chose an autonomous car. Depending on their choice and prior reference mode and car ownership, their reference mode for the following choice experiments will be changed. After the respondents have responded to the choice experiments, they are asked whether they would buy the an aRP rebate card at a certain price. Note that we randomly assign the type of rabate card presented depending on current travel card ownership and apply various price levels.

The fourth part starts with attitudinal questions. These are captured by use of a likert-scale batteries, i.e. sequences of seven statements on which the respondents can declare their level of agreements on each. The seven statements are regarding the use of autonomous ridepooling minibuses versus the mode they currently use (car of public transportation). These factors cover aspects that were not covered by the attributes in the choice experiments, as for instance the seat comfort and the degree of feeling uncomfortable due to the presence of other passengers. The second battery includes questions on personal attitudes with regards to the propensity to share vehicles and mobility preferences in general. The fourth part ends ends with questions on further sociodemographic details and the house-

hold of the respondent that were not included in the first questionnaire.

4.3 Survey sample

4.3.1 Recruitment

We choose to recruit the respondents via the existing web-based panel of the Swiss market research firm Intervista. We aim for 1'000 survey participants who are at least 18 years old. Compared to recruiting participants using postal addresses as provided by official authorities or commercial companies, recruiting via an existing web-panel has several advantages. First, we can include screening questions such as for identifying our target group of "innovators", "early adopters" and "early majority" whereas the screened out participants are invoiced at a massively reduced tariff. Second, Intervista has a series of socio-demographic variables on the participants which allows to shorten the questionnaire and enables to preselect participants should we observe an over-representation of certain types of respondents, or should we wish an over-representation of certain types of respondents. Third, our calculation showed that the cost of recruiting the participants with the web-based panel is significantly lower as compared to mailing and handling letters as well as sending reminder letters required to achieve the targeted response rate of 20%.

We instructed Intervista to preselect of participants. First, to exclude people from the Italian speaking parts of Switzerland. Second, to exclude people living in communities that are not situated in agglomerations. The reason to exclude people from the Italian speaking parts of Switzerland is because with a popuilation share of about 5% of the sample, it would be to small to reliably describe a potentially different mode choice behaviour. The reason to exclude participants living in communities that are not situated in agglomerations is that in this regions it will be economically not feasible to run ridepooling services, and thus, for those regions we will not simulate ridepooling services.

4.3.2 Sampling

On top of the pre-selection criteria we impose some additional ones. In terms of sampling respondents, as opposed to the qualitative interview conduced in this project, we let only respondents who are early adapters and or innovative persons to participate. In this way, we adopt the conclusion of the literature review that the preferences of these people are likely to be more representative for the preferences of average people in the future when the aRH/aRP services will actually be available. We thus select the respondents who choose at least the third option ("part-part") in at least one of the following two questions: "Compared to the average population in Switzerland, I am among the first who can imagine to buy an electric car" or "Compared to the average population in Switzerland, I am among the first who try out new mobility services, e.g. car sharing, bike sharing, shared e-scooters, or cab rides booked via app".

With respect to trips we also impose a filter, to exclude respondents with very short trips since for these (autonomous) ridehailing and ridepooling options are not attractive due to the waiting time and (initial) cost, as compared to other modes of transport, in particular walking, cycling and car driving. We thus consider only participants with trips of at least 2km to reference. To avoid a too high share of leisure trips with a long distance, in 60% of the cases we added an additional question to ask the respondents, if they have done also a trip with a lenght of 2 .. 10km.

In terms of modes, we only consider participants who conducted their trips by car or public transportation, since we assume that ridepooling and ridehailing services are primarily competing these modes.

Note, that with regards to the number of trips, the types of trips asked for cover about 40% of all trips. However, taking into account trip distance, 70% of the distance travelled by residents in Switzerland is captured.

Technically, the sampling process is conducted as shown in the following Fig. 4.

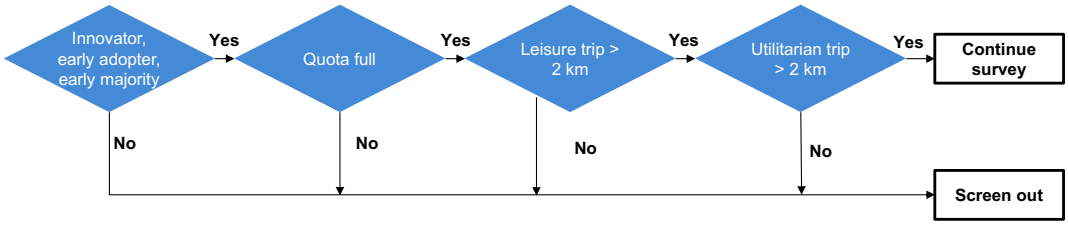


Fig. 4 *Sampling of respondents and trips considered for the stated choice experiments*

4.3.3 Quotas

On top of the sampling as described above, we imposed quota on some sociodemographic attributes. We do so despite of the fact that we do not need a representative sample to calibrate our model. However, we need some sampling to limit the proportion of respondents owning a flat rate travel card (GA) or a regional travel card (Verbundsabo) which is overrepresented in our sample otherwise. Also, we maintain a quota on the age groups and on being employed or in education. We further set a quota on owing a driving licence and owning a car to avoid an over-representation as well. At last, we set a quota for German versus French speaking participants to maintain the possibility to identify their differences that could be shown in other studies in the field of transportation.

4.4 Visual material

4.4.1 Introduction

Ridepooling and autonomous vehicles are two new mobility services, which are relatively unknown to the general public. Conducting a stated preference survey about topics where the level of information varies and many people only have little or no knowledge leads to biased and unreasonable results. Through the combination of moving images and audio, video is a medium that allows to communicate complex information. Compared to text, information conveyed in videos is more approachable and less strenuous to be processed. Therefore, we decided to show the survey participants short videos to introduce the basic concepts of ridepooling and autonomous vehicles. The main objectives of those videos are to ensure a common level of knowledge among all respondents and address the main concerns towards those new transport offers as identified in the literature review and the qualitative interviews.

In accordance with the survey structure, two videos were produced. The first video covers the concept of ridepooling (without autonomous vehicles) and is followed by the corresponding choice sets in the survey. In a second part, the participants are informed about autonomous vehicles. The second video explains the technical aspects of these vehicles and introduces autonomous vehicles (respectively ridepooling with autonomous vehicles) as a potential travel mode.

The content of the videos was compiled based on findings from the literature review (see Section 2) and the findings from the qualitative interviews (see Section 3). The main body of the visual material was collected online through researching video material and footage of already existing ridepooling and AV-ridepooling providers as well as AV manufacturers. Additional video material was created for this research project to address specific aspects for which no suitable existing material was found.

The understanding of the videos was tested with the participants of the qualitative interviews. Their feedback served as validation and was the basis for improvements before the start of the actual stated preference survey. The following Sections 4.4.2 to 4.4.4 provide an overview about the thought and work processes behind the design of the videos and the procedure for the collection of the visual material.

4.4.2 Ridepooling

As the mobility offer of ridepooling is relatively new, the video[14] first puts the service in the context of the entire mobility system and highlights that the service is already in use in certain cities in Germany and Switzerland, indicating that there is a demand for this mobility service. This is followed by an update about the ridepooling offerings in Switzerland to establish a connection to the Switzerland-based survey participants. In both of these first two sequences, the acoustic information is underlined by the visual material, which shows existing ridepooling vehicles driving on streets in the cities mentioned during the video. The corresponding material consists of images and short clips which were collected online from marketing images / videos of ridepooling providers, such as MOIA in Germany and Pikmi in Switzerland (tagesschau, 2019; VBZ Züri-Linie, 2021).

In a next sequence, the concept of ridepooling is explained in more detail. The main objective is to give the viewers a good impression of how ridepooling compares to other transport modes and how a ridepooling trip could take place. As the public transport system bears the closest resemblance with ridepooling (i.e., it is a public service and one is driven instead of having to move oneself), the main distinctions between these two modes are listed in the beginning. This is followed by a description of the entire journey, including the booking process, the particularities for the pick-up, the trip itself, drop-off and payment. The information about the payment options is complemented with prices for the competing modes to give the participants an idea about the incurring costs and set them in relation to each other. The video material for this sequence could mostly be taken from the Swiss ridepooling provider Pikmi, who created an extensive and educational video where they advertise their service (VBZ Züri-Linie, 2021). Missing segments such as the additional pick-up locations and the overview about the costs were completed with illustrations we specifically commissioned for this purpose and images from the internet.

The third main pillar of the introduction video about ridepooling addresses the concerns of the people towards this new mobility offering. These concerns were mainly taken from the literature review (see Section 2). One of these concerns is the driver – whom are they trusting when they use a ridepooling service. It is therefore mentioned in the video that the drivers are trained by trusted public transport companies and do also provide support in the case of issues or if disabled people need help. This section is especially important for women, elderly people and people using a wheelchair. Again, the visual material was taken from Pikmi.

Another concern is availability and reliability, i.e., the duration of the waiting time and the variability in the estimated time of arrival at the destination. For this purpose, an actual booking process is illustrated in the video by showing a smartphone screen with bandwidths for waiting and travel time, complemented with a general benchmark for the waiting time to represent the availability. To give a better understanding of why these variances in waiting and travel times exist, the video does also explain the dynamic re-routing process which takes place to bring all the customers to their destination in the most efficient way. A deeper knowledge of the ridepooling process and the reasons behind the changes in pick-up and drop-off times is expected to increase the understanding and the acceptance towards the less predictable ridepooling schedule. This part of the video is composed out of a combination of specifically commissioned material (app screen) and video material from Pikmi (re-routing) (VBZ Züri-Linie, 2020, 2021).

Further aspects which were identified in the literature review and are also covered in the video include the pick-up and drop-off procedures. Regarding pick-up and drop-off, it is important to mention what the potential pick-up and drop-off locations are (e.g., at the front door, virtual stations and regular public transport stations), and if and in what ways (and why) these locations can change between the time of booking and the arrival at the destination. This information was added in the video at the suitable locations and with similar visual language as in the preceding and subsequent sections.

[14] Available in german `https://vimeo.com/798786264` and french `https://vimeo.com/798784532`.

The last part of the video covers the interaction with other passengers. The smaller size of the ridepooling vehicles compared to a bus or tram leads to a more intimate atmosphere between the passengers. As this perception might cause unease for some people who have never used this service before, it is important to point out that experiences in the past have shown that often passengers and drivers alike appreciate the interaction between each other. This statement is underlined with visual material which has been assembled from online images and video material from the ridepooling providers Pikmi and MOIA (VBZ Züri-Linie, 2020; MOIA, 2021a).

4.4.3 Autonomous vehicles

The notion of autonomous vehicles (AVs) causes distress for a lot of people as they are not comfortable with the idea of giving up control of the vehicle to a computer and trusting an algorithm with their life. For this reason, the first portion of the video[15] focuses on demonstrating that AVs are already part of everyday life in certain cities and that they are capable of driving under unfavorable conditions, e.g., in the rain and / or at night. The corresponding video material was taken from AV-ridepooling providers in the US and China such as GM Cruise, Waymo and AutoX.

The vehicles which are currently used in field trials are based on existing car models and therefore look very similar to the cars we see in daily life. These vehicles are displayed first in the video in order to create a familiar visual environment for the viewer. Afterwards, the video draws attention towards the fact that car manufacturers have started to develop AVs which are explicitly designed for ridepooling and look very futuristic by today's standards (Zoox, 2020). To convey a realistic impression, it is mentioned that the development and construction of AVs is rather expensive – the possession of an own vehicle is not a realistic scenario in the near future. In such a context, AV-taxis and AV-ridepooling will be the only forms of autonomous vehicles that are available for the majority of the population. This fact might have a significant impact on the perception of the choice situation and hence the answers in the stated preference survey.

The video does also show interior footage of an AV driving on the streets to simulate the experience for the viewer. This is important because – while knowing that the car is driving without a driver – it is an entirely different feeling to observe the steering wheel moving without any exterior influence. The corresponding video material was compiled online from the AV-ridepooling provider Waymo who promoted its services (Waymo, 2018).

Next, the video explains the functionality of autonomous vehicles. This is the core part of the video and rather technical. The idea behind this sequence is to provide insights into the setup that makes autonomous driving possible and decompose the abstract image of autonomous vehicles into understandable pieces which make sense and are comprehensible. The viewer is made aware of the numerous sensors that are required for safe driving, and is presented with the most relevant sensors and their respective tasks. The viewer is then guided through the different aspects the algorithm takes into account to locate its own position on the road, predict the behavior of other road users and finally make a decision about its imminent driving behavior.

The previous sequence transitions seamlessly into the section about safety on the road and the legal aspects. The literature review (see Section 2) has shown that many people are wondering about the requirements and safety standards for AVs. Autonomous vehicles have to collect data for several millions of kilometers in order to train the underlying algorithms, be able to make the right decisions in difficult situations and eventually pass the numerous tests and meet the stringent requirements to obtain the permission to operate on the streets. To illustrate this to the viewer, the visual material shows a situation in which the car has to navigate through a narrow road with a lot of other road users, obstacles and potential hazards. The imagery is consistent with the previous sequence and thus spans the arc to the technical aspects discussed before, intended to facilitate the understanding of the complex coherences. The video material for both the previous and the current sequence

[15] Available in german `https://vimeo.com/752105590` and french `https://vimeo.com/791515498`.

was taken from a very detailed explanatory video from Waymo, an AV-ridepooling provider in the US (Waymo, 2018).

After the technical part, the video focuses on some special characteristics of autonomous vehicles to provide the viewer with a better picture of positive and negative aspects of AVs. On the positive side for environment and society, this includes that AVs built for ridepooling offer more space in the seating area which supports a higher occupancy rate and thus the potential to reduce congestion. This statement is accentuated with adequate visual material, with a focus on highlighting the different designs of AVs which have evolved from cars as we know them today to purpose-built ridepooling-AVs (Cruise, 2021).

The last part of the video addresses potentially negative aspects of AVs and concerns derived from the literature review. Standing out in this regard are the security and safety aspects. The former revolves mainly around interactions and uncomfortable situations with other passengers – a concern that gains in importance in the absence of a driver who takes responsibility for the vehicle and has been raised especially by women. However, manufacturers are aware of those concerns and plan to implement several features to mitigate them. The video addresses this topic by showing specifically commissioned illustrations depicting smelly food and riders who harass other passengers. The viewer is then made aware of the precautions taken by the manufacturers. Security features such as cameras, language commands and buttons in the seating area are displayed in form of online images as well as specifically commissioned visualizations.

4.4.4 Design process

Before collecting video material, the video texts were outlined with the desired topics and content that should be included in the video. In this step, time was an important aspect as the videos were supposed to be as concise and short as possible in order not to lose the attention of the viewer. In the process of drafting the video texts, it turned out that a length of roughly 2 minutes seemed to be suitable for the videos at hand. On the one hand, it was still an acceptable duration and on the other hand, it was not possible to shorten the videos without having to remove substantial content.

Based on the video texts, storyboards were drawn. Within these storyboards, the video texts are broken down into smaller sequences and each sequence consists of sample visual material and the corresponding text. The visual material has been collected given the video texts and then been assigned to the respective sequences.

Choosing video material always bears the risk of inducing a bias. Certain depictions might guide the viewers towards a certain attitude regarding a topic (positive or negative), subsequently affecting the outcome of the survey. As a consequence, careful selection of the video material is of utmost importance to avoid influencing the decision-making process and the resulting problems with biased survey results. In the footage selection process, special care was therefore taken to ensure that no obvious marketing videos with unrealistic positive sceneries are used as this could easily induce a bias (in both directions). Furthermore, provocative imagery as well as imagery expressing extreme stances and positions was rejected to avoid influencing the viewer.

As the videos are assembled from already existing video material, copyright was an additional aspect to be considered. Since the usage of the copyright-protected video material in this research project is considered to be all under the legal doctrine of fair use, the material can be used without permission from the copyright owner (Youtube, 2022). By adding a small note in the bottom right corner of every sequence, the video refers to the corresponding copyright owner (for example, «Source: GM Cruise»).

4.5 Design of choice experiments

4.5.1 Introduction

In the following we present the choice set generation for the choice experiments of the main survey.

4.5.2 Design principles

The key aim of our design is to limit cognitive load while still including all relevant attributes of the mode choice decisions with autonomous ridepooling and ridehailing options. We address this aim through the following five design approaches.

First, we follow a pivot design approach with a two-stage survey. In the first stage, respondents report key information for an utilitarian trip (commuting to work or education) and a trip to a leisure activity. For all choice situations, the alternatives are generated based on those reported trips. In this way, the respondents are familiar with the choice situation and thus need less cognitive effort is required as compared to a situation with purely fictive alternatives.

Second, the choice sets only include two or three alternatives. For the existing mode alternative, we include the chosen mode of the reported trip assuming that this mode provides the highest utility to the respondent. To decide whether to include ridesharing as direct mode or as feeder in combination with other public transport offers, we compute the a priori utility for both options based on the reported trip and the same priors as used to optimise the experimental design. In case one option is substantially more attractive, we select the respective option. Otherwise, we randomly chose whether the ridesharing options are specified as direct trip or feeder in combination with public transport (see section 4.5.4).

Third, we restrict the number of considered attributes according to the findings from previous research and the purpose of our study. The attributes have been selected based on results of past studies as documented in section 2.2. Only attributes that demonstrated to be relevant to explain mode choice decisions with ride sharing options are considered. In addition, we reduce the number of attributes to avoid too much detail. For instance we only display the cumulative walking and transfer durations of trips, instead of displaying access and egress duration as well as the transfer duration at each specific transfer specifically.

Fourth, we use different choice designs for different intervalls of trip durations. With increasing trip lengths, we also increase the step levels of the attributes. However, we do not use attribute step level differences that are proportional to the trip duration, since this would result in small absolute attribute step level differences for short trips. Instead, we choose over-proportional attribute step level differences for short trips to ensure sufficiently large utility differences.

Fifth, we chose the attribute levels of the ridesharing alternatives in a way that ensures that those alternatives seem both realistic and allow for interesting trade-offs with the reference alternative. We choose a random design, since we do not know the values of the final parameters values sufficiently accurately, and thus to choose a d-efficient design could lead to substantial biases in estimated parameters.

4.5.3 Overview of choice experiments

The stated choice experiments include two or three alternatives and are organised in three parts as indicated in Tab. 3. All alternatives are defined based on the reported trip. The first alternative is based on the chosen mode of the reported trip (RM). The further alternatives feature ridesharing options. Whether those are defined as direct mode (RH, RP, aRH, aRP) or as feeder in combination with public transport (PT&RH, PT&RP, PT&aRH, PT&aRP) depends on the attractiveness of those two options given the origin and destination of the reported trip (see section 4.5.4 for more details).

The two choice experiments of the first part include two choice situations each and refer to the reported utilitarian and leisure trip.

The second part contains two choice experiments, each with three choice sets. The choice sets include three labeled alternatives. The mode of the first alternative is again defined based on the reported trip ("reference alternative"). The mode of the second alternative is always ridehailing, the mode of the third alternative is always ridepooling. Again, those alternatives are defined as direct or feeder mode depending on the attractiveness of those

Tab. 31 *Overview of choice experiments*

	Trip type	Alternatives		Number of choice sets
		Direct	**Feeder**	
Part 1	Utilitarian	RM/RP	RM/PR&RP	2
	Leisure	RM/RP	RM/PT&TP	2
Part 2	Utilitarian	RM/aRH/aRP	RM/PT&aRH/PT&RP	3
	Leisure	RM/aRH/aRP	RM/PT&aRH/PT&RP	3
		Mobility tool adaptation		
Part 3	Utilitarian	RM/aRH/aRP	RM/PT&aRH/PT&RP	3
	Leisure	RM/aRH/aRP	RM/PT&aRH/PT&RP	3

options given the origin and destination of the reported trip.

After the second part, the respondents are asked to indicate whether they would reconsider mobility tool ownership given that aRH and aRP are established as reliable and save new mode alternatives. Besides adapting car ownership and public transport travel cards, respondents can also indicate whether they would acquire monthly travel cards which offer different discounts for aRH/aRP services (25% discount, half fare, flat rate).

The third part includes the same type and number of choice sets as part two. However, the considered alternatives and cost attribute levels are chosen conditional to the new - potentially different - mobility tool ownership situation.

Across all three parts, each respondent will be given 14 choice sets.

4.5.4 Selection of alternatives

In order to limit the complexity of the choice tasks, we limit the number of alternatives in the choice sets to two or three. We always display the reference mode, which is the mode of transport for the respondents reference trip, namely car or PT. Respondents who were passenger in a car are attributed to the car reference mode.

The mechanism that describes how the alternative modes (a)RH and (a)RP are selected is illustrated in Fig. 5. Whether the (a)RH and (a)RP alternatives are presented as direct modes or as part of an intermodal trip combined with public transport depends on the attractiveness of those two options. For the direct trip option, we derive information on travel time and distance by car from the Google Distance Matrix API. The utility of this option is then computed based on the following assumptions with regards to the various attributes: travel cost of 0.4 CHF/km, 5% longer travel time than by car, no transfer, 2 minutes walking time to a pick up point, one additional passenger in the ridepooling vehicle and a reaction time of six minutes in the city, eight minutes in the suburbs and eleven minutes in rural locations. For the feeder option, we check whether the most attractive public transport connection includes any train legs. If so, we replace any leg between the trip origin and the railway station where the first train leg begins by (a)RP. The same applies for any leg between the railway station where the last train leg ends and the trip's destination. Should the PT trip not include a train leg, we take the longest leg of a PT mean of transport as a train leg and compute the (a)RP legs as in the case where there are train legs. To compute the cost and travel time for the (a)RP legs, the same assumptions as for the intermodal trip option as for the direct trip option are used. For the train legs, we assume travel cost of 0.2 CHF/km, corresponding the average price when owning a half fare ticket (Halbtax). Regarding transfers, we assume the same disutility for transfers between (a)RP and train as for any transfer between public transport services. However, in the case of feeder mode, we do not assume a fixed cost for the (a)RP modes; we only only take into account the fixed cost of using public transportation. To compute the utility of each option, we use the

same priors as used for optimizing the experimental design (see Tab. 63 and Tab. **??** in the Appendix).

Direct trip options are chosen if the probability of choosing a direct (a)RP mode vs. the feeder mode relating to the reported trip is more than 85%. If in contrast, this probability is less than 15%, only options where (a)RP and (a)RH services serve as feeders to reach railway stations are presented. If the probability is within the interval 15 .. 85%, we will randomly choose with a 50% probability either to display choice experiments with (a)RP and (a)RH services as direct modes or as feeder in the presented alternatives.

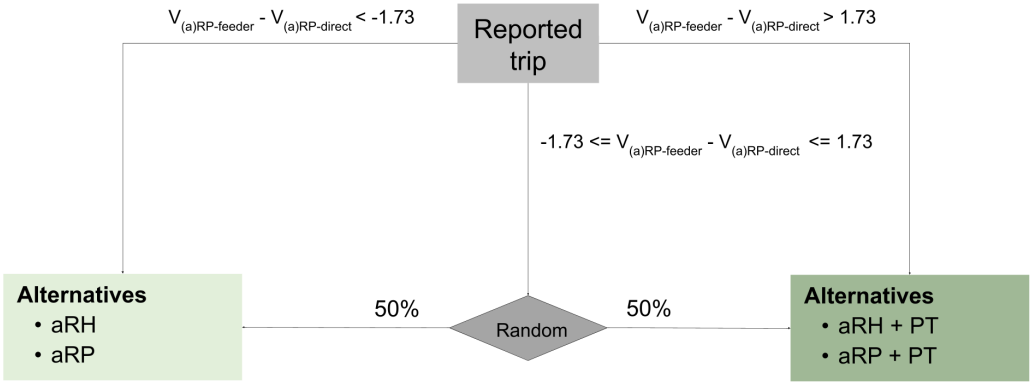


Fig. 5 *Selection of (a)RH/(a)RP mode alternative (direct vs. feeder)*

Note: The number +/-1.73 indicates the level, at which the probability is 0.15 or 0.85 respectively. This results from using a standard MNL model for comparing the two alternatives.

4.5.5 Attributes of the alternatives

To limit the complexity of the choice tasks and to account for the limited screen size of mobile devices, we restricted the description of the alternatives to the attributes as listed in this table. Note that due to the restricted number of respondents, we will be able to estimate only a limited number of parameters and therefore it is pointless to collect data of a vast number of attributes describing the alternatives.

To reduce the cognitive load the questionnaire lists first information on total travel time. However, additional information on the amount of walking time for access and egress and transfer duration is provided as well. The experiment plan foresees that attribute levels for all three travel time attributes are independently permuted ensuring that the variables will not be correlated. In this way, it will also be possible to estimate a parameter for the attribute in-vehicle travel time instead of total travel time. For example, in the case of the PT&(a)RP mode, the attribute level for in vehicle travel time (tiv) can be computed according to Equation 1.

$$tiv_h = ttt_h - twl_h - ttr_h - trp_h \tag{1}$$

The attributes defining travel duration uncertainty tuc is varied throughout the experiment but also offset depending on the mode and the total travel time ttt. The travel duration uncertainty tuc is assumed to be zero for any PT service, walking time twl and transfer time ttr. Thus, tuc is fully attributed to the in-vehicle time of car and (a)RH/(a)RP.

4.5.6 Attribute levels

To reduce the complexity of the choice tasks, we will display only a limited number of discrete values for scalar attributes. We limit the number of discrete values to a maximum of five, but in most cases just to three levels. In the case of level for total travel time ttt, we always use three levels.

Tab. 32 *Attribute levels of total travel time variables* ttt

Alternative	**Levels of trip duration**	**Comment**
Car	(0.85, 1, 1.15) · $\text{TT}_{car,reported}$	Experiment plan defines absolute levels, e.g. for trips between 36-50 min $\rightarrow$ -6 min | 0 | +6 min
PT	(0.9, 1, 1.1) · $\text{TT}_{PT,reported}$	
RP, if car	(1.0, 1.15, 1.3) · $\text{TT}_{car,reported}$	average detour factor of 1.15
RP, if PT	(0.6, 0.7, 0.8) · $\text{TT}_{PT,reported}$	
aRH, if car	(0.85,1, 1.15) · $\text{TT}_{car,reported}$	
aRH, if PT	(0.5, 0.6, 0.7) · $\text{TT}_{PT,reported}$	
aRP, if car	(0.95, 1.1, 1.25) · $\text{TT}_{car,reported}$	detour factor of 1.15 plus policy measure preferred lanes: 0.95
aRP, if PT	(0.6, 0.7, 0.8) · $\text{TT}_{car,reported}$	
PT + aRH, if Car	(0.85, 1.00, 1.15) · $\text{TT}_{car,reported}$	
PT + (a)RP, if Car	(0.9, 1.05, 1.20) · $\text{TT}_{car,reported}$	
PT + RH, if PT	(0.75, 0.90, 1.05) · $\text{TT}_{PT,reported}$	
PT + (a)RP, if PT	(0.80, 0.95, 1.1) · $\text{TT}_{PT,reported}$	

In this case, we use always levels that are in a fixed proportion to the duration of the reference trip in the base design[16], which are either 20min, 40min or, 60min. Thus in the case of the alternative RP, we will use the following levels given the reference trip mode is car:

$$ttt_{RP} = \{1.0, 1.15, 1.3\} \cdot 40min = \{40, 46, 52\}min \tag{2}$$

In the case of the levels of the cost attributes, we use a cost function, that refer to the trip distance. We use the distances $\{10, 40, 70\}km$relating to the durations of the reference trip durations of the base designs $\{20, 40, 60\}km$.

In the case of the cost of the alternative RP, we thus get the following attribute levels of the for the base design relating to a travel duration of 40min:

$$cos_{RP} = 2 + \{0.5, 0.75, 1.0\} \cdot 40km = \{22, 32, 42\}CHF \tag{3}$$

We use the distances $\{10, 40, 70\}$ km relating to the reference trip durations of the base designs $\{20, 40, 60\}$ min. We omitted the fixed cost of 2 CHF for the trip duration of 60 minutes, as including it would make this alternative even less attractive due to its high cost.

For the attribute frequency fre, the number of pax in a (a)RP service pax and the occupancy level in public transportation occ, we choose the levels such, that we can assume that the steps between the levels correspond to equal differences in utility. This enables use to use a linear specification in the utility function. The considered attribute levels are listed in the Appendix in Tab. 63. Note, that the levels of some attributes depend on the levels of other

[16] Regarding the definition of the base design, see paragraph "Base designs" in chapter 4.5.7

Tab. 33 *Attribute levels of cost variables*

Alternative	Levels of trip cost	Comment
Car	(0.25, 0.3, 0.4) · Dcar	Based on TCS Autokosten 2022
PT	2 + (0.15, 0.2, 0.25) · Dcar	Based on average cost for trips with Halbtax
RP	3 + (1.0, 1.25, 1.5) · Dcar	Based on Mobilisk and Moia
aRH	3 + (0.5, 0.6, 0.7) · Dcar	Based on Boesch et al. 2018
aRP	2 + (0. 3, 0.4, 0.5) · Dcar	Based on Boesch et al. 2018
PT + RP	2 + (0.3, 0.4, 0.5) · Dcar	0.8 · PT + 0.2 · RP
PT + aRH	2 + (0.25, 0.3, 0.35) · Dcar	0.8 · PT + 0.2 · RP
PT + aRP	2 + (0.2, 0.25, 0.30) · Dcar	0.8 · PT + 0.2 · RP

attributes. For instance, the attribute levels of the total transfer time ttr depends on the level chosen for the number of transfers ttr : If the case for the mode $h = "PT\&aRP"$ the number of transfers is $ntr_h = 2$, the values for ttr_h must be one of these: $ttr_h = \{4, 6, 9\}$. In contrast, if the number of transfers is $ntr_h = 4$, the values for ttr_h must be one of these: $ttr_h = \{8, 10, 13\}$.

For details regarding dependencies of attribute levels, see paragraph 4.5.8 further below.

4.5.7 Choice set adaption to reference trip

Introduction

In order to adapt the choice experiments to the reported trips we use a set of attributes from pre-produced base designs that are optimized to trip durations of 20 min, 40 min or 60 min. This means, that we have the "base design" produced by the software package Ngene which contains the values that vary between the attributes; the final values that will be displayed are produced by various types of adaptation, which are explained below. The result of those adaptions is called the display design.

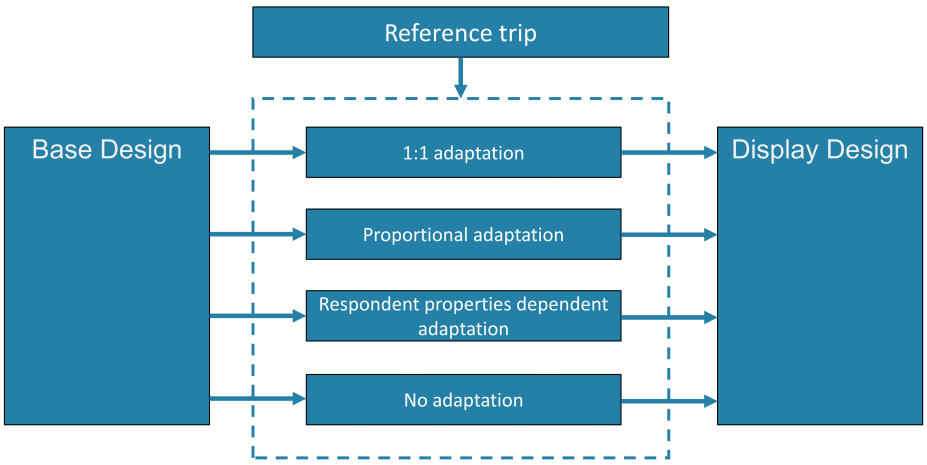


Fig. 6 *Types of adaption for producing the display design*

Example (1): Computing the displayed values of the reaction time tre of the ridepooling mode RP

A simple example is the adaptation of the reaction time tre of the ridepooling mode RP which denotes the time-delay between the order and the arrival of the vehicle at the pickup place. To maintain realistic choice sets, we want to make sure that the respondent will see reaction times tre that are plausible. Thus, we add some offset values – so-called base adaption values – that depend on the type of place where the respondents live, expressed by the so-called agglomeration type. In this case, we find the values $\{-4, -2, 0, 2, 4\}$ in the base design. Since the respondent lives in a community that is classified as core city area ("Kernstadt"), the base correction values amounts to 6 min. We thus will display the values $\{6 + (-4), 6 + (-2), 6 + 0, 6 + 2, 6 + 4\}\, min = \{2, 4, 6, 8, 10\}\, min$.

Since the adaption of the values of the base design to produce the values of the display design is always conducted by adding a base correction value, we can express the adaptation by the following formula:

$$x = \Delta\overline{\overline{x}} + x^* \tag{4}$$

where x stands for any attribute that is adapted, $\Delta\overline{\overline{x}}$ for base adaption value, and x^* for the value in the attribute of the base design.

The base adaption value is computed as follows:

$$\Delta\overline{\overline{x}} = \overline{\overline{x}} - \overline{\overline{x}}^* \tag{5}$$

where $\overline{\overline{x}}$ stands for the base value of the display design, and $\overline{\overline{x}}^*$ for the base value of the base design. The asterisk "$*$" stands for base design. In example (1) above, the base value of tre_{RP} in the base design is zero, $\overline{\overline{tre}}^*_{RP} = 0$, and the base value of tre_{RP} in the display design is $\overline{\overline{tre}}_{RP} = 12$. Thus, the base adaption value for tre_{RP} is $\Delta\overline{\overline{tre}}_{RP} = \overline{\overline{tre}}_{RP} - \overline{\overline{tre}}^*_{RP}$. Note, that with exception of the total travel time and the cost, all base values of the base designs are zero and thus the base adaption value is equal to the base value of the resulting design $\overline{\overline{x}}$. This means, that with exception of the total travel time and the cost, all values in the base design are "Delta-values" that define the deviation from the base value of the display design.

There are various ways of computing the base adaption value $\Delta\overline{\overline{x}}$. In the following, we present the four different types of computing the base adaption value $\Delta\overline{\overline{x}}$ as indicated in Fig. 6.

1:1 adaptation

In this case, the base level is equal to the value of the reference trip (car/PT). This adaptation corresponds to the one presented in Example (1) above.

$$\overline{\overline{x}}_{1to1} = \overline{\overline{x}}^*_{1to1} \tag{6}$$

This type of adaption holds for the attribute of the total travel time of the base alternatives $ttt_{\bar{k}}$, the number of transfers ntr, the frequency of PT services, and the reaction time tre in the case of ridepooling modes.

To illustrate – in contrast to Example (1) – the case with a non-zero base value of an attribute in the base design, we present the adaptation process for the example of the total travel time of the PT mode ttt_{PT}.

Example (2): Computing the displayed values of for total travel time ttt of the PT alternative:

In this example, the Google Distance Matrix API indicated for the origin/destination (OD) of the reference trip declared by the respondent a total travel time of $45\,min$. We thus want the base value of the display design $\overline{\overline{ttt}}_{PT}$ to be also $45\,min$, $\overline{\overline{ttt}}_{PT} = 45\,min$. Let's assume that in the base design the value of the total travel duration is $\overline{\overline{ttt}}^{*}_{PT} = 40\,min$. The base adaptation value $\Delta\overline{\overline{ttt}}^{*}_{PT}$ is thus as follows:

$$\Delta\overline{\overline{ttt}}_{PT} = \overline{\overline{ttt}}_{PT} - \overline{\overline{ttt}}^{*}_{PT} = 45\,min - 40\,min = 5\,min \tag{7}$$

Since the values of ttt_{PT} in the base design are $ttt^{*}_{PT} = \{36, 40, 44\}$, the values of ttt_{PT} that will be displayed to the respondents are $ttt_{PT} = \{41\,min, 45\,min, 49\,min\}$:

$$ttt_{PT} = \Delta\overline{\overline{ttt}}_{PT} + ttt^{*}_{PT} = 5\,min + \{36\,min, 40\,min, 44\,min\} = \{41\,min, 45\,min, 49\,min\} \tag{8}$$

Proportional adaptation

The proportional adaptation works as follows:

$$\Delta\overline{\overline{x}}_{prop} = \overline{\overline{x}}_{prop} - \overline{\overline{x}}^{*}_{prop} \tag{9}$$

where:

$$\overline{\overline{x}}_{prop} = \frac{\overline{\overline{ttt}}_{\bar{k}}}{\overline{\overline{ttt}}^{*}_{\bar{k}}} \cdot \overline{\overline{x}}^{*}_{prop} \tag{10}$$

Therefore:

$$\Delta\overline{\overline{x}}^{*}_{prop} = \left(\frac{\overline{\overline{ttt}}_{\bar{k}}}{\overline{\overline{ttt}}^{*}_{\bar{k}}} - 1 \right) \cdot \overline{\overline{x}}^{*}_{prop} \tag{11}$$

where x_{prob} stands for any attribute which base value is adapted with the proportional adaptation method, $\overline{\overline{ttt}}_{\bar{k}}$ stands for the total travel time of the reference trip, $\overline{\overline{ttt}}^{*}_{\bar{k}}$ for the base level of the total travel in the base design, and $\overline{\overline{x}}^{*}_{prob}$ for the base value of the attribute in the base design that shall be adapted. Note, that for all attributes for which proportional adaptation is applied, the base values of the base designs correspond either to the median level, and in the case where there is an odd number of levels, the nearest value above the median value.[17]

The index $\bar{k}$ denotes the base alternatives car and PT, $\bar{k} = \{ttt_{car}, ttt_{PT}\}$.

The proportional adaptation is applied to all total travel times of the non-base alternatives ttt_k, where k stands for the non-base alternatives $k = \{"PT\&RP", "RH", "RP", "PT\&RP", "PT\&aRH", "PT\&aRP", "PT\&RP\}"$.

To illustrate this adaption we use Example (3). For Example (3), we use the same values for ttt_{PT} as in Example (2). We assume the case of the choice set with the alternatives

[17] The following four examples illustrate this:

(i) $x^{*}_{prob} = \{5, 6, 9\} \Rightarrow \overline{\overline{x}}^{*}_{prob} = 6$

(ii) $x^{*}_{prob} = \{12, 15, 18, 21, 25\} \Rightarrow \overline{\overline{x}}^{*}_{prob} = 18$

(iii) $x^{*}_{prob} = \{12, 15, 19, 23\} \Rightarrow \overline{\overline{x}}^{*}_{prob} = 19$

(iv) $x^{*}_{prob} = \{12, 15\} \Rightarrow \overline{\overline{x}}^{*}_{prob} = 15$

$b = "PT"$, $g = "PT\&aRH"$ and $h = "PT\&aRP"$ and we show how the values of ttt_h are adapted.

Example (3): Computing the displayed values of the total travel time of the alternative PT&aRP

$$\Delta\overline{\overline{ttt}}_{aRP} = \left(\frac{\overline{\overline{ttt}}_{PT}}{\overline{\overline{ttt}}^*_{PT}} - 1\right) \cdot \overline{\overline{ttt}}^*_h = \left(\frac{45\,min}{40\,min} - 1\right) \cdot 42\,min = 5\,min \tag{12}$$

Note, that $45\,min$ is the value of ttt_{PT} the reference trip found by the Google Distance Matrix API, $40\,min$ is the base value of ttt_{PT}, $\overline{\overline{ttt}}^*_{PT} = 45\,min$, the base value in the base design where $ttt^*_{PT} = \{36\,min, 40\,min, 44\,min\}$, and $42\,min$ is the base value of ttt_h the base value in the base design $\overline{\overline{ttt}}_h = 42\,min$ where $ttt^*_h = \{36\,min, 42\,min, 48\,min\}$.

Thus, for ttt_{aRP} the following values to be displayed result:

$$ttt_h = \Delta\overline{\overline{ttt}}_{aRP} + ttt^*_{aRP} = 5\,min + \{36\,min, 42\,min, 48\,min\} = \{41\,min, 47\,min, 53\,min\} \tag{13}$$

Adaptation depending on properties of the respondent

In this case, the base value of the attribute depends on some properties of the respondent.

$$\Delta\overline{\overline{x}}_{respondent} = \overline{\overline{x}}_{respondent} - \overline{\overline{x}}^* \tag{14}$$

where $x_{respondent}$ stands for any attribute which base value is adapted based on properties of the respondent. In our choice design, we selected only the base values of the reaction time ttr of alternatives containing aRH/(a)RP services to depend on properties of the respondent, namely on its type of place of living pli, where $pli = \{"urban", "agglo", "rural\}$ and the offset values are $6\,min$, $8\,min$ and $11\,min$.

This case corresponds to Example (1), where

$$\Delta\overline{\overline{tre}}_{RP} = \overline{\overline{ttt}}_{RP,corecityarea} - \overline{\overline{ttt}}^*_{RP} = 6\,min - 0\,min = 6\,min \tag{15}$$

$$\begin{aligned} tre_{RP} = \Delta\overline{\overline{tre}}_{RP} + tre^*_{RP} = ... \\ ... = 6\,min + \{-4\,min, -2\,min, 0\,min, 2\,min, 4\,min\} + ... \\ ... = \{2\,min, 4\,min, 8\,min, 10\,min, 12\,min\} \end{aligned} \tag{16}$$

No adaption

In this case, no adaption of the values of the base design takes place. Thus the final values that are displayed are equal to the ones in the base designs.

$$x_{\text{No adaption}} = x^*_{\text{No adaption}} \tag{17}$$

where $x_{\text{No adaption}}$ stands for any attribute which the base value is not adapted. No base adaptation takes place for the scalar attributes walking time twl and transfer duration ttr, the ordinal attribute number of pax[18] pax, and the categorical attributes type pick-up point[19] pup and bookable[20] bok.

[18] Note, that the number of pax pax is coded as $pax = \{"mostly\,alone", "1-2", "3-4"\}$

[19] The attribute type pick-up point pup is coded as follows: $pup = \{"at\,home", "virtual\,stop", "PT\,stop"\}$

[20] The attribute type pick-up point pup is coded as follows: $bok = \{"yes", "no"\}$.

In this case an illustrative example is straight forward.

Example (5): No adaption of the total transfer time, example of PT ttr_{PT}

$$ttr_{PT} = ttr^{*}_{PT} = \{0\,min, 2\,min, 3\,min, 4\,min, 5\,min, 7\,min\} \tag{18}$$

This example shows, that the displayed values of total transfer time ttr_{PT} are exactly the same as the ones in the base design $\overline{\overline{ttr}}^{*}_{PT}$.

Overview of attributes and their type of base value adaptions

The following Tab. 34 presents the list of all attributes and their type of base value adaptions:

Tab. 34 *Overview of attributes and their type of base value adaptions*

		Base adapted variating attributes			
	Name	**1:1 adaptation**	**Proportional adaptation**	**Depending on properties of respondent**	**No adaptation**
Cost	cos			x^{*}	
Total travel time	ttt	$x^{(PT,Car)}$	x		
Travel time uncertainty	tuc			x	
Walking time	twl			x	
Number of transfers	ntr	x			
Transfer duration	ttr				x
Frequency	fre			x	
Occupancy	occ				x
Travel time (a)RH/(a)RP	trp		x		
#pax	pax				x
Reaction time	tre			x	
Pick-up point	pup				x
Bookable	bok				x

Note: The first group are attributes that are used to describe all alternatives. the second group are attributes related to PT. the last group indicates attributes that describe alternatives that contain RH/(a)RP modes. "0" stands for variables that are fixed per respondent and thus do not vary between alternatives. X^{*}: The Cost values of PT and PT&(a)RH/PT&(a)RP are adapted if the respondent owns a flat-rate PT card (GA). In the case of the main survey in part 3 the cost of aRP and PT&aRP are adapted according on the ownership of aRP rebate cards

Base designs

Altogether, we use 48 base designs in order to adapt the situation we assume in the choice

sets are sufficiently well adapted to the situation the respondents faced in their reference trips. We thus produce separate choice designs relate to three different total travel times of the base mode car or PT, namely 20min, 40min and 60min.[21] This insures that the attribute levels that will be displayed in the choice experiments do not differ too much from the ones in the base choice designs. This approach enables also to use different absolute level differences for the three different designs.

We will also produce separate choice designs for regular/utilitarian trips and leisure trips. Four different sets of alternatives other than the base alternatives car and PT exist. Thus, a total of eight designs for each combination of trip types and total travel times (20min, 40min, 60min) must be produced. Therefore a total of $3 \cdot 2 \cdot 8 = 48$ base choice designs result.

The selection of the correct base design for computing the values to be displayed to the respondent is thus based on the criteria "Set of alternatives to be displayed", "trip type" and "total travel time of the base modes for the reference trips". In the latter case the following thresholds hold:

- Base design 20 min: $\overline{\overline{ttt}}_{\bar{k}} <= 30$
- Base design 40 min: $30 < \overline{\overline{ttt}}_{\bar{k}} <= 50$
- Base design 60 min: $50 <= \overline{\overline{ttt}}_{\bar{k}}$

Endogeneity As outlined in tables 32, 32, and 34, the pivot design foresees a) different forms of adaptation of variables of the reported trip and b) random assignment of different attribute levels for each choice situation. Hence, we mininize potential issues with regards to endogeneity that can arise if the choice situations are constructed based on a reported trips (pivot design).

The selection whether the hypothetical modes were presented as direct or intermodal trips depends on the a priori utility of those mode (unpivoted). We decided to do so to restrict the choice experiment to three alternatives as this has considerable advantages with regards to screen design and response burden as compared to a design that includes five alternatives.

As proposed by members of the BK in the second meeting and documented in Fig. 5, we randomly assigned whether the alternatives are direct or intermodal in cases where the preference for one or the other option would not be obvious based on the (a priori) utility of aRP alternative.

In summary, we feel we have appropriately addressed the endogeneity issue; however, we do not claim to have fully resolved it in all aspects, which is a common limitation in any choice experiment using a pivot design approach.

4.5.8 Implementation in Ngene

Utility functions

To produce the base designs, we use the software package Ngene. Ngene produces choice designs that fulfil a number of conditions that are important to us:

1. It ensures a good level balance. This means that each level of each attribute will be displayed a similar number of times across the entire choice design.

2. If respondents have to solve repeated choice tasks, it ensures that the alternatives differ substantially between the choice tasks in order to avoid that respondents may choose always the same alternative.

3. It offers to impose restrictions on attribute levels like “if attribute x has a high level, attribute y should not have a high level”. This functionality allows to create alternatives that are realistic. For instance, if a PT connection includes three transfers ntr,

[21] Note, that the alternatives car and PT both have the same base level in the base design, $ttt_a = ttt_{PT}$.

the transit travel time ttr must be at least 10 minutes to ensure that the alternative displayed is realistic.

4. Ngene permits to create a random design , whilst maintaining level balance even when imposing restrictions like the ones mentioned above.

Our model is linear in the parameters and follows the standard MNL specification apart from the fact, that we add some error terms to the deterministic components of the utility functions V. It is also – with the exception of an interaction term to account for the perception of occupancy levels in relation to in vehicle travel time in the case of alternatives containing RH/(a)RP linear in the attributes. Here are the specification of the utility function of the car and the RP alternatives as an example:

$$V_{car} = \beta_{cos} \cdot cos_{car} + \beta_{ttt_{car}} \cdot ttt_{car} + \beta_{twl} \cdot twl_{car} \tag{19}$$

$$\begin{aligned} V_{RP} = \alpha_{RP} + \beta_{cos} \cdot cos_{RP} + \beta_{ttt_{RP}} \cdot ttt_{RP} + \beta_{tuc} \cdot tuc_{RP} + ... \\ ... + \beta_{twl} \cdot twl_{RP} + \beta_{tre_{RP}} \cdot tre_{RP} + \beta_{pup} \cdot pup_{RP} + ... \\ ... + \beta_{pax} \cdot pax_{RP} \cdot ttt_{RP} + \beta_{bok_{RP}} \cdot bok_{RP} \end{aligned} \tag{20}$$

Restrictions

Ngene allows to impose restrictions on the attribute values it actually may use in the choice sets. In our case, we use the following two types of restrictions.

Restrictions to avoid dominance

We assume that respondents strongly focus on the two attributes cost cos and total travel time ttt. As a consequence, we believe that if an alternative dominates the other alternatives in these two attributes, the respondents are likely to ignore the other attributes and chooses the alternative that dominates the others by these two attributes. Since this would lead to biased estimated parameters and lower t-values, we avoid that Ngene produces such alternatives.

As for example in the case of choice experiments containing the alternatives car, aRH and aRP, we do so by imposing the following restrictions:

$$\begin{aligned} ((cos_{car} >= cos_{aRH}) \wedge (ttt_{car} <= ttt_{aRH})) \wedge ... \\ ... \wedge ((cos_{car} >= cos_{aRP}) \wedge (ttt_{car} <= ttt_{aRP})) \wedge ... \\ ... \wedge ((cos_{aRH} >= cos_{aRP}) \wedge (ttt_{aRH} <= ttt_{aRP})) \end{aligned} \tag{21}$$

Note, that this restriction only avoids strongly dominated alternatives in these two attributes.

Restrictions to ensure realistic features of alternatives

We also want to make sure to present realistic attribute values to the respondents. We do this for the attributes total transfer time ttr and the number of transfers ntr, and the attributes walking time twl and pick-up point pup.

In the case of the total transfer time ttr we add each 2min per additional transfer:

$$ttr = 2 * ntr + ttr \tag{22}$$

In the case of total walking time twl for the modes (a)RP and PT&(a)RP, the values we display depend on the type of the pick-up point pup: If $pup =$ "$at\,home$" $\Rightarrow 0\,min$, if $pup =$ "$virtual\,stop$" $\Rightarrow \{2\,min, 4\,min\}$", and if $pup =$ "$PT\,stop$" $\Rightarrow \{4\,min, 6\,min\}$.

In the case of the in-vehicle time tiv for short trips of 20 min duration, it might be that the values resulting from Equation 1 are unrealistically small. Therefore, we impose some restrictions. Since Ngene cannot handle restrictions like the sum of attributes must be smaller that a certain value, we impose the following restrictions that avoid too high values of the sum of ttr and twl in the case of the base design referring to a duration of the reference trip of 20km:

$$TTR_{aRH} >= 5 \Rightarrow TWL_{aRH} < 4 \tag{23}$$

$$TWL_{aRH} >= 4 \Rightarrow TTR_{aRH} < 5 \tag{24}$$

$$TTR_{aRP} >= 5 \Rightarrow TWL_{aRP} < 4 \tag{25}$$

$$TWL_{aRP} >= 4 \Rightarrow TTR_{aRP} < 5 \tag{26}$$

Should the duration of the reference trip be equal or less than 12 minutes, we apply a multiplicative adaption to avoid unrealistic small values for the in vehicle time tiv. This means that we multiply all times attributes of all alternatives t by the ratio of the total travel time ttt of the reference mode $\overline{\overline{ttt}}$ and the base value of the base design $\overline{\overline{ttt^*}}$.

$$t = \left(\frac{\overline{\overline{ttt}}}{\overline{\overline{ttt^*}}} \right) \cdot t \tag{27}$$

where t stands for the time variables ttt, trp, ttr and twl. We maintain a minimum value of one and two minutes for twl and ttr in the cases where these may not be zero. Note, that for the final values, we round these results to integer values and then we compute the in-vehicle time tiv by use of Equation 1.

Priors

Regarding the choice set design for the pretest, due to the risk of large differences between the parameters mapping their behaviour and the parameters found in the literature we chose a random design. However, we check, that there are - if any - only very few alternatives that will be chosen with a very low probability: We checked, if there were less than 10% alternatives in the case choice sets that would be chosen with a probability of 5% or less, assuming a standard MNL model with the prior parameters described above. Checking all random base designs referring to a 40min trip duration showed that in each of them, even not one observations was found that would be chosen with a probability of less than 5%. To compute these probabilities, we need to assume prior parameters. These stem from willingness to pay measures from previous studies;Since we use an MNL model with linear utility functions, the willingness to pay can be computed by the ratio of the corresponding parameters. We thus know all ratios β_x/β_{cos}, where x stands for all attributes we use. For example, the willingness to pay for transfer duration time savings for the mode $a = "car"$, wtp_{ttt_a}, is equal to the ratio of the following parameters:

$$wtp_{ttr_{PT}} = \frac{\beta_{ttr_{PT}}}{\beta_{cos}} \tag{28}$$

Since we know $wtp_{ttr_{PT}}$ from other studies, we can compute the prior value of the parameter ttr_{PT} as follows:

$$\beta_{ttr_{PT}} = wtp_{ttr_{PT}} \cdot \beta_{cos} \tag{29}$$

Tab. 35 *Prior parameter values for regular/utilitarian trip*

Variable	VTTS (CHF/H, CHF)	Utility / Prior	Comment	Source
Cost		-1(1 / CHF)		
TT_{car}	31.45	-0.52 (1 / min)		SN 41 822a
TT_{PT}	16.08	-0.27 (1 / min)		SN 41 822a
TT_{aRH}	13.67	-0.23 (1 / min)	15% less than PT $\rightarrow$ 12.6 CHF / h	Own estimate, literature
$TT_{(a)RP}$	14.47	-0.24 (1 / min)	10$\%$ less than PT $\rightarrow$ 12.6 CHF / h	Own estimate, literature
TT_{Walk}	23.44	-0.39 (1 / min)		SN 41 822a
Transfer (number)	2.45	-2.45	9 Min (PT)	SN 41 822a
Transfer duration	4.31	-0.07 (1 / min)		
Frequency (per step)	4.58	-0.38	5 Min Step @ 10 Min	SN 41 822a
Reaction time	32.16	-0.54 (1 / min)	2.2x TT_{PT}	Hörl et al. 2019, relative to TT_{PT}
Additional passenger RP		0.1*Pax*$TT_{(a)RP}$	Interaction term with TT_{RP}	Own estimate
Pickup point	(0, -2, -1)	(@home, pick-up pount, PT stop)		Own estimate

Note: The prior values relating to the leisure trip can be found in Tab. 64 in the appendix.

The parameter referring to the cost β_{cos} we take from (Hörl *et al.*, 2019b), p. 87, which is $\beta_{cos} = -0.012$. Thus, from the value in Tab. and equation 29 follows:

$$\beta_{ttr_{PT}} = wtp_{ttr_{PT}} \cdot \beta_{cos} = 4.31 \cdot (-0.012) = -0.05172 \tag{30}$$

The parameters referring to the random components of the cost parameters are $\sigma_{ttt} = 0.0315$ for all cost parameters and thus is about half of the values of the expectation values of the random parameters μ_{ttt}. Note, that the latter are equal to the values used for the non-random parameter. For instance, the willingness to pay for travel time savings - also called "value of time" - for the PT mode for regular/utilitarian trips (see Tab.) is $\beta_{ttt_{PT}} = wtp_{ttt_{PT}} \cdot \beta_{cos} = 16.08 \cdot (-0.012) = -0.19296$.

To determine the alternative specific constants $\alpha_{\{\bar{k},k\}}$ due to a lack of comperabel specifications in existing studies, we took some assumption of the willingness to pay for each mode for the case where the respondents would see the average value of the levels for each attribute we will display, ($\bar{x}$). Below there is a table the presents our assumptions.

Tab. 36 *Alternative specific constants and utility levels at average attribute levels (Reference alternative car)*

			Car			
$Altern.\{\bar{k},k\}$	$-\alpha_{\bar{k},k}/\beta_{cos}$	$\alpha_{\bar{k},k}$	$\alpha^*_{\bar{k},k}$	$\bar{V}_{\bar{k},k} - \alpha_{\bar{k},k}$	$\bar{V}^*_{\bar{k},k} - \alpha^*_{\bar{k},k}$	$\bar{V}_{\bar{k},k} \equiv \bar{V}^*_{\bar{k},k}$
Car	0.000	0.000	-0.579	-4.863	-4.284	-4.863
RP	-2.400	-0.288	-0.803	-6.892	-6.377	-7.180
PT & RP	-2.800	- 0.336	-1.760	-5.297	-3.873	-5.633
aRH	-3.000	-0.360	-0.875	-4.962	-4.447	-5.322
aRP	-3.200	-0.384	-0.899	-4.338	-3.823	-4.722
PT & aRH	-3.100	-0.372	-1.796	-4.758	-3.334	-5.130
PT & aRP	3.300	-0.396	-1.820	-4.617	-3.193	5.013

Note: These probability levels refer to a standard MNL model.

The Tab. 36 shows, that we assume an a priori disutility for RP (α_{RP}) corresponding to a monetary value of 2.40 CHF compared to the alternative car, given the attributes level of both alternatives are equal to the average alternative levels the alternative levels that can be displayed. The table also shows, that for the base design that will be produced byNgene, the alternative specific constants differ from these ones. The reason for that is, that the attribute levels used by Ngene differ from the ones that are finally displayed. The values $\overline{V}_{\{\bar{k},k\}}$ and $\overline{V}^*_{\{\bar{k},k\}}$ denote the utility values of the alternatives at the displayed average attribute levels.

$$\overline{V}_{\{\bar{k},k\}} = \alpha + \beta \cdot \overline{x} \tag{31}$$

$$\overline{V}^*_{\{\bar{k},k\}} = \alpha^* + \beta \cdot \overline{x}^* \tag{32}$$

where $\overline{x}$ denote the average attribute levels being displayed to the respondents and $\overline{x}^*$ denote the average attribute levels used in the based design.

Note, that $\overline{V}_{\{\bar{k},k\}}$ and $\overline{V}^*_{\{\bar{k},k\}}$ are identical, because the alternative specific constants used for the base design α^*, are adjusted correspondingly:

$$\alpha^* - \alpha = \beta \cdot \overline{x}^* - \beta \cdot \overline{x} = \beta \cdot (\overline{x}^* - \overline{x}) \tag{33}$$

where β corresponds to the vector of parameters and $\overline{x}$ to a vector containing the average displayed values and $\overline{x}^*$ to a vector containing the average attributes in the base design.

Since the differences between $\overline{x}^*$ and $\overline{x}$ equal to the base adaptation values $\Delta\overline{\overline{x}}$, equation 33 simplifies to:

$$\alpha^* - \alpha = \beta \cdot (\overline{x}^* - \overline{x}) = \beta \cdot \Delta\overline{\overline{x}} \tag{34}$$

Note that it is important to adapt the alternative specific constants as described in equation 34 to ensure that the utilities in the base designs are equal to those displayed alternatives.

The following example illustrates the adaption of the alternative specific constant for the base design.

Example (7): Computing the alternative specific constant for the Base design

As an example, Tab. 37 illustrates the equation (33) for the alternative Car and Tab. 38 for the alternative RP with the utilities corresponding to the equations 19 (car) and 20 (RP) .

In the following alternative RP, the difference in the alternative specific constant does not arise because there is an attribute that is not part of the base model: In this case the difference in the alternative specific constant arises because the levels of attributes reaction time of the RP mode (TRE) are adapted by the base shift value $\Delta\overline{\overline{TRE}} = 8min.$

Tab. 37 *Calculation of the alternative specific constant for the base design (Alternative RP, reference alternative Car, regular/utilitarian trip of 40min duration)*

	Car				
	β	$\bar{x}$	$\bar{x}^*$	$\beta * \bar{x}$	$\beta * \bar{x}^*$
COS	-0.1200	15	15	-1.800	-1.800
TTT	-0.0629	40	40	-2.516	-2.516
TUC	-0.0965	6	6	-0.579	
TWL	0.0160	2	2	0.032	0.032

Note: These probability levels refer to a standard MNL model.

It is important to choose the attribute levels such that each alternative will be - on average - chosen with a probability that exceeds a certain value. The reason for this is, that we would not gain any information from presenting alternatives that would be chosen very rarely and thus the corresponding parameters could not be estimated with an accuracy that permit to forecast mode choice probabilities with a sufficient precision. We choose a minimal probability level of 15%.

The probabilities that follow from Equation 34 conditional on the reference alternative being car are listed in Tab. 39. It turns out that given the chosen attribute levels and prior parameters, the probabilities of all alternatives, apart from the RP alternative exceed the requested 15%. Note, that the case of the choice probability of the RP alternative being below 15% is not relevant, since for that case the choice set including PT and PT&RP will always be displayed as shown in Fig. 5.

Tab. 38 *Adaption of the alternative specific constant for the base design (Alternative RP, reference alternative Car, regular/utilitarian trip of 40min duration)*

	RP				
	β	$\bar{x}$	$\bar{x}^*$	$\beta * \bar{x}$	$\beta * \bar{x}^*$
COS	-0.1200	42	42	-5.040	-5.040
TTT	-0.0216	28	28	-0.605	-0.605
TUC	-0.0965	3	3	-0.289	-0.289
TWL	-0.0253	3	3	-0.076	-0.076
TRE	-0.0643	8	0	-0.515	0.000
PUP	-0.1200	1	1	-0.120	-0.120
PAX	-0.0022	56	56	-0.121	-0.121
BOX	0.2400	0.5	0.5	0.120	0.120

Note: These probability levels refer to a standard MNL model.

Tab. 39 *Choice probabilities at average attribute levels (Reference alternative car, regular/utilitarian trip of 40min duration)*

	Car			
$Altern.\{\bar{k}, k\}$	$P_{\{\bar{k},k\}}(\%)$	$P_{\{\bar{k},k\}}(\%)$	$P_{\{\bar{k},k\}}(\%)$	$P_{\{\bar{k},k\}}(\%)$
Car	91.0	68.3	35.9	38.1
RP	9.0			
PT & RP		31.7		
aRH			22.7	
aRP			41.4	
PT & aRH				29.2
PT & aRP				32.8

Note: These probability levels refer to a standard MNL model. The rows correspond to the various types of choice sets as indicated in Fig. 3.

Note that in the case of the base designs referring to a trip with 60min duration, the alternatives aRP and aRH are chosen with a probability lower than 15%. This is because these services are too expensive for long distances and believe we should not adapt the cost attributes such that they become more attractive to avoid implausible values. Since we expect most reference trips in the range up to 50min duration, we will have a sufficient amount of respondents choosing these alternatives for being able to estimate the corresponding parameters. An overview of the utility levels and choice probabilities for all base designs can be found in the appendix.

4.6 Survey instrument

The survey is split into two questionnaires: The first questionnaire, Questionnaire 1 “Screening survey”, serves for two purposes. First, to identify whether the respondent belongs to the desired group from which we want to collect data, and second, to collect data on trips recently conducted by the respondents which is used to generate personalised choice experiments. The second questionnaire includes stated choice experiments, mobility tool experiments, and questions to collect sociodemographic and attitudinal data. We use the survey software platform Qualtrics to implement the web-based survey. To automatically generate the person-specific choice experiments of the second questionnaire, we have developed scripts in the programming language R. To create the base designs for the SP experiments, we use Ngene.

In the following we present the content of the questionnaires in a summarized form and give some details on the technical implementation where needed.

4.6.1 Questionnaire 1: Screening survey

Questionnaire 1 “Screening survey” consists of three parts. In the first part, we identify whether a person belongs to the target group. We do so as illustrated in Figure 4. Qualtrics is able to filter out participants who to not fulfill the screening questions. Further, Qualtrics is also able to count quota conditions. If the quota is fulfilled, Qualtrics is branching out participants. Qualtrics is also providing the data on the quota counters while the survey is running. This data is provided to intervista, the panel provider, which uses it do modify their criteria with regards to selecting new respondents. By doing so, the proportion of respondents failing the filter criteroa can be reduced and thus, recruitment cost can be saved. The second part is to collect data on trips recently conducted by the respondents. We first ask if the respondents conduct a trip on a regular basis which is longer than 2km and usually conducted by car or public transport. If so, we ask about the exact place of destination using an interactive GoogleMaps interface with text-based location search. We also ask about the number of fellow travelers. Second, we ask if the respondent has conducted a leisure trip of at least 2km within the last two weeks. If so, we further ask about the mode of transport, the number of fellow travelers separated by adults and kids, and the exact place of destination using again an interactive map interface. We further ask on which day of the week and at what time of the day the trip was conducted and what type of leisure time activity was conducted at the destination. The third part is to collect data on the ownership of a driving license and mobility tools, namely public transportation cards, membership cards of car sharing providers, and the availability of the cars. At last the respondents indicate their place of residence through the interactive map interface. At the end of the first questionnaire, we inform the respondents that they will receive an invitation for the second, personalised questionnaire in a few days time.

4.6.2 Generation of personalised choice experiments

The creation of choice experiments with attribute levels adapted to the reference trips is conducted in three steps: First, we compute the trip duration for the reference mode of the base Design based on information collected with the Google Directions API. Second, we select a block of choice experiments from the base design. Third, the adaptation of the attribute levels as described chapter (4.5.7)”.

First, we collect information on the trips through Google’s Directions API based on the origin and destination locations as indicated in the Questionnaire 1. All the remaining computa-

tions are conducted in R.

Second, a question block of the Base Design is selected that matches the distance class of the reported trip. Thereby we make sure that all blocks of SP experiments are sampled with the same likelihood. Depending on the actual trip duration, the display design of each choice set is generated and stored specifically for each respondent.

4.6.3 Questionnaire 2: Main survey

Questionnaire 2 “Main survey” consists of five parts: In the first part, the respondents must first watch the short video that explains how ridepooling works. Afterwards, two stated choice experiments that contain the reference mode (public transportation or car) and ridepooling or ridepooling combined with public transportation are presented.

In the second part, the respondents must again watch first the second short video which explains how autonomous vehicles allow to offer new ridehailing and ridepooling services. Afterwards, the respondents have to indicate their preferences in six stated choice situations. Each choice set contains three alternatives: reference mode (public transportation of car), ridehailing and ridepooling or ridehailing and ridepooling combined with public transportation, whereby all ridehailing and ridepooling services are operated with autonomous vehicles.

In the third part, rebate cards (25% discount, half fare, flat rate) for autonomous ridepooling services – or none – are randomly attributed to respondents with the same R script that also computes actually displayed choice attributes for the experiments (display design). This R code also provides the adaptation of the cost of the aRP and PT&aRP modes conditional on the attributes rebate cards. Further, the respondents are asked whether or not they would own a car in a world where aRH/aRP services exist, and if so, if they chose an autonomous car. Depending on their choice and prior reference mode and car ownership, their reference mode for the following choice experiments will be changed. Since we cannot anticipate the respondents responses on car ownership, we have prepared all display designs for both reference modes and programmed Qualtrics in a way that it can automatically allocate the appropriate design depending on the choice of the respondent with regards to the mobility tools.

Before starting those two choice experiments, we ensure that each respondents has watched each of the two videos explaining ridepooling and ridepooling with autonomous vehicles (see chapter 4.4) until the end by inhibiting skipping forward before the video has ended. After the respondents have responded to the choice experiments, they are asked whether they would buy the rebate card that was attributed for this experiment for a certain price. This price is randomly varied for each respondent to be able to calibrate a choice experiment that explains the probability an individual buys such a rebate card. The displayed values are saved by Qualtrics to the respondent’s data.

The fourth part only consist of pre-defined questions and therefore is fully covered by Qualtrics. It starts with attitudinal questions. The first questions on the attractiveness of autonomous ridepooling minibuses versus the mode they currently use (car of public transportation). It continues with questions on personal attitudes with regards to the propensity to share vehicles and mobility preferences in general. The fourth part ends with questions on sociodemographic details of the household and the respondent that were not included in the first questionnaire.

4.6.4 Visualization of the questionnaire and navigation

The web-based questionnaire is implemented in a responsive design and all the display of all questions is optimised given the screen size and device type the respondent is answer the survey. In case the respondent uses a smartphone, only one alternative of the choice set can be shown on the screen at once. To view all alternatives, the respondents thus need to scroll from alternative to alternative by swiping over the screen. In contrast, for the case of tablets and PCs all alternatives are displayed on one screen. The respondents may navigate back and forth within the different parts of the questionnaire and adapt their

responses. However, we do not track whether responses have been changed.

4.7 Pretest

4.7.1 Overview

Given the challenges stated above and the novelty of the survey instrument, the survey was conducted in four phases: pre-launch, two pretests (pretest 1 and pretest 2) and main phase. This step-wise approach enabled to improve the survey instrument and the recruiting procedure based both on qualitative feedback and quantitative measures.

4.7.2 Pre-launch

The objective of the pre-launch was to collect feedback on the understandability and the technical functionalities of the questionnaire. The participants were recruited among the members the project's advisory committee, member of staff at the FHNW as well as friends and family. It total 12 persons filled the questionnaire. The feedback collected during the pre-launch phase was mainly related to the wording of questions.

4.7.3 Pretest 1

The first pretest addressed the following objectives:

1. To test the technical functionality of the questionnaire in connection with the intervista's online panel and with a wide variety of respondents and units used to fill in the questionnaire.

2. To test the survey design and quality of the responses by analysing the share of non-trading behaviour and estimating simple MNL models for the different stated choice experiments

3. To find out the proportion of respondents who comply with the innovation criterion

4. To find out whether there is a difference in preferences between participants who fulfil the innovation criterion versus the ones who do not fulfil this criterion

5. To find out if each relevant sociodemographic group has a sufficient proportion of observations in the final dataset containing the respondents who finished the survey

4.7.4 Participants

For this first pretest, 359 persons were recruited from the intervista online panel. All these persons fulfilled the sampling criteria with regards to age (19-75 years old) and spatial type of the resident municipality.

In this first pretest we did not filter out respondents if they did not comply the criterion regarding being innovative (see chapter 4.3.2), because we wanted to examine the differences in the choice behaviour in the choice experiment. We found that 46% of the respondents who finished have met the criterion regarding being innovative. We also did not filter respondents because of quota restrictions.

21% (76) of the participants did not comply with the requirement of having conducted both a utilitarian trip and a leisure trip longer than 2km by public transport or car over the course of the last two weeks. Another 19% (70) respondents did not finish Questionnaire 1. Most of the latter stopped during the questions on trips, 19 did not like to respond on the question regarding their place of living and quit the survey. In total 41% (146) of the participants either were failing some of the conditions of participation or stopped filling in Questionnaire 1, 59% (213) finished. All these were invited to participate Questionnaire 2, however, only 148 – 69% of those who were invited – started it. From these, 125 – 35% of the 359 persons that were recruited – finished Questionnaire 2, and thus both questionnaires.

We calculated the number of respondents for each subgroup for we want be able to compute differences in preferences. We did so for the age-groups, respondents owning a GA (flat rate travel card valid for public transport everywhere in Switzerland) or regional travel card (flat

Tab. 40 *Number of participants and finishers (Pretest 1)*

Stage	Participants	Percentage
Starters Questionnaire 1	359	100%
Finishers Questionnaire 1	213	59%
Starters Questionnaire 2	148	41%
Finishers Questionnaire 2	125	35%

rate travel card valid in regional networks), respondents who have a driving licence and have a car available, people who are employed or in education, and French speaking people.

Tab. 41 *Sociodemographic groups of finishers (Pretest 1)*

Variable	Attribute	#	%
Age	under 19 years	0	0%
	19 - 29 years	22	18%
	30 - 44 years	37	30%
	45 - 64 years	55	44%
	65 years or older	11	9%
Employment	work or training	108	86%
	no work or training	17	14%
Season ticket	GA or local: yes	61	49%
	GA or local: no	64	51%
Drivers licence & car	yes	55	44%
	no	70	56%
Language	de	100	80%
	fr	25	20%

4.7.5 Non-traders

Non-traders are respondents, who always choose the same alternative within an choice experiment. Non-traders are either people with a strong preference for a specific alternative, which they choose regardless of its attributes and the attributes of the alternatives. However, non-traders may also be respondents, who do not seriously solve the choice tasks and thus choose always the same alternative in order to save efforts. The latter respondents may create significant bias with regard to the alternative specific constants and bias the parameter related to the attribute towards zero. However, the first aforementioned cannot be distinguished from the latter, and thus it is generally a good sign, if the proportion of non-traders in a survey is low, because these rules out that there is a large number of the latter ones in the sample. In our survey, we find only 18% of respondents, who always choose the same alternative across the experiments including autonomous ridepooling services.[22]

[22] Note, that if a respondent has different reference modes in his questionnaire, and always chooses the reference mode, then he is counted as non-trader when computing this number. However, if the alternative mode varies between direct and feeder mode across the choice sets, a respondent who always selects the mode containing a ridehailing mode or a ridepooling mode is not counted as non-trader. However, if a respondents has for instance car as a reference mode in the utilitarian trip, but public transport in the leisure trip and in both experiments always chooses the reference mode, then this is counted as non-trading.

When looking on the level of the Experiments 2 and 3, each containing six experiments, we find the following proportions of non-traders:

Tab. 42 *Non-traders across experiments*

Trip type		Choice experiments					
		Exp. 2		Exp. 3		Exp. 2 & 3	
Utilitarian	Leisure	Non-trad.	N	Non-trad.	N	Non-trad.	N
Car	Car	44%	50	51%	68	39%	49
PT	PT	29%	7	55%	20	40%	5
Different modes		12%	67	17%	47	7%	81
Average		26%	124	42%	124	21%	124

Note: This table reads as follows. E.g. the second top-left cell means that of the respondents, who have car as reference mode in the second choice experiments in both the choice experiments for the utilitarian trip and the leisure trip, 38% of the participants are non-traders. The top-left cell means that in the second experiments, 24% of the participants are non-traders.

All in all, we found only a low proportion of non-traders in our survey, especially as compared to the value of 60% found in the SP of the Swiss Mobility and Transport Microcensus (MTMC)(Weis *et al.*, 2016). Therefore, we decided not to exclude non-traders from our survey. This is particularly true, when we look at the level of all experiments, containing twelve choice experiments. We observe that the there are more non-traders in Experiment 3 and then in Experiment 2. We believe that this results from the two following reasons: First, because of the self-selection impact of the mobility tool choice experiment: Respondents with high preferences for ridepooling services are choosing rebate cards for ridepooling services and thus tend to choose always the ridepooling services, since they got cheaper. Second, because of the increased tiredness of the respondents who try to save efforts by non-trading. This is particularly true for the respondents who did not choose to buy a rebate card for the mobility tool experiment: Despite the same level of prices were presented in the choice experiments, they showed an approx. 50% increase in non-trading behaviour Experiment 3 as compared to Experiment 2.

4.7.6 Model estimation

We estimated separate MNL models for each of the eight types of experiments (Car vs. RP, Car vs. PT&RP, PT vs. RP, PT vs. PT&RP, Car vs. aRH/aRP, Car vs. PT&aRH/PT&aRP, PT vs. PT&aRH/PT&aRP, PT vs. PT&aRH/PT&aRP). The results show, that not in all cases the cost parameters are statistically significant, however the parameters on the total travel time are. The parameters of the renaming parameters are not significant in the most cases, however they mostly have the sign we do expect. When pooling the the data of the experiments PT vs. PT&RP, Car vs. aRH/aRP, and of the experiments Car vs. PT&aRH/PT&aRP, PT vs. PT&aRH/PT&aRP and modelling the difference of the reference alternative by the dummy PT, we get cost parameters that are statistically significant. We also could show, that being in innovator has a strong impact on the preference for choosing a ridepooling mode. The results also suggest that owning PT rebate cards or choosing ridepooling rebate cards have a positive impact on choosing the ridepooling alternatives. This implies that the impact of the choice of ridepooling rebate cards on the choice of ridepooling alternatives goes beyond what the induced price reduction implies. We observe, that the parameters on the total travel duration were – in contrast to the experiments where ridepooling services are included as feeder modes – not statistically significant for experiments including ridepooling services as feeder mode. Further, we observe that the parameters relating to the cost and the total travel duration are statistically less significant in Experiment 3 than in Experiment 2.

Tab. 43 *Parameters on cost and total travel duration*

Direct trip						
Experiment	Exp.2		Exp.3		Exp.2 & Exp.3	
Reference mode	Car or PT		Car or PT		Car or PT	
	Paramter	Sign.	Paramter	Sign.	Paramter	Sign.
Cost[CHF]	-0.270***	0.000	-0.095*	0.014	0.160***	0.000
Total duration[min]	-0.060	0.140	-0.052	0.190	0.056	0.018
wtp[CHF/h]	14		33		21	
Intermodal trip (feeder mode)						
Experiment	Exp.2		Exp.3		Exp.2 & Exp.3	
Reference mode	Car or PT		Car or PT		Car or PT	
	Paramter	Sign.	Paramter	Sign.	Paramter	Sign.
Cost[CHF]	-0.092*	0.024	-0.180***	0.000	-0.130***	0.000
Total duration[min]	-0.058*	0.018	-0.055*	0.041	-0.059***	0.001
wtp[CHF/h]	38		18		27	

4.7.7 Mobility tool choice experiment

The mobility tool experiment is to capture the respondents' choice of rebate cards on automated ridepooling services. This is a very relevant aspect for the demand on ridepooling services, since people who have a high preference for such service will buy the cards and as result of the induced lower prices will demand these services even more. However, we observe that the proportion of people who bought a rebate card was rather low, namely 43%. In addition of that the respondents who do not choose a rebate card only choose ridepooling modes in 27% of the cases – as compared to 48% overall respondents in experiment 2 – and thus do not create a lot of information. An additional reason for this rather low proportion of respondents choosing these rebate cards could be that the experiment imposes a too high cognitive burden, since the respondent have to choose among three different types of rebate tickets on aRP services which do not exist yet. We also observe that the people who choose one of these rebate cards, choose ridepooling alternatives more frequently.

Tab. 44 *Choice of RH and RP alternatives before and after mobility choice experiment*

	Modes			Observations	
	Ref.(%)	RH(%)	RP(%)	N	N(%)
Exp.2	52	20	28	124	100
Exp.3, all	60	12	28	124	100
Exp.3, none	73	11	16	71	57
Exp.3, 25%	44	12	44	33	27
Exp.3, 50%	44	18	39	18	15
Exp.3, 100%	25	25	50	2	2

The second mobility tool experiment was on car ownership (no car, car, AV-car). No major changes in car-ownership occurred, however it must be considered, that we did measure the car ownership by the question on the car availability, namely car ownership if owning a

driving license and if "Car is available on request within the household" or "Car is available on request outside the household".

Tab. 45 *Change in vehicle ownership when AV cars and automated ridepooling services exist*

Current situation	If AVs exist			Total
	No Car	AV car	non-AV car	
No car	25	1	1	27
Car ownership	10	17	61	88
No driving licence & no car	5	3	1	9
Total	40	21	63	124

The results show, that one third respondents who do not have a driving licence and do currently not own a car, would buy an AV car.

4.7.8 Distribution of travel distances

For the utilitarian trips we would like to have a sample that is rather evenly distributed over the categories 10..30min, 31..50min, and 50min+, while as for leisure trips we would like to have double the observations in the 10-30min category than in the other two. We so do, because we believe that in the case of leisure trips, the ridepooling services are less attractive for long trips due to the lower willingness to pay for saving travel time as compared to utilitarian trips.

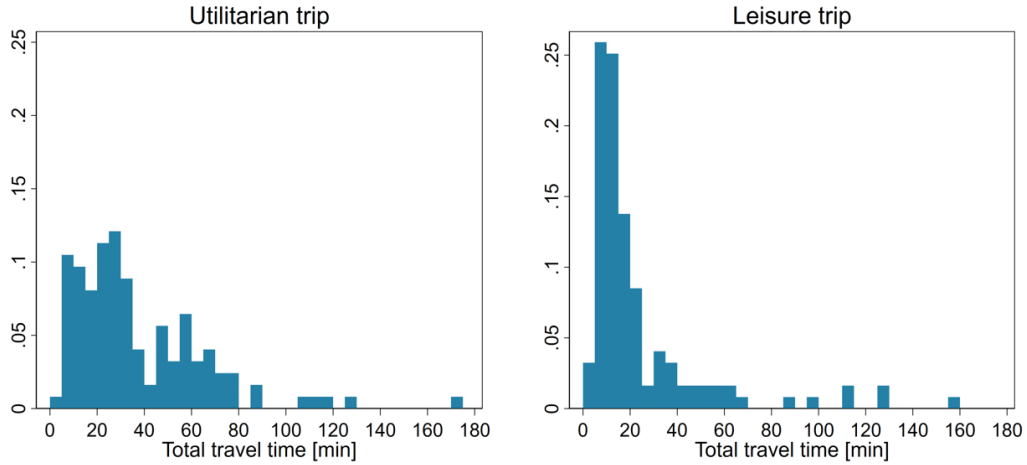


Fig. 7 *Distribution of total travel duration of reference trips*

Fig. 7 shows that there are far more observations in the range of 10..30min than we targeted.

4.7.9 Modifications after pretest

We implemented the following six major changes for the main study:

First, we imposed quota to get the desired levels of car and GA owners, age groups, respondents who are working or in education, and respondents who live in the French speaking part of Switzerland. We do so, to enable modelling the differences in preferences among those groups. We also coordinated with Intervista to provide these quota data so that they can pre-sample sub-groups of their panel to reduce the number of screened out participants and thus to reduce costs.

Second, we change the probabilities of including the additional question to decrease the number of respondents who report on leisure trips shorter than 10km to reduce the oversampling of short trips as seen in Fig. 7.

Third, we modified the levels of the cost attributes for ridepooling alternatives for some experiments in order to improve their attractiveness and to increase the t-values of the cost parameters. We also changed the levels of the total travel duration of ridehailing and ridepooling alternatives attributes for the same reason, especially for the 20min base design. Those adaptations also ensure a more reasonable and wider range for the corresponding wtp distribution.

Forth, we do not ask the respondents to select a ridepooling rebate card between the second experiment and the third experiment but randomly assign one out of three rebate levels taking into account the respondents current travel cards. We do so for to solve the problems mentioned in paragraph 4.7.7, namely the low proportion of people who actually selected a rebate card, to reduce the tiredness of the respondents in the choice Experiment 3, and to reduce the proportion of non-traders in the choice experiment by eliminating the self selection problem. After the third experiment, we evaluate the respondent's willingness to pay for the given rebate card by asking if the respondent would be willing to acquire such a card for a given price whereby on out of three price levels is randomly assigned.

Fifth, we reduced the complexity of the mobility tool choice experiment on the rebate cards for ridepooling services. After the third experiment, we evaluate the respondent's willingness to pay for the given rebate card by asking if the respondent would be willing to acquire such a card for a given price whereby one out of three price levels is randomly assigned.

Sixth, in the question on car ownership in the case of the existence of AV car and AV ridepooling services, we will randomly vary the price for the AV upgrade. We do so to enable to calibrate a choice model that contains the price for an AV upgrade as attribute.

4.8 Main survey

4.8.1 Sample

The sample was drawn in collaboration with the market research firm intervista 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 2 kilometers.

Representative quotas for this target population were derived based on MZMV 2015 regarding car availability, age groups, employment status, sex, language, and spatial type of the residence municipality. With regards to travel card availability, we increased the quota for respondents holding a national travel card (GA) or regional travel card from 20% to 33%. In this way, we can more reliably test whether people who frequently use public transport differ from other people with regards to aRP and aRH preference.

Those quotas were applied when recruiting the respondents of the first questionnaire. Depending on the willingness to complete both questionnaires and the suitability of the reported trip to generate the choice experiment, the composition of the respondents who completed the stated choice experiment can differ from those quotes. Tab. 46 shows how well the quotas were met through the different survey phases. Overall, the composition of respondents with regard to car availability, travel card availability, age, and preferred survey language did not change substantially throughout the different phases.

Tab. 47 describes how well the sample represents the target population with regards to sex and the spatial type of the residence municipality. Thanks to focusing on certain respondent groups towards the end of the sampling process, the targeted quotas with regards to sex and spatial type of residence municipality were also met well with regards to those two variables.

Household income was not used as a quota when drawing the sample. Consequently, the

Tab. 46 *Response rates depending on survey progress*

		MZMV 2015	Completed Q1		Invited for Q2		Completed SP	
			n=1364	%	n=1089	%	n=812	%
Car	available	70%	846	72%	677	73%	545	67%
	not available	30%	327	28%	253	27%	267	33%
Travel card	GA or regional travel card	20%	456	33%	363	33%	274	34%
	Halbtax, other or no subscription	80%	908	67%	726	67%	538	66%
Age	18-29	17%	264	19%	216	20%	173	21%
	30-44	26%	406	30%	333	31%	254	31%
	45-64	36%	448	33%	347	32%	252	31%
	65+	21%	246	18%	193	18%	133	17%
Trip purpose	Work / education	71%	1067	76%	835	77%	638	79%
	Repeated trip	29%	327	24%	254	23%	174	21%
Language	German	73%	1029	75%	833	76%	641	79%
	French	27%	335	25%	256	24%	171	21%

income group distribution in the sample differs from that of the base population. Specifically, households with an income below 6,000 CHF per month are underrepresented, while those with an income above 8,000 CHF per month are overrepresented. Nevertheless, there are sufficient respondents from all income groups to identify potential impacts of household income on choice behavior.

The openness to innovative mobility offers was measured with two Likert scale questions. The respondents were asked to assess to which extent they consider themselves to be among the first to buy an electric car and to test new shared mobility offers as compared to other Swiss residents. For both questions, the different levels of agreement are similarly distributed. With 26% and 27%, respectively, the largest group of respondents neither agrees or disagrees with those statements. 36% of the respondents agree or strongly agree with the statement concerning the openness to buy an electric car, 30% with the one concerning the testing of new forms of mobility. The relatively equal group sizes for both variables support testing for systematic differences in preferences for aRP and aRH as new and innovative transport modes.

Fig. 8 shows the distribution and spatial type of the respondents' municipality of residence. Almost two thirds of the respondents live in municipalities which are part of Switzerland's biggest urban agglomerations, namely Zurich, Bern, Basel, Geneva and Lausanne. However, 35% of all respondents live in smaller agglomerations such as Fribourg, Neuchâtel, St. Gallen, Lucerne, Zug, Olten, Chur, Vevey, Sion or Brig. Hence, the sample is suitable to understand autonomous vehicles choice behaviour for residents' in different Swiss agglomerations.

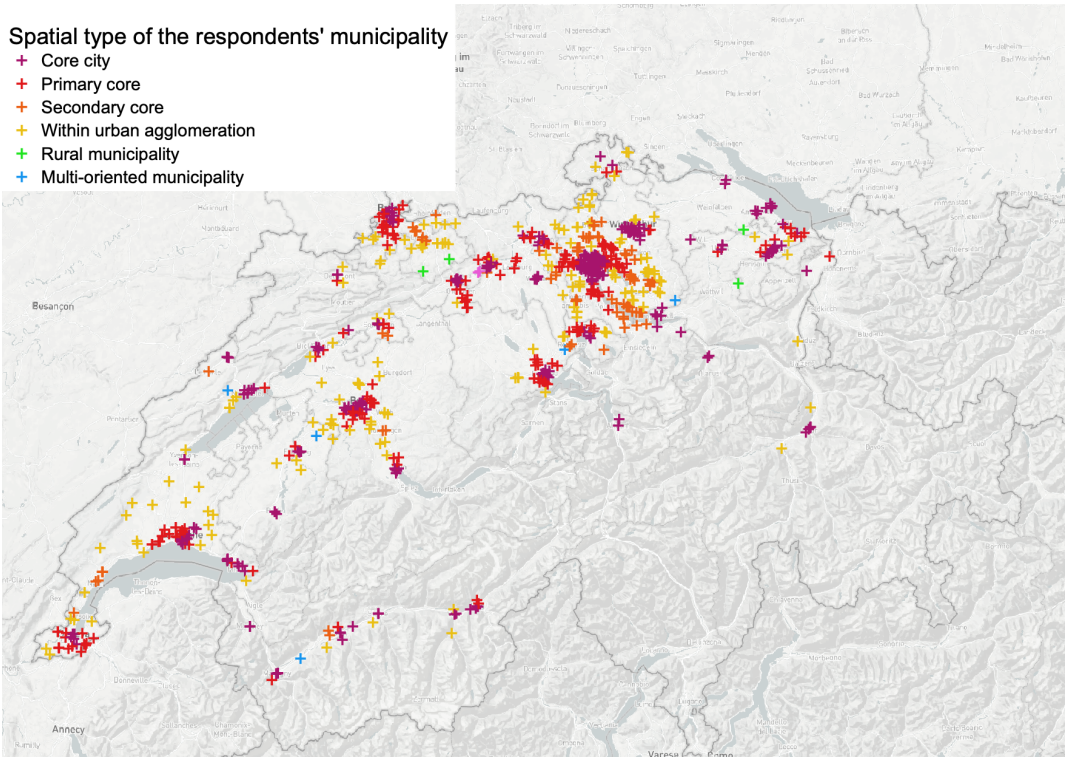


Fig. 8 *Spatial distribution of respondents who completed the stated preference questionnaire*

4.8.2 Mode choice

Descriptive analysis The dataset consists of 8361 observed choices made by 812 respondents. This dataset includes answers from the second and third choice experiment of main study respondents as well as from the second choice experiment of pretest respondents. Responses from the third experiment of the pretest were omitted from the analysis. Those choice sets were constructed based on the respondent's interest to acquire ridepool-

Tab. 47 *Representativeness of the sample with regards to further variables*

		MZMV 2015 / Quota	Completed SP n=812	
Sex	female	51%	404	50%
	male	49%	408	50%
Spatial type of residence municipality	Kernstadt	39%	331	41%
	Hauptkern	32%	220	27%
	Nebenkern	10%	85	10%
	Gürtel	20%	165	20%
	Other	0%	11	1%
Income	below CHF 2'001	2.5%	16	2.3%
	2k - 4k CHF	14.7%	57	7.0%
	4k - 6k CHF	18.0%	117	14.4%
	6k - 8k CHF	14.8%	124	15.3%
	8k - 10k CHF	10.5%	122	15.0%
	10k - 12k CHF	7.3%	85	10.5%
	12k - 14k CHF	3.9%	76	9.4%
	14k - 16k CHF	3.3%	40	4.9%
	above 16k CHF	5.0%	58	7.1%
	not available	20.2%	114	14.0%
I am among the first to buy an electric car (compared to national average)	Strongly disagree	-	146	18%
	Disagree	-	161	20%
	Neither agree or disagree	-	210	26%
	Agree	-	174	21%
	Strongly agree	-	121	15%
I am among the first to test new shared mobility offers (compared to national average)	Strongly disagree	-	131	16%
	Disagree	-	215	26%
	Neither agree or disagree	-	222	27%
	Agree	-	153	19%
	Strongly agree	-	91	11%

ing discount cars and therefore might be subject to a self-selection bias as the higher share of non-traders among this group of respondents in experiment three indicates. Responses from the first choice experiment were omitted because it focused on ridehailing and ride-pooling services with drivers, which were included in the questionnaire solely to familiarise respondents with the concept of shared trips.

Whether the aRH and aRP alternatives of the choice experiment are presented as direct modes or as part of an intermodal trip combined with public transport depends on the attractiveness of those two options for the reported trip (see Fig. 5). Due to cost structure of aRH and aRH, direct trips are usually more attractive for shorter and intermodal trips for longer distances. Fig. 9 shows the distribution of trip distances for the different trip types. The mean routed distance of reported trips for which the choice experiments included direct ridehailing and ridepooling trips as alternatives amounts to 12.3 km if the reported trips has made by car and 10.9 km in the case of a reported public transport trip. In both cases, the distribution is positively skewed, with most trips being shorter than 30 km. If the alternatives included intermodal trips with ridehailing and ridepooling as a rail feeder, the mean routed distance amounts to 50.9 km if the reported trips was made by car and 51.5 km in the case of a reported public transport trip. Here, the distribution is much more spread out and 43% of all reported trips cover distances longer than 50km.

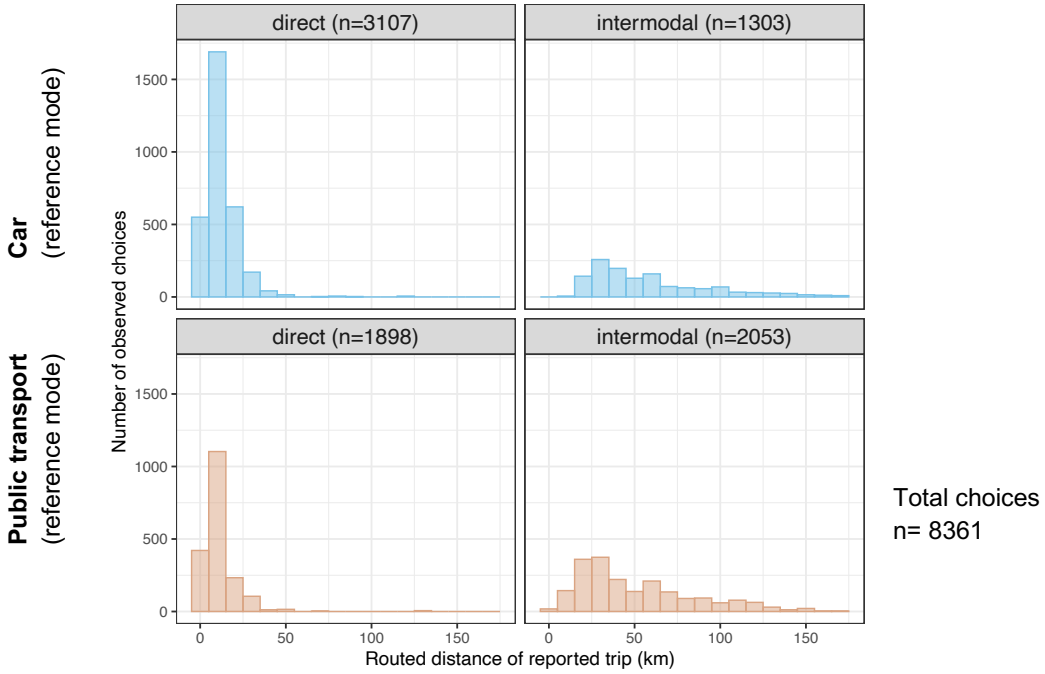


Fig. 9 *Number of observations by reference mode and trip type*

The choice experiment was designed to create meaningful trade-offs between different alternatives and related variables using a random design approach. We used priors from our literature review to ensure that the random designs generated by NGene did not include alternatives with low a priori probabilities (see Section 4.5. The overall shares of chosen mode alternatives, illustrated in Fig. 48 by reference mode and trip type, show that in most cases, the mode reported for the reference trip was maintained. However, aRH and aRP alternatives were chosen in 12% to 31% of the cases. This demonstrates that the experiment design strategy worked as expected and that the database is suitable for estimating meaningful choice models independent of the reference mode and aRH and aRP trip type.

The share of respondents who did chose the same alternative across several choice situations is a helpful metric to analyse the extent to which respondents demonstrate trading off the different mode alternatives in choice experiment. Tab. 48 lists this metric for the two considered reference modes and trip purposes. Usually each respondent was presented

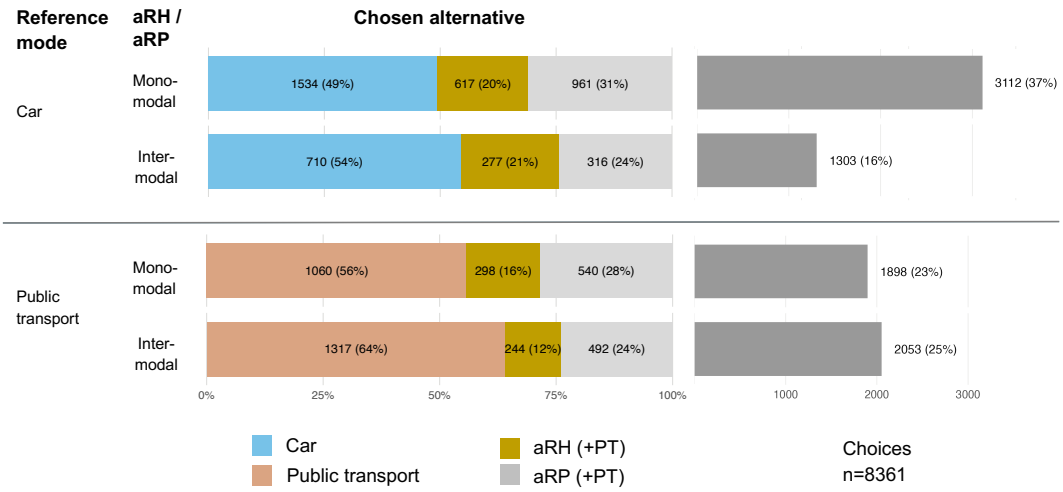


Fig. 10 *Share of chosen mode alternative by reference mode and trip type*

six choice situations for each of the resulting combinations of reference mode and trip purpose. However, if respondents chose to acquire a private autonomous car or gave up car ownership, the reference mode was adjusted after the first set of choice experiments. In this case, each combination of reference mode and trip purpose resulted in three choice situations.

For leisure trips, out of 478 respondents who use a car for leisure trips, 43% consistently chose the same alternative, indicating a higher degree of non-trading behavior. The 280 respondents using public transport for leisure trips as reference mode exhibited with 33% a lower share of non-trading behavior.

For utilitarian trips, 35% of the 359 car users consistently chose the same alternative, showing a moderate level of non-trading. Similarly, 33% of the 435 public transport users for utilitarian trips demonstrated non-trading behavior.

Without differentiation for trip purpose, the number of choice alternatives across which non-trading behaviour is identified amount to 12 choice situations. In this case, 27% of the 550 car users and 28% of the 503 public transport users consistently chose the same alternative.

Tab. 48 *Share of non-trading respondents for different reference modes and trip purposes*

Reference mode	Trip purpose	Number of respondents	Share non-trading
Car	Leisure	478	43%
	Utilitarian	359	35%
Public transport	Leisure	280	33%
	Utilitarian	435	33%
Car	All	550	27%
Public transport	All	503	28%

In summary, the analysis shows that the great majority of respondents did chose different mode alternatives across the different choice experiments which indicates that the experiment design successfully created competitive aRP and aRH alternatives. The Tab. 48 reveals that car users have a slightly higher tendency to exhibit non-trading behavior in leisure trips compared to utilitarian trips. Public transport users show a consistent level of

non-trading behavior across both trip purposes. Overall, the share of non-trading respondents is relatively similar between car and public transport users when considering all trip purposes.

Utility functions The utility for the alternative *car* is defined by the following equation:

$$\begin{aligned} u_{\text{car,i}} =& \beta_{\text{ivt,car}} \cdot \xi_{\text{TD,car,i}} \cdot ivt_{\text{car,i}} + \\ & \beta_{\text{cost}} \cdot \xi_{\text{CD,i}} \cdot cost_{\text{car}} + \\ & \beta_{\text{et,car}} \cdot et_{\text{car}} + \beta_{\text{ttu,car}} \cdot ttu_{\text{car}} \end{aligned} \tag{35}$$

with ivt_{car} describing the in-vehicle travel time in minutes, $cost_{\text{car}}$ the cost in CHF, at_{car} the egress time to reach the final destination for the parking lot and ttu_{car} the travel time uncertainty (width if the expected travel time window). The parameter $\beta_{\text{ivt,car,i}}$ has been separately estimated for trip purpose i (utilitarian or leisure). The term $\xi_{\text{TD,car,i,j}}$ describes the distance-based elasticity of the perception of travel time depending on the travel distances routed on the street network for trip purpose i. For all other parameters, no trip purpose specific differentiation was specified. The term ξ_{CD} describes the distance-based elasticity of the cost perception. All temporal units are described in minutes for all modes.

The distance-based elasticity of travel time $\xi_{\text{TD,mode,i}}$ for a given mode and trip purpose i is defined as:

$$\xi_{\text{TD,mode}} = \left(\frac{\text{RD}}{\widehat{\text{RD}_i}} \right)^{\lambda_{\text{TD}_{\text{mode,i}}}} \tag{36}$$

with RD as the routed distance for the given trip, $\widehat{\text{RD}_i}$ as the average routed distance for trip purpose i and the exponent $\lambda_{\text{TD}_{\text{mode,i}}}$ describing the slope of the distance-based travel-time perception for a particular mode and trip purpose i.

The distance-based elasticity $\xi_{\text{CD,i}}$ of cost for trip purpose i is defined as:

$$\xi_{\text{CD}} = \left(\frac{\text{RD}_{\text{mode}}}{\widehat{\text{RD}_i}} \right)^{\lambda_{\text{CD}}} \tag{37}$$

Since we decided to not differentiate the perception of cost between different modes, we also do not differentiate the exponent of the elasticity term by mode.

The utility for the alternative *public transport* is defined be the following equation:

$$\begin{aligned} u_{\text{pt}} =& \beta_{\text{ivt,pt,i}} \cdot \xi_{\text{TD,pt,i}} \cdot (1 + \beta_{\text{occ-high,pt}} * d_{\text{occ-high,pt}}) \cdot ivt_{\text{pt}} \\ & \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{pt}} + \\ & \beta_{\text{nt,pt}} \cdot nt_{\text{pt}} + \beta_{\text{trt,pt}} \cdot trt_{\text{pt}} + \\ & \beta_{\text{headw,pt}} \cdot headw_{\text{pt}} + \beta_{\text{at,pt}} \cdot at_{\text{pt}} + \\ & \beta_{\text{ptq,i}} \cdot ptq_{\text{i}} + \\ & \beta_{\text{ht,pt}} \cdot d_{\text{ht}} + \beta_{\text{ga,pt}} \cdot d_{\text{ga}} + \beta_{\text{tcard,pt}} \cdot d_{\text{tcard}} \end{aligned} \tag{38}$$

The terms to account for travel time and cost are defined in the same manner as in the case of the car alternative. Additional terms are included in the utility function to account

for the transfer time (trt), numbers of transfer (nt), headway between two subsequent services ($headw$), access time (at) and vehicle occupancy level (occ) as indicated in the choice situation (low as reference category, medium, high). In addition, further variables include the public transport service quality at the place of residence (ptq) as well as whether the respondent holds a half fare card (ht), a general abonnement (ga) or a regional travel card (tcard).

The utility for the alternatives *aRP* as a direct mode is defined by the following equation:

$$\begin{aligned} u_{\text{aRP}} = &\beta_{\text{ASC,aRP}} + \beta_{\text{leisure, aRP}} \cdot d_{\text{leisure}} + \\ &\beta_{\text{inno-sm}} \cdot d_{\text{inno-sm}} + \beta_{\text{inno-ev}} \cdot d_{\text{inno-ev}} + \\ &\beta_{\text{ivt,aRP,i}} \cdot ivt_{\text{aRP}} + \\ &\beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRP}} + \\ &\beta_{\text{rt,aRP}} \cdot rt_{\text{aRP}} + \\ &\beta_{\text{at,aRP}} \cdot at_{\text{aRP}} + \\ &\beta_{\text{ttu,aRP}} \cdot d_{\text{ttu,aRP}} + \\ &\beta_{\text{booking,aRP}} \cdot d_{\text{booking,aRP}} + \\ &\beta_{\text{ttu,aRP}} \cdot ttu_{\text{aRP}} + \\ &\beta_{\text{ht,rh}} \cdot d_{\text{ht}} \end{aligned} \tag{39}$$

with $d_{\text{inno-sm}}$ and $d_{\text{inno-ev}}$ as dummy variables taking the value of 1, if the respondents at least partly sees her- or himself earlier than the general population using new shared mobility services or considering to buy an electric vehicle. These two parameters were jointly estimated for all alternatives involving aRP or aRH segments. They describe the higher propensity of individuals who are open to mobility innovations to choose these new modes of transport.

The utility function does not include an elasticity term for travel time perception because the corresponding model parameter was not statistically significant. This is likely due to the relatively short trip distances in the decision experiments involving aRH and aRP alternatives.

Further utility components include rt for the response time between booking and passenger pick up, at for access time to the pick up location and $\text{d}_{\text{booking,aRP}}$ as a dummy variable taking the value of 1, if the aRP service can be booked in advance. The attribute ttu describes the travel time uncertainty as the width of the expected travel duration window. With regards to travel card attributes, the utility function only includes the half fare card as a dummy variable since the consideration of dummy variables for GA and regional travel cards did not yield statistically significant parameters.

The utility for the alternative *aRH* as a direct mode is defined by the following equation:

$$\begin{aligned} u_{\text{aRH}} = &\beta_{\text{ASC,aRH}} + \beta_{\text{leisure, aRH}} \cdot d_{\text{leisure}} + \\ &\beta_{\text{inno-sm}} \cdot d_{\text{inno-sm}} + \beta_{\text{inno-ev}} \cdot d_{\text{inno-ev}} + \\ &\beta_{\text{ivt,aRH,i}} \cdot ivt_{\text{aRH}} + \\ &\beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRH}} + \\ &\beta_{\text{rt,aRH}} \cdot rt_{\text{aRH}} + \\ &\beta_{\text{booking,aRH}} \cdot d_{\text{booking,aRH}} + \\ &\beta_{\text{ht,rh}} \cdot \cdot d_{\text{ht}} + \beta_{\text{tcard,rh}} \cdot d_{\text{tcard}} \end{aligned} \tag{40}$$

The utility function has the same structure as in the case of aRP except for the following points:

- No parameter for access time was estimated, as the choice anticipated that aRH services would pick up passengers at their point of origin in the choice experiments.

- Despite travel time uncertainty being a variable element in the experiment plan, the related parameter was not statistically significant.
- In addition to the half-fare card, the parameter for the regional travel card is included, whereas the parameter for the GA card was statistically insignificant. This suggests that GA holders — people who frequently use public transport for long distance trips — have a lower inherent preference for aRH compared to those with other travel cards. One possible reason for this could be that they are highly satisfied with the current public transport services (which is why they hold a GA) and, therefore, do not feel the need to use aRH.

The utility function for the intermodal alternatives *aRP+PT* and *aRH+PT* combine attributes of the aRP or aRH segement and the public transport segment(s) as defined in the following equations. Besides this, they also include variables on mobility innovation and ownership of travel cards:

$$\begin{aligned} u_{\text{aRP+PT}} = & \beta_{\text{ASC,aRP+PT}} + \beta_{\text{leisure, aRP+PT}} \cdot d_{\text{leisure}} + \\ & \beta_{\text{inno-sm}} \cdot d_{\text{inno-sm}} + \beta_{\text{inno-ev}} \cdot d_{\text{inno-ev}} \\ & \beta_{\text{ivt,aRP+PT,i}} \cdot ivt_{\text{aRP}} + \\ & \beta_{\text{ivt,pt,i}} \cdot \xi_{\text{TD,pt,i}} \cdot ivt_{\text{pt}} + \\ & \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRP+PT}} + \\ & \beta_{\text{at,aRP}} \cdot at_{\text{aRP}} + \\ & \beta_{\text{rt,aRP}} \cdot rt_{\text{aRP}} + \\ & \beta_{\text{nt,pt}} \cdot nt_{\text{pt}} + \beta_{\text{trt,pt}} \cdot trt_{\text{aRP+pt}} + \\ & \beta_{\text{headw,pt}} \cdot headw_{\text{pt}} + \\ & \beta_{\text{booking,aRP+PT}} \cdot d_{\text{booking,aRP}} + \\ & \beta_{\text{ht\|tcard,aRP+pt}} \cdot \cdot d_{\text{ht\|tcard}} \end{aligned} \tag{41}$$

$$\begin{aligned} u_{\text{aRH+PT}} = & \beta_{\text{ASC,aRH+PT}} + \beta_{\text{leisure, aRH+PT}} \cdot d_{\text{leisure}} + \\ & \beta_{\text{inno-sm}} \cdot d_{\text{inno-sm}} + \beta_{\text{inno-ev}} \cdot d_{\text{inno-ev}} \\ & \beta_{\text{ivt,aRH+PT,i}} \cdot ivt_{\text{aRH}} + \\ & \beta_{\text{ivt,pt,i}} \cdot \xi_{\text{TD,pt,i}} \cdot ivt_{\text{pt}} + \\ & \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRH+PT}} + \\ & \beta_{\text{rt,aRH}} \cdot rt_{\text{aRH}} + \\ & \beta_{\text{nt,pt}} \cdot nt_{\text{pt}} + \beta_{\text{trt,pt}} \cdot trt_{\text{aRH+pt}} + \\ & \beta_{\text{booking,aRH+PT}} \cdot d_{\text{booking,aRH}} + \\ & \beta_{\text{headw,pt}} \cdot headw_{\text{pt}} \end{aligned} \tag{42}$$

Similar to the direct modes of aRH and aRP, the travel time component for the aRH and aRP segments does not include an elasticity term. However, elasticity terms are included for the public transport segments. The utility functions for the aRH+PT alternative follow the same structure as those for aRP+PT, but differ in the following ways:

- The inclusion of a dummy parameter representing innovation in the intention to buy electric vehicles was not statistically significant for the aRH+PT alternative and was therefore omitted.
- A variable capturing travel card ownership is included only for the aRP+PT alternative, as its inclusion for the aRH+PT alternative did not yield a statistically significant parameter. For aRP+PT, the respective parameter was estimated jointly for individuals holding either a half-fare card or a regional travel card. When estimated separately,

both parameters had approximately the same value and were statistically significant only with 90% confidence.

Similar to the direct modes of aRH and aRP, the travel time component for the aRH and aRP segments does not include an elasticity term. However, elasticity terms are included for the travel time component of the public transport segments. The utility functions for the aRH+PT alternative follow the same structure as those for aRP+PT, but differ in the following ways:

- The inclusion of a dummy parameter representing innovation in the intention to buy electric vehicles was not statistically significant for the aRH+PT alternative and was therefore omitted.
- A variable capturing travel card ownership is included only for the aRP+PT alternative, as its inclusion for the aRH+PT alternative did not yield a statistically significant parameter. For aRP+PT, the respective parameter was estimated jointly for individuals holding either a half-fare card or a regional travel card. When estimated separately, both parameters had approximately the same value and were statistically significant only with 90% confidence.

Despite travel time uncertainty being a variable element in the experiment plan, the related parameter was not statistically significant, neither for aRH+PT nor aRP+PT, and therefore was omitted from the utility function.

Results Tab. 49 presents the results of two models. The first, referred to as the "detailed model" includes all variables as defined in the utility functions described above. The second, termed the "MATSim model" restricts the parameters to those available within the standard functionalities of the MATSim scenarios. Specifically, travel time uncertainty and public transport occupancy are excluded from the analysis, as generating these variables within the MATSim framework would require additional capabilities. Furthermore, the utility function of the MATSim model omits parameters related to "innovation." For the case studies, we assume a state where most people are familiar with the new modes. Consequently, we include an additional positive constant to represent a situation in which the technology has diffused across all adoption groups (see section 7.

Additionally, the "MATSim model" was estimated using a smaller sample that excludes respondents from the pretest. In the pretest, respondents were asked to update both car and travel card ownership between the first and second set of choice experiments featuring aRH and aRP options. Based on their decisions, we adjusted the travel costs displayed in the choice experiment. However, a descriptive analysis of the pretest responses revealed a self-selection bias in the second choice experiment. Due to a coding error, we excluded not only the second choice experiment from the sample used to estimate the "MATSim model" but also the first experiment. This error was identified later in the project, but by then, the MATSim scenarios had already been computed. Finally, the "MATSim model" includes elasticity terms to account for distance based travel time perception also for aRP and aRH as direct modes. Despite this, Tab. 49 shows that the values of the parameters included in both models do not substantially differ between the two models, suggesting that the impact on scenario results depending on the employed set of behavioral parameters is likely minimal. However, the following analyis and interpretation of the results refers only to the results of the detailed model.

Tab. 49 *Estimated parameters*

		Detailed Model		MATSim Model	
Mode	Parameter	Est.	rob. s.e.	Est.	rob. s.e.
All modes	Cost	-0.099	-10.965	-0.096	-10.189
	λ cost-distance	-0.486	-7.912	-0.513	-7.862
Car	Constant	-			

		Detailed Model		MATSim Model	
Mode	Parameter	Est.	rob. s.e.	Est.	rob. s.e.
	In-vehicle time leisure	-0.039	-5.374	-0.043	-5.925
	In-vehicle time work	-0.046	-5.596	-0.053	-6.605
	λ in-vehicle time-dist.	-0.291	-3.207	-0.354	-4.188
	Access time	-0.067	-2.883	-0.073	-2.946
	Travel time uncertainty	-0.020	-1.656	-	-
PT	Constant	-	-	-	-
	In-vehicle time leisure	-0.029	-5.269	-0.028	-4.390
	In-vehicle time work	-0.043	-7.395	-0.045	-7.297
	λ in-vehicle time-dist.	-0.362	-3.905	-0.472	-3.945
	Number of transfers	-0.295	-4.117	-0.250	-3.473
	Transfer time	-0.030	-3.164	-0.037	-3.954
	Headway	-0.011	-4.939	-0.012	-4.817
	Access time	-0.067	-2.883	-0.073	-2.946
	Occupancy medium	-	-	-	-
	Occupancy high	0.275	3.080	-	-
	PT Quality A	-	-	-	-
	PT Quality B	-0.290	-1.514	-0.366	-1.868
	PT Quality C	-0.348	-1.801	-0.346	-1.685
	PT Quality D	-0.342	-1.688	-0.277	-1.288
	PT Quality Non	-0.444	-1.223	-0.146	-0.363
	Half-fare card	0.584	2.385	0.381	1.515
	GA	0.547	1.963	0.317	1.101
	Regional travel card	0.832	4.140	0.932	4.225
aRP	Constant aRP	-1.611	-5.865	-1.639	-5.308
	Add. constant aRP leisure trip	0.492	2.165	-	-
	In-vehicle time leisure	-0.039	-5.134	-0.041	-5.168
	In-vehicle time work	-0.035	-4.439	-0.043	-4.102
	λ in-vehicle time-dist. leisure	-	-	-0.119	-0.718
	λ in-vehicle time-dist. work	-	-	-0.181	-0.866
	Booking	0.138	2.037	-	-
	Travel time uncertainty	-0.036	-2.434	-	-
	Half-fare card	0.293	1.867	0.446	2.540
aRP+PT	Constant	-1.382	-5.045	-1.306	-4.602
	In-vehicle time leisure [aRP segm.]	-0.029	-5.269	-0.041	-3.180
	In-vehicle time work [aRP segm.]	-0.050	-3.757	-0.043	-4.102
	Additional pt transfer	-0.200	-2.658	-0.389	-2.449
	Travel time uncertainty	-0.038	-2.538	-	-
	Booking	-	-	-	-
	Half-fare card or travel card	0.395	2.519	0.407	2.510
aRP/aRP+PT	Innovation Mobility Services	0.386	2.808	0.270	1.744
	Innovation E-Car	0.370	2.710	-	-
	Response time	-0.028	-2.935	-0.024	-2.340
	Access time	-0.056	-3.849	-0.065	-3.355
	Occupancy	-	-	-	-

		Detailed Model		MATSim Model	
Mode	Parameter	Est.	rob. s.e.	Est.	rob. s.e.
	Type of pick-up point	-	-	-	-
aRH	Constant aRH	-2.077	-7.163	-1.592	-4.777
	Add. constant aRH leisure	0.650	2.469	0.238	0.699
	In-vehicle time leisure	-0.059	-3.164	-0.049	-3.954
	In-vehicle time work	-0.039	-4.939	-0.057	-4.817
	λ in-vehicle time-dist. work	-	-	-	-
	λ in-vehicle time-dist. leisure	-	-	-0.322	1.85
	Booking	0.354	4.281	-	-
	Half-fare card	0.307	1.824	0.326	1.746
	Travel card	0.339	1.839	0.357	1.543
aRH+PT	Constant	-1.460	-4.979	-1.253	-4.183
	In-vehicle time leisure	-0.074	-4.239	-0.076	-4.213
	In-vehicle time work	-0.074	-3.061	-0.071	2.831
	Additional pt transfer	-0.055	-0.671	0.008	0.089
aRH/aRH+PT	Innovation Mobility Services	0.498	4.079	0.384	2.722
	Innovation E-Car	0.130	2.217	-	-
	Response time	-0.018	-1.646	-0.023	-1.740
	Adjusted ρ^2	0.450		0.452	
	n	8136		7539	

As expected, the cost parameter is negative and highly significant. The related λ-parameter indicates a diminishing perception of marginal changes of cost for longer trips confirming findings for earlier Swiss travel behavior studies such as Hörl *et al.* (2021) and Weis *et al.* (2016).

The behavioral parameter for the mode car also in line with the results from earlier studies. Travel time is perceived more negatively for commuting compared to leisure trips, and sensitivity to travel time decreases as trip length increases. The value of time for a typical trip distance of 13 km amounts 15.2 CHF/h for commuting and 12.4 CHF/h for leisure trips by car. Since the parameter $\lambda_{\text{cost-distance}}$ cost-distance shows a lower value than $\lambda_{\text{in-vehicle time-distance}}$, the value of time increases with longer trips distance as indicated in the first graph of Fig. 11. Those values confirm those as identified in the most recent stated preference survey 2021 on mode and route choice which was conducted as part of the MZMV (Quittelier *et al.*, 2024) and features a more extensive sample of 3553 respondents.

We also tested whether the household income influenced the perception of travel cost. However, different to other travel behaviour studies in Switzerland, the corresponding elasticity parameter was not statistically significant and therefore omitted. However, it did show the expected sign.

Car access time is perceived between 45% (work) and 70% (leisure) more strongly as compared to in-vehicle time, whereas travel time uncertainty - defined as the width of the expected travel time window - is perceived about half as much as in-vehicle time.

Similarly, for public transport, travel time during commuting is perceived more negatively compared to leisure trips, and sensitivity to travel time decreases as trip length increases. The parameter $\lambda_{\text{cost-distance}}$ is a lower value than $\lambda_{\text{in-vehicle time-distance}}$ leading to an increase in the value of time with longer trip distances for public transport as well (see Fig. 11). For a 13 km trip by public transport, the value of time amounts to 23.6 CHF/h for commuting and 15.9 CHF/h for leisure. The value for commuting is about 4 CHF higher as found Quittelier *et al.* (2024). We assume that the higher perception of public transport in-vehicle time might be due to the following reasons:

- Unlike earlier studies, only individuals who reported a trip using public transport participated in the choice experiment with public transport as the reference alternative. In other surveys, respondents with a strong preference for cars or other modes might have disregarded public transport travel time, leading to a lower parameter estimate for travel time.

- In this choice experiment, public transport is compared to aRH and aRP, which are accessible to everyone. In previous experiments, modes like car or bicycle might not have been accessible to all respondents due to the lack of a driving license or the inability to cycle. Therefore, public transport travel time might have influenced decision-making more directly as respondents could realistically consider all presented options.

Each transfer between public transport vehicles is valued at the equivalent of 6.8 minutes of in-vehicle time for commuting and 10.1 minutes for leisure trips. Additionally, each minute spent during transfers is valued almost as highly as in-vehicle time for leisure trips and 32% less for commuting trips.

For both commuting and leisure trips, a one-minute decrease in headway is perceived as roughly one-fourth to one-third as relevant as the same decrease in in-vehicle time, respectively. However, access time is perceived as approximately 1.5 times more than in-vehicle travel time for commuting trips and 2.3 times more for leisure trips. Again, both results confirm findings from earlier studies on public transport travel behaviour in Switzerland such as Weis *et al.* (2021a) and Schmid *et al.* (2021).

While the parameter for medium occupancy of public transport vehicles was not significantly different from the low occupancy reference category, the public transport alternative is perceived 28% more negatively when vehicle occupancy is indicated is high.

The utility of the public transport option decreases with lower public transport service quality (ÖV-Güteklasse) at the respondent's residence. Conversely, individuals with a half-fare card, GA, or regional travel card were more likely to choose public transport, even though the prices in the choice situation reflected zero cost for GA and regional travel card holders as well as lower price levels for half-fare card holders. Similar findings were also presented by Weis *et al.* (2021a) and Hörl *et al.* (2021).

The negative coefficient (-1.611) of the aRP constant with highly significant t-values (-5.865) indicates a general disfavor towards choosing aRP, implying that without considering other factors, aRP is less likely to be chosen compared to the reported reference mode. However, the positive coefficient (0.492) and significant t-value (2.165) indicates that for leisure trips, individuals are more inclined to choose aRP, making leisure trips more favorable for aRP adoption.

Regarding the perception of in-vehicle time for ridepooling, this variable was considered only linearly since the trip distance-based elasticity component was not statistically significant and thus omitted from the final model. This likely results from the relatively short trip distances for aRP and aRH trips (mean distances of 12.3 km for car trips and 10.9 km for public transport trips, see Fig. 48), leading to limited variability. Notably, in-vehicle time for ridepooling is perceived less for commuting compared to leisure trips. Specifically, the parameter for commuting trips is -0.035 (t-value 4.439), while for leisure trips it is -0.039 (t-value 5.134). Applied to a trip over 13 km, this represents a 1.8 times higher valuation for leisure trips and a 1.1 times higher valuation for commuting trips compared to public transport. Compared to car, travel time for a trip over 13 km in aRP is valued about 1.25 higher for leisure trips and about the same for commuting trips.

The positive coefficient (0.138) for booking, with a significant t-value (2.037), indicates that booking availability or convenience increases the likelihood of choosing aRP. This suggests that the ability to book is valued at 2.02 CHF for a typical trip over a 13 km distance. For intermodal trips, the parameter related to booking was not statistically significant and was therefore omitted from the presented model.

The negative coefficient (-0.036), with a significant t-value (-2.434), for the travel time uncertainty parameter indicates that the probability of choosing aRP decreases as the expected travel duration window becomes more uncertain.

With regards to travel cards, only the parameter related to half-fare card turned out to be statistically significant. Persons holding such a card are more likely to chose the aRP alternative.

People who consider themselves as more open to mobility innovations such as shared mobility services or electric cars have as statistically significant higher propensity to chose aRP. This parameter was jointly estimated with the intermodal aRP+PR alternative, as an alternative-specific inclusion of these parameters produced nearly identical values. The same applies to the valuation of response time.

The value of -0.028, with a significant t-value (2.935), indicates that the duration between ordering an aRP trip and pick-up is valued about 30% less than in-vehicle time. This makes intuitive sense, as this waiting time can often be spent more comfortably at the current activity location rather than in the vehicle.

For intermodal trips with aRP as a feeder to rail, the general disfavor towards using aRP is less compared to direct trips. The related constant (-1.382) with a significant t-value (-5.045) also accounts for the fact that any intermodal trip includes at least one transfer, between aRP and public transport.

For the aRP feeder leg, the parameter for in-vehicle travel time of the aRP segment turn only out to be significant for commuting trips. The respective parameter amounts to -0.050 (t-value 3.757) which indicated an increase of travel time perception of 16% as compared to for public transport. For leisure trips, the estimated parameter was negative, as expected, and in the same range as the travel time parameter for public transport trips, but not significant. Therefore, this parameter was constrained to take the same value as the one for travel time in public transport.

The in-vehicle travel time for the aRP segment is slightly more negatively valued compared to public transport travel time. Specifically, the parameter for commuting trips is -0.050 (t-value 3.757), while for leisure trips it is -0.029 (t-value 5.269). This represents a 16% higher valuation for commuting trips and a 33% higher valuation for leisure trips compared to public transport.

Additional transfers between public transport vehicles are valued 32% less as compared to monomodal public transport trips, while no significant difference was found in the valuation of transfer time. Thus, we employed a joint parameter for both intermodal and monomodal trips.

Access time in the context of mono- and intermodal trips with aRP is considered 16% less as compared to monomodal public transport trips. Respondents might have assigned less value to these short walking segments as access times are generally shorter for ridepooling compared to public transport.

Travel time uncertainty for intermodal trips including an aRP leg is similarly valued as in the case of monomodal aRP trips. We also tested if booking the ridepooling segment enhances the perceived utility of the intermodal option. However, this parameter did not show statistical significance and was thus omitted from the model's utility function. The same applies to vehicle occupancy and type of pick-up point, neither of which were significant for the utility of either monomodal or intermodal aRP alternatives. This is surprising, as both variables were included in the experiment plan and were part of the displayed decision variables in the choice experiment. It seems that respondents did not place much emphasis on these variables or were overwhelmed by the complexity of the experiment, focusing instead on the variables of highest relevance to them.

The negative coefficient (-2.077) of the aRH constant with highly significant t-values (-7.163)

indicates an even higher general disfavor towards choosing aRH as in the case of aRP. Again, this coefficient is substantially smaller for leisure trips indicating a ceteris paribus higher willingness to use aRH for monomodal leisure trips.

As with aRP, in-vehicle time for aRH was considered only linearly in the utility function since the trip distance-based elasticity component was not statistically significant and was omitted. In-vehicle travel time is slightly more negatively valued than public transport travel time. For commuting trips, the parameter is -0.039 (t-value 4.939), and for leisure trips, it is -0.059 (t-value 3.164). For a 13 km trip, this represents a 2.9 times higher valuation for leisure trips and a 1.3 times higher valuation for commuting trips compared to public transport. Relative to car travel time, aRH in-vehicle time is valued 2 times more for leisure trips and 1.15 times more for commuting trips over a 13 km distance.

The ability to book an aRH trip is valued more positively as compared to aRP. The parameter value of 0.354 (t-test 4.281) implies that the value of booking amounts to 5.2 CHF for a typical trip over a 13 km distance. Like in the case of aRP, the booking parameter for intermodal trips with an aRH segment, the parameter related to booking was not statistically significant and was therefore omitted from the presented model.

Respondents who currently hold a half-fare card or regional travel card are more likely to chose aRH as compared to rest of the sample. The related parameter values of 0.307 (half-fare) and 0.339 (travel card) are in the same range as in the case of aRP (0.395).

Respondents who consider themselves more open to current shared mobility services show a significantly higher propensity to choose the aRH alternative. The related parameter value of 0.498 is higher than for aRP and was jointly estimated for both monomodal and intermodal trips. Additionally, respondents with a higher-than-average willingness to buy an electric car also show a greater propensity to choose any aRH alternative, though the effect is smaller with a parameter value of 0.13, but still statistically significant.

The parameter related to response time was jointly estimated for both direct and intermodal aRH trips. The negative parameter value of -0.018 indicates that the aRH alternative becomes less attractive as response time increases. This effect is 35% weaker compared to the aRP case. Additionally, the parameter is significantly different from zero only at a 90% confidence level.

The value of the aRH+PT constant suggests that this alternative has a low initial likelihood of being preferred over the reference mode. However, its propensity is higher compared to monomodal aRH alternatives. Travel time of the aRH segment is perceived similarly, regardless of the trip purpose, and valued about twice as much as in public transport.

Unexpectedly, the parameter for additional transfers between public transport vehicles is not statistically significant. This may be because respondents were overwhelmed by the information in the choice experiment, focusing only on the most relevant attributes. The same applies to aRH travel time uncertainty for both mono- and intermodal trips.

Value of travel time Fig. 11 shows the value of travel time (VOT) based on travel distance for cars, public transport, and both aRP and aRH, as direct and intermodal trips. For all modes, VOT increases with trip distance. When interpreting those graphs, it is important to consider the trip distance distribution from the different choice experiments, which form the basis for the estimated parameters. In experiments featuring aRP and aRH as direct modes, the average trip distances are 12.4 km and 11.2 km for commuting and leisure trips, respectively. For experiments with aRP and aRH as feeders to rail, the average trip distances are 50.2 km and 58.7 km. Therefore, the curves for cars and public transport are well supported across the entire indicated distance range. However, for aRH and aRP as direct modes, approximately 80% of data used to estimate distance-based elasticity parameters fall within the distance band of under 25 km.

The slopes for car and public transport confirm the finding of Quittelier *et al.* (2024) which also show increasing differences between VOT for work and leisure trips by public transport

for longer trip distance as compared to car.

Different to car and public transport, travel time perception for both aRH and aRH, either as direct model or feeder, was modeled with only a linear term in the utility function. Hence, the increase in VOT values with longer distances stems solely from the distance-based elasticity parameter for trip cost.

The slopes for aRP and aRH as direct modes show a more pronounced increase in VOT values with longer trip distances compared to car and public transport. This suggests that travel comfort with these modes is perceived less favorably for longer trips, which intuitively makes sense: in public transport, different types of vehicles are used to serve various trip lengths, whereas respondents likely assumed that aRP and aRH would use the same type of vehicle regardless of distance.

For aRP, VOT is higher for utilitarian trips compared to leisure trips. This finding aligns with the results of this and earlier studies regarding car and public transport. However, for aRH, VOT is higher for leisure trips than for utilitarian trips because travel time is perceived more negatively for leisure trips. This is counterintuitive because one would expect travel time to be valued less on leisure trips, regardless of the travel mode. We suggest to verify this in future studies.

Interestingly, the steepness of the slope for aRP and aRH is similar, indicating that longer trip distances are not perceived more negatively in aRP compared to aRH. This could suggest that traveling with strangers in the same minibus for longer periods is not particularly disliked. Note that the slope for aRH leisure trips is steeper than for commuting trips due to the related travel time perception parameters as the travel cost elasticity parameter does not differentiate between trip purposes.

The VOT values for travel time savings with respect to the aRP and aRH segments of intermodal trips are plotted only for distances above 10 km, aligning with the range used in the choice model. For shorter trip distances, intermodal trips a rarely more attractive than a direct trip with aRH or aRP. Similar to aRP and aRH as direct modes, the slope is determined by the linearly modeled parameter of travel time perception for the aRH or aRP segments and the distance-interacted cost perception of the whole trip. Please also note that the range of the y-axis is different as compared to the other two graphs.

The graph indicates that travel time reductions of the feeder segment are generally higher valued as compared to travel time in public transport. This particularly applies to aRH. The respondents might particularly prefer shorter travel times, as this could be seen as reducing the likelihood of missing the connection with the subsequent train segment.

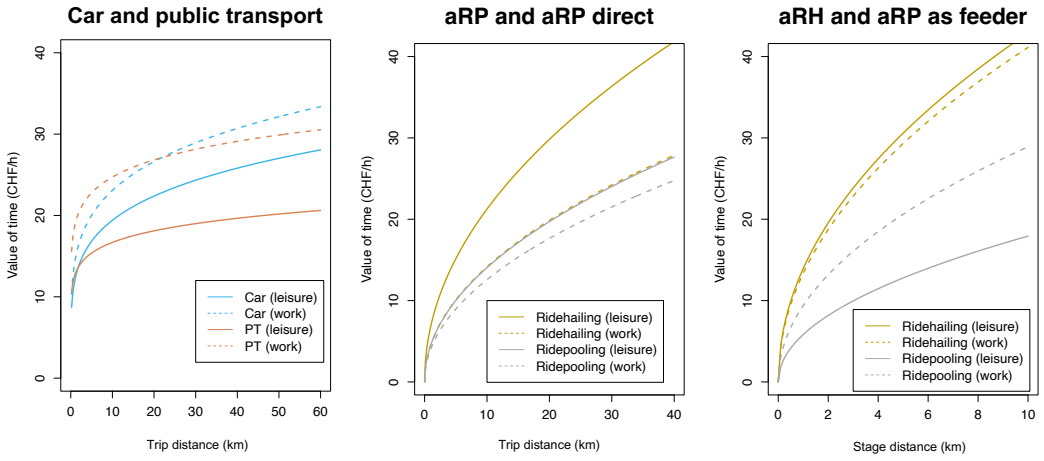


Fig. 11 *Value of time by mode and trip distance*

The cost and travel time elasticities presented in Fig. 12 have been calculated as arc elasticities. This was done by altering the travel cost or time of the respective modes by 1% for all responses and analyzing the extent to which the choice probabilities change. Since the resulting elasticities differ only slightly by trip purpose, the results are presented without such differentiation as average values. The results cannot be directly compared to values from other studies because elasticities are influenced by trip distance and the relative attractiveness of various mode alternatives. Other studies, such as (Quittelier *et al.*, 2024), address this issue by using choice situations based on a wide range of distances and reweighting the results to reflect the travel time distribution in the general population. However, this approach is not suitable in this case, as the choice situations were specifically designed to fit certain distance ranges where aRH and aRP are competitive with other modes, thereby maximizing the information that can be extracted from the sample. Nevertheless, comparing the elasticity values provides valuable insights into how sensitive each mode reacts to changes in cost or travel time.

The cost elasticity for aRP and aRH is substantially higher than for car or public transport. Since the utility functions for all modes include a joint cost parameter, these differences arise from the lower choice probabilities (smaller denominator when calculating the elasticity) and the generally higher trip costs (larger numerator) associated with aRP and aRH modes which also explains the higher elasticity value of aRH, which is more expensive than aRP. This insight indicates that mode shares for aRP and aRH are highly sensitive to changes in travel costs. Hence, the attractiveness of these modes can be significantly improved with subsidies.

Unlike for cost, mode-specific parameters were estimated to account for the different perceptions of travel time and are taken into account when calculating the elasticities. However, as in the case of cost elasticity, also differences in choice probabilities of each mode and travel time (for aRP and aRH in average lower than for public transport but longer than for car) impact the results presented in Fig. 12. Given the parameters presented in Tab. 49, a marginal change in travel time is generally perceived more for aRP and aRH than for car or public transport. At the same time, given the lower choice probability of those modes (also due to the negative constants), a change with regards to the utility of the travel time component results in a lower relative change of choice probability (smaller denominator). Those two effects mitigate each other. As a result, the travel time elasticities of aRP and aRH are only slighlty higher than compared to car or public transport. In the case of aRP as direct mode, the related travel time elasticity of -0.4 is lower than for public transport (-0.6) or car (-0.6) which indicates a general willingness for detours to pick up and drop of other passengers.

Conclusion and limitations Based on the results of the mode choice experiment the following conclusions are drawn:

- The mode choice experiment, which restricted alternatives to the chosen mode of a reported trip and new aRP and aRH options, confirmed earlier findings on the perception of different travel time elements and costs. This supports the validity of the design approach that limited the number of alternatives. However, an exception was found with public transport in-vehicle time, which was valued higher in our experiment compared to previous ones. This difference likely stems from the sampling process, which resulted in the participation of predominantly regular public transport users in the survey. Many of these respondents either have a preference for shared modes, such as those driven by environmental concerns, or are captive users. For these individuals, aRH and aRP represent new modes with typically lower travel times. As a result, they may have valued public transport in-vehicle time more due to the increased competition.

- The negative constants for aRP and aRH alternatives indicate a general reluctance among respondents to choose these new modes, directly affecting their expected market shares. This reluctance is less pronounced among individuals who consider themselves more open to mobility innovations compared to the general population.

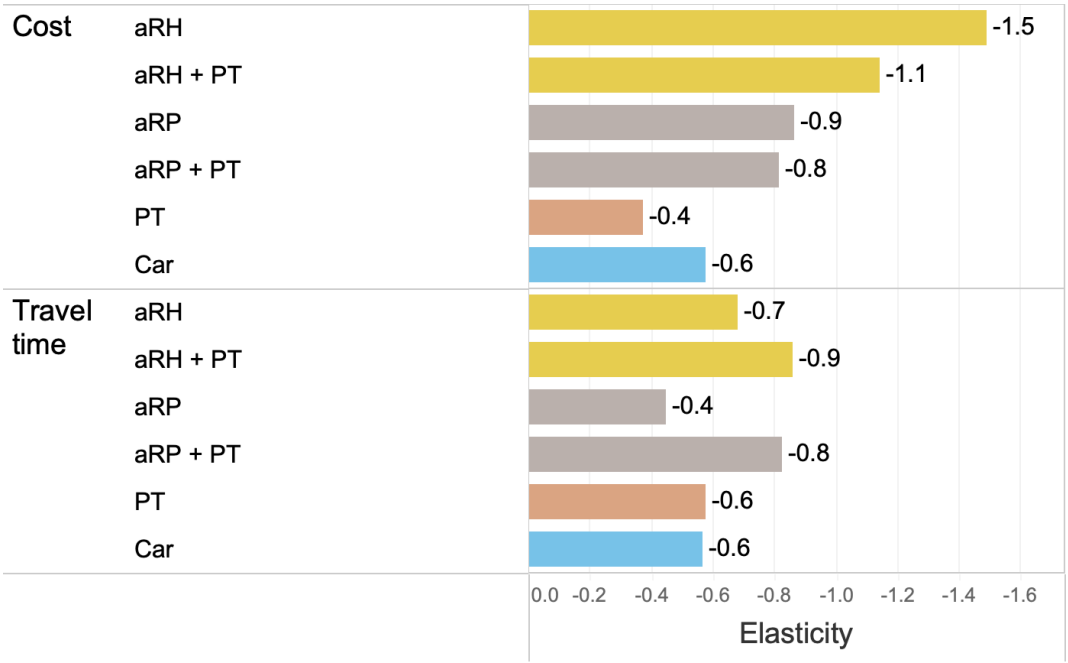


Fig. 12 *Elasticity with regards to cost and time for different modes*

However, this adjustment means that the resulting mode shares will directly reflect these changes and should be interpreted accordingly. Therefore, when employing the presented parameters for travel demand modelling, we recommend focusing on relative comparisons of mode shares for the new modes across different scenarios, rather than deriving insights from absolute mode shares alone.

- Travel time for aRP and aRH is valued more negatively than for public transport and car trips, in particular for leisure trips. This means that the travel time gains that those modes offer in comparison to public transport due a more direct service with fewer (aRP) or no stops (aRH) are to a certain degree mitigated. However, the more negative perception of travel times might also be caused by the unfamiliarity with the travel experience with those new modes.

- The high cost elasticity for aRP and aRH underscores that forecasts computed with a travel demand model based on the results of this choice experiment are very sensitive to any assumption about the actual costs of these modes. Simultaneously, the user cost that operators of such modes must charge depends directly on usage frequency and the ability to distribute fixed costs among many users. Therefore, it is crucial for the travel demand model to include a feedback loop between aRP and aRH travel demand and the resulting marginal user costs.

Based on the experiment design, the available sample and the results of the choice experiment, the following limitations need to be taken into account:

- To limit the complexity of the survey, the choice experiment included only three alternatives: the chosen mode for the reported trip, and alternatives for aRH and aRP. The mode of the reference trip was adjusted only if the respondent indicated certain changes in car ownership in the mobility tool experiment. This means none of the choice situations considered trade-offs between monomodal and intermodal trips involving aRH or aRP. However, such trade-offs are relevant for trips ranging from 10 to 30 km. In this distance range, the utility of a monomodal trip by aRH or aRP is expected to be comparable to that of an intermodal trip with aRH or aRP, as the monomodal alternative is usually faster but more expensive.

- Despite having sufficient respondents from all income groups, a parameter to account for income-dependent perception of travel costs could not be estimated statistically significantly. In other stated preference surveys on travel behavior, income is typically an important factor that mitigates cost perception.

- For the following variables included in the experiment design, the estimated parameters did not turn out to be statistically significant: number of additional passengers in the aRP vehicle, type of pick-up or drop-off point, and travel time uncertainty of aRP and aRH alternatives. This suggests that choice experiment was so demanding that respondents tended to focus on the most important variables, potentially neglecting the less critical ones.

For future research, it would be valuable to conduct a similar stated preference survey with individuals who have actually experienced traveling with aRP and aRH. This would allow for an analysis of the extent to which the general reluctance to use these modes is attributable to specific disadvantages, such as the need to call a ride and the uncertainty of travel and arrival times, as opposed to other factors like current unfamiliarity with these modes. In addition, choice situations that include both monomodal and intermodal alternatives with aRH or aRP would allow for a more comprehensive understanding of the actual trade-off between those options.

4.8.3 Car ownership

After completing an initial set of six choice scenarios with aRP and aRH alternatives, each participant was asked whether their household would consider adjusting car ownership. They were instructed to envision a world where private autonomous vehicles as well as aRH and aRP options are widely available, with pricing and availability similar to those described in the initial choice experiments.

In the car ownership experiment, participants were presented with the following three options:

- No car ownership

- Owning at least one conventional car

- Owning at least one autonomous car

For each participant, one of three different price premiums (CHF 3000, CHF 6000, CHF 9000) was randomly assigned representing the additional cost to purchase an autonomous car compared to a conventional one. Consequently, insights drawn from this data are derived from a between-subject analysis. Since this choice experiment was changed after the pretest (see last paragraph in chapter 4.7, the results presented below refer only to respondents who participated in the main survey.

Descriptive Analysis Fig. 13 illustrates the intention to adapt car ownership depending on current car availability. Among respondents who currently have a car available in the household, 18% indicated to give up car ownership while 22% would replace a conventional car with an autonomous vehicle. The remaining 60% would not change the current vehicle ownership.

Among respondents who currently do not have a car available within the household, about 10% would acquire a private autonomous car if those were commercially available. Interestingly, about the same share indicated to buy in such a situation a conventional private car which is surprising as neither the cost nor the access to such cars was changed in the choice experiment. It seems as if that some of those respondents might have misinterpreted the question. Therefore, the descriptive analysis presented in Fig. 15 restricts to data collected from respondents who currently have a car available in their household.

As expected, the proportion of respondents willing to purchase a private autonomous vehicle is lowest at the highest tested price level. At a premium of CHF 9,000, approximately

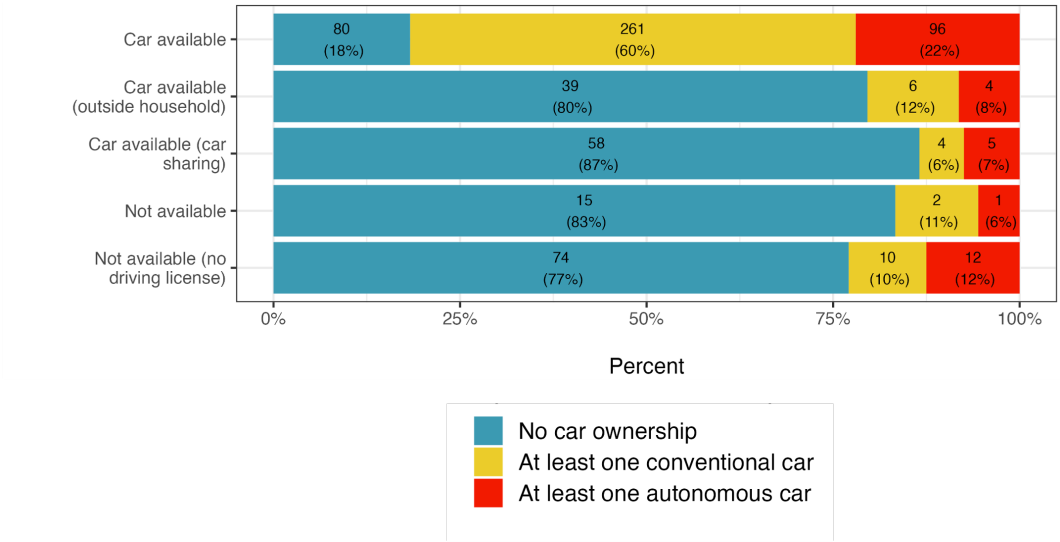


Fig. 13 *Intention to adapt car ownership depending on current car availability*

10% of respondents expressed interest in acquiring such a vehicle. Interestingly, the highest percentage of respondents willing to purchase a private autonomous vehicle was 31% at a premium of CHF 6,000. At a premium of CHF 3,000, this share was slightly lower at 26%. Given the relatively small sample size, these differences could be due to statistical error, but they might also indicate varying expectations regarding the technological feasibility of private autonomous vehicles across different price points. The latter argument would also serve as an explanation why the share of respondents to give up car ownership consistently increases with a higher premium.

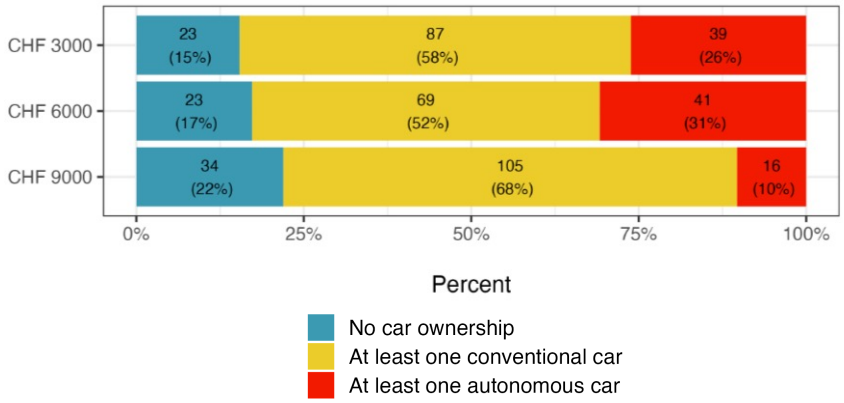


Fig. 14 *Intention to adapt car ownership as a function of the presented price premium for an autonomous car*

Model results To identify which factors, besides the indicated price premium, explain the observed behavior in the car ownership experiment, we estimated a simple multinomial logit model. 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, and openness to mobility innovations.

Tab. 49 lists the parameters of two choice models, which differ only in how the variable describing openness to mobility innovations is operationalised. In the "full model," a separate parameter is used for each level of openness ("partly," "much," and "very much"), reflecting the extent to which respondents consider themselves more open to mobility innovations compared to the general population. In the model used to inform the assignment of private

autonomous vehicles for the MATSim case studies (see chapter 7), these three levels were aggregated into a single variable.

The most relevant factors associated with respondents indicating that they would not own a private conventional or autonomous car are currently living car-free and owning a GA travel card. Other factors that also statistically significantly increase the likelihood of choosing this option include holding a regional travel card or half fare card, being female, and living in a residence located in an area with the highest public transport service quality level A. Additionally, respondents who consider themselves more open to using shared mobility services than the average population are more likely to forgo car ownership. Factors accounting for the spatial type of residence and additional levels of public transport service quality were tested but ultimately omitted, as the related parameters showed low and statistically insignificant values.

The most relevant factors associated with a higher likelihood of choosing an autonomous vehicle are a high household income, not holding a driving licence and being open for mobility innovation expressed through the willingness to acquire an electric vehicle.

Tab. 50 *Results of the car ownership model*

		Full Model		MATSim case study	
		Estimate	rob. s.e.	Estimate	rob. s.e.
No car	Constant	-1.738	-3.246	-1.848	-3.490
	No car today	1.938	5.006	2.051	5.303
	PT quality A	0.631	2.662	0.649	2.760
	Female	0.507	2.303	0.511	2.334
	GA	2.124	5.227	2.169	5.412
	Regional travel card	0.554	1.954	0.558	2.005
	Half fare card	0.644	1.846	0.676	1.930
	Innovation Mobility Services:				
	partly/much/very much	-	-	0.582	2.572
	partly	0.297	1.129	-	-
	much	0.586	2.029	-	-
	very much	1.340	3.490	-	-
Car	Constant	-	-	-	-
	Owns a car	0.950	2.307	0.888	2.157
Private AV	Constant	-0.486	-0.842	-0.651	-1.128
	AV price (1k CHF)	-0.139	-3.285	-0.127	-3.014
	Household (1k CHF/month)	0.093	3.423	0.097	3.764
	No driving license available	0.776	1.590	0.822	1.683
	Half fare card	-0.371	-1.507	-0.341	-1.401
	Innovation electric vehicle:				
	partly/much/very much	-	-	0.748	2.981
	partly	0.521	1.753	-	-
	much	0.762	2.485	-	-
	very much	1.199	3.679	-	-
	Adjusted ρ^2	0.284		0.276	
	n	667		667	

Conclusion

- Limitation: The level of price premium might trigger varying expectations regarding the technological feasibility of private autonomous vehicles.

4.8.4 Ownership of aRP Travel card

Based on the experience in the pretest (see chapter 4.7.9) and to reduce the proportion of non-traders in the second choice experiment, the experiment on the willingness to purchase ridepooling travel cards was conducted after the second set of six mode choice decisions with aRH and aRP alternatives. Depending on the respondents' travel card availability, the possibility of purchasing a certain type travel card for aRP services was presented depending on the respondent's current travel car availability, whereby the indicated price level was randomly assigned:

- aRP-Discount of 25%: respondents with half fare card or no travel card at 50, 100 or 200 CHF per month.
- aRP-Discount of 50%: all respondents at 50, 100 or 200 CHF per month.
- aRP-Discount of 100%: respondents with a Half-Fare card or regional travel card at 250, 500 or 1000 CHF per month or GA at 500, 1000 or 1000 CHF per month

The purchase of such a discount card makes economically only sense if the incurred costs are outweighed by the expected savings on aRP travel cost. Therefore, the decision to purchase a discount card can be interpreted as an indication of the willingness to use aRP as a frequently utilised travel mode.

Descriptive Analysis Fig. 15 illustrates the proportion of respondents willing to purchase an aRP travel card, based on their existing travel card ownership and the indicated price level in the choice experiment. Approximately half of the individuals who currently do not use any travel card are willing to purchase a travel card offering a 25% fare reduction on all aRP rides. Among those who already hold a travel card, about one-third expressed interest in buying such a discount card. The price level has a minimal impact on these proportions, except in the case of the 25% discount card. Here, the proportion of respondents willing to purchase the card at the highest price level decreases by about 7 percentage point compared to the medium or low price levels.

The influence of the indicated price on the willingness to buy a travel card that offers a 50% discount is more pronounced for both person groups. Depending on the price level, 14% to 56% of respondents indicated they would purchase such a travel card. Interestingly, at the medium price level, the proportions are very similar between the two groups, with 35% of those without a travel card and 32% of those with a travel card expressing interest.

Despite the high prices for a 100% discount card, ranging from CHF 250 to CHF 1000 per month, the proportion of respondents willing to purchase such a card remains significantly higher, between 62% and 17%, depending on the price level, compared to the 50% discount card. It is important to note that choice experiments involving the 100% discount card were only presented to individuals who already hold a half fare, regional travel card or GA.

Model results To model the intention to buy an aRP travel card, any alternative that was not offered to the respondent is considered "not available." Consequently, the only alternative available to all respondents is "no aRP travel card" which is represented by a constant that the model constrains to a value of zero. The utility of the three different travel card alternatives is described as a linear combination including the following elements:

- Alternative specific constant
- Price level
- today's travel card ownership
- Information on residence location: spatial type and public transport service quality

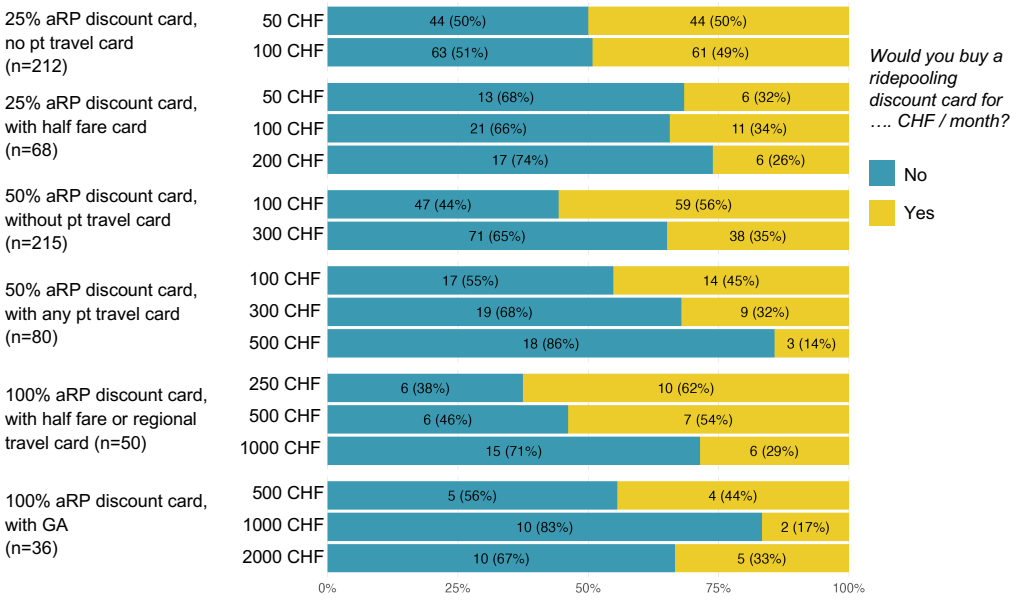


Fig. 15 *Intention to purchase an aRP travel card depending on existing travel card ownership and price level*

- Chosen mode for the reported utilitarian and leisure trips.
- Self-indication of openness to innovations

The choice model was developed by sequentially extending the utility function for each alternative with additional variables, following the sequence listed above. Variables with parameters that were not statistically significant were omitted from the utility function, except for those describing the price level. Two type of models were estimated. The full model includes all available and statistically significant variables. For the simplified model, variables that are not available when applying the model to the synthetic population of the case studies were omitted.

For the aRP travel card offering a 25% discount, no statistically significant impact of the price level was detected. While individuals owning a half-fare travel card are significantly more likely to choose a 25% aRP travel card, those holding a regional travel card and those living in a core city (Kernstadt) are less likely to opt for such a card. Any other variable did not turn out to be statistically significant.

A more nuanced picture emerges for the choice of the 50% discount card. Higher price levels are significantly associated with lower choice probability. The same applies if the reported leisure trip is conducted by car. In contrast, the probability of selecting the 50% discount card increases significantly if the individual owns a Half-Fare travel card, resides in an area with medium public transport serive quality, and has expressed interest in purchasing an autonomous vehicle in the car ownership choice experiment. Respondents who consider themselves to be more open to shared mobility services or willing to buy an electric vehicle as compared to the general population are also statistically more likely to chose an aRP 50% discount card.

Similar findings apply for the choice of the 100% discount card which only was offered as an alternative if the respondent currently owns a Half-Fare regional travel card or GA. Higher price levels lead also to significantly lower choice probability and the openness to buy an electric vehicle is also associated with a higher probability of choosing such a discount car. However, openness to shared mobility services does not significantly impact the choice probabilities.

Interestingly, persons holding a regional travel card or GA are significantly less likely to opt for a 100% aRP discount card. Apparently, they generally do not consider aRP as mode that they would regularly use if it was available. This suggests that the aRP 100% discount card is primarily attractive to those who currently use public transport only occasionally and therefore hold a Half-Fare card.

Tab. 51 *Results of the aRP travel card ownership model*

		Full Model		Simplified model	
		Estim.	rob. s.e.	Estim.	rob s.e.
No aRP travel card	Constant	0	-	0	-
aRP travel card 25%	Constant	-0.434	-1.799	-0.514	-1.897
	Price level: medium	0.155	0.624	0.155	0.624
	Half-fare card	0.629	2.281	0.628	2.278
	Spatial type core city	-0.489	-1.644	-0.509	-1.690
	Regional travel card	-1.652	-2.945	-1.648	-2.950
aRP travel card 50%	Constant	-1.012	-2.721	-0.468	-1.740
	Price level: medium	-0.820	-3.106	-0.751	-2.963
	Price level: high	-1.913	-2.730	-1.696	-2.623
	Half-fare card	0.451	1.597	0.636	2.376
	PT service quality C	0.666	2.273	0.543	1.978
	Private AV chosen	0.740	2.158	-	-
	Repeated leisure trip by car	-0.504	-1.722	-	-
	Innovation Mobility Services partly/much/very much	0.654	2.384	-	-
	Innovation electric vehicle partly/much/very much	0.548	1.891	-	-
aRP travel card 100%	Constant	0.065	0.067	1.198	1.626
	Price level: medium	-0.547	-0.827	-0.870	-1.460
	Price level: high	-0.914	-1.410	-0.968	-1.696
	GA	-2.621	-2.606	-1.353	-1.915
	Regional travel card	-2.182	-2.100	-1.013	-1.421
	Repeated leisure trip by PT	1.119	2.070	-	-
	Innovation electric vehicle: partly/much/very much	1.995	3.157	-	-
	Adjusted ρ^2	0.413		0.398	
	n	667		667	

Conclusion The experiment shows that a significant share of respondents is willing to purchase aRP discount cards, which can be interpreted as a general willingness to use aRP frequently. The offer is particularly attractive to individuals who currently use a Half-Fare card, live in areas with medium public transport service quality, and are more open to mobility innovations compared to the general population. However, individuals who currently use a regional travel card or a GA (frequent public transport users) show lower interest in aRP discount cards. They find aRP services comparatively less attractive and, therefore, have a lower intention to purchase such discount cards.

Due to the limited sample size and the rather abstract concept of the aRP discount card, caution is required when interpreting the results and generalising the findings. To deter-

mine if an aRP discount card is economically viable, a respondent must evaluate both the cost and frequency of their intended aRP trips. This allows them to compare the potential savings from the discount card against its purchase cost. Such comparison is a cognitive demanding task including also uncertainties with regards to personal travel demand and the attractiveness of alternative modes. Since this choice experiment was presented at the end of the questionnaire, it is likely that most respondents did not meticulously evaluate the costs and benefits of the aRP discount card. Instead, they likely answered the question based on a general consideration of how frequently they would use aRP as a travel mode if it were available.

In addition, the willingess to buy such a discount card might have been influenced by the prices for aRP but also alternative modes in the prior mode choice experiments and the service quality of alternative modes for frequently visited destinations. Due to the random design of the mode choice experiment, the first factor is likely to be of minor importance. But the second factor has not been tested and might provide further explanatory power.

Additionally, the willingness to buy such a discount card might have been influenced by the prices for aRP and alternative modes in the prior mode choice experiments, as well as by the service quality of alternative modes for frequently visited destinations. However, due to the random design of the mode choice experiment, the influence of the first factor is likely to be minor. The second factor, though not tested due to time constraints, might offer further explanatory power.

The results must also be interpreted with the cost ranges considered for aRP in the mode choice experiment. As indicated in Tab. 33, aRP cost were based on the assumption of a base fare of 2 CHF and distance-based fare between 0.3 and 0.5 CHF/km.

4.8.5 Attitudes

In the last section of the questionnaire, respondents were asked to compare aRP with conventional public transport and cars across various criteria. The idea behind this question was to identify the perceived advantages and disadvantages of aRP relative to these other modes of transportation.

Fig. 16 indicates to what extent the respondents agree the various statement how aRP compares in their opinion with public transport and car. While aRP is generally considered as eco-friendly as public transport, the majority of respondents view traveling by aRP as more eco-friendly than traveling by car.

In terms of travel time, the general expectation is that aRP is somewhat faster than public transport but considerably slower than traveling by car. The same applies to comfort, although the advantage of traveling by car is seen as less pronounced than in the case of travel time.

In terms of cost, respondents generally view aRP as more economical than traveling by car but less so compared to public transport. While data privacy is not a major concern for most respondents, about one-third are worried that their data might fall into the wrong hands when using aRP.

Regarding safety, nearly half of the respondents perceive no difference between aRP and either public transport or cars. However, a slightly larger proportion of respondents view aRP as less safe compared to public transport or cars, rather than as safer.

Only one in four respondents views reduced disturbances from other passengers as an advantage of aRP compared to public transport. It seems that the lower number of passengers in smaller aRP vehicles enhances their appeal to only a limited audience. Conversely, the potential for disturbances from other passengers in aRP vehicles is a factor that, for nearly half of the respondents, distinguishes aRP from cars.

Overall, aRP is considered a better alternative to cars in environmental terms and cost but falls short in terms of potential disturbances by other passengers. In comparison to public

transport aRP is generally considered to be more favorable with regards to travel time and comfort but falls short in terms of cost and data privacy.

Although incorporating latent variables into the choice model could offer insights into how these attitudes influence observed choice behavior, we have opted not to pursue this approach due to time constraints within the scope of this project. We recommend exploring this avenue in future studies to gain a deeper understanding.

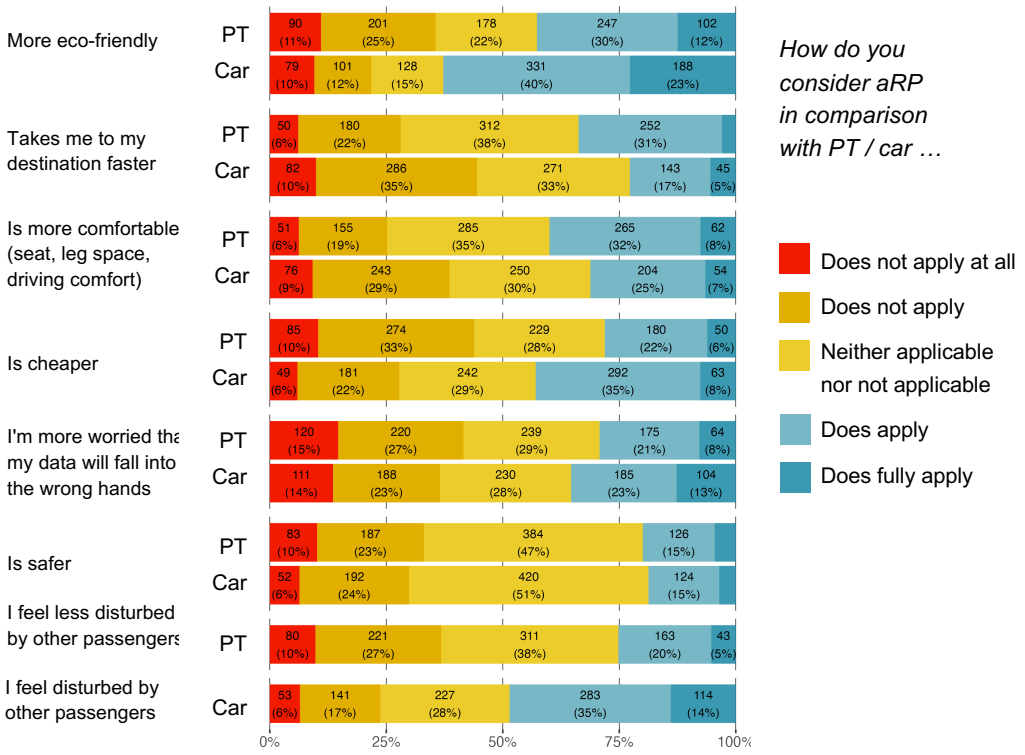


Fig. 16 *Attitudes towards aRP compared to car and public transport*

4.9 Discussion

Interpretation of the results The mode choice experiment indicates that both aRP and aRH have the potential to replace trips currently taken by public transport or car. However, the negative constants associated with these alternatives reveal a strong tendency among respondents to stick with their current modes for both utilitarian and leisure trips. This inertia is somewhat reduced among respondents who view themselves as more open to new mobility options, such as car sharing or electric vehicles, compared to the general population. While it is reasonable to expect that a similar shift in attitude will gradually affect the broader population as new modes become more established, it is challenging to predict the extent to which the inertia effect will diminish over time as aRH and aRP become more commonly used transport modes. Therefore, we suggest for the case studies to assume that the entire population assesses aRH and aRP as those respondents who view themselves as more open to new mobility options, but not to adjust the mode-specific constants. As a result, the mode shares of aRH and aRP computed in the case studies will represent the lower end of the expected demand range.

For both aRH and aRP, the alternative-specific constants are less negative when these modes are used as feeder services to public transport, indicating a higher willingness to use them for intermodal trips. Environmental considerations might be one reason why the intermodal use of aRH or aRP is evaluated more favorably, as such usage results in lower additional mileage and hence lower impact on the transport systems. However, to simplify the experiment, none of the choice scenarios included both monomodal and intermodal

options. Therefore, future studies will need to verify the direct trade-offs between these alternatives.

The value of time (VOT) indicators for aRP and aRH derived from the mode choice model align intuitively with expectations. Specifically, in-vehicle travel time is perceived as more burdensome for aRP compared to public transport, resulting in a higher VOT for aRP. This is likely because the larger public transport vehicles are perceived to offer greater riding comfort than the smaller aRP minibuses. Furthermore, the attitude survey indicated that aRP is generally not viewed as superior to public transport with regards to potential disturbances from other passengers, meaning it cannot offset the lower comfort associated with the smaller vehicles.

The higher value of time (VOT) for aRH compared to a car can be attributed to the reduced comfort associated with aRH. Though comparable with regards to the ability to travel alone, the perceived comfort when traveling with a private car is considered higher, as it offers a more personal space and an environment which can be tailored to personal needs which enhances the overall travel experience.

The car ownership experiment reveals that the widespread availability of aRH and aRP would encourage about 20% of current car owners to relinquish their vehicles. Among those who choose to retain a private car, one-third would prefer a vehicle with autonomous driving capabilities. Conversely, only about 10% of individuals who currently do not own a car would opt for an autonomous vehicle. Overall, this would lead to a decline in the number of privately owned vehicles. This finding contrasts with Hörl *et al.* (2019b), which observed that car ownership rates would remain constant if autonomous cars were available for purchase by the general public. However, their study had a smaller sample size and was limited to residents of the canton of Zurich. Additionally, approximately half of their car-owning respondents indicated a preference for purchasing an autonomous vehicle, which may reflect a more innovation-oriented audience. Generally, we can derive that a majority of the population still intends to own private vehicles even if aRH and aRP services will be readily available.

Almost half of the respondents who currently do not hold any public transport travel card indicated a willingness to purchase an aRP discount card that grants fare reductions of either 25% or 50%. This suggests that people who rarely use public transport see aRP as a viable alternative to their car for frequent trips. Interest in purchasing such discount cards is less pronounced among those who already hold a public transport travel card. However, depending on the assumed price level, about one-third of these respondents would still consider purchasing a discount card if aRP were readily available. Given the uncertainties regarding the actual reliability and availability of aRP services at different times of day and in various areas, as well as the actual user costs, these results should be interpreted with caution. Consequently, we do not recommend applying the related discount card ownership model for case study applications. Nevertheless, it is evident that offering such discount cards could be beneficial for aRP operators as a way to reduce marginal usage costs and increase ridership.

Limitations and future research To keep the choice experiment simple, we did not include scenarios where respondents had to choose between using aRP or aRH as a direct mode versus a feeder mode for accessing public transport. Additionally, we designed the experiment so that aRP and aRH as direct modes were only options for shorter trips, with most trip distances being less than 20km. It is expected that intermodal trips would generally appear more attractive for longer journeys due to lower travel time perception and lower marginal distance costs in public transport. However, depending on actual operating cost of aRP (which might differ depending of time of day) and the prevalence of aRP travel cards, aRP as a direct mode might also be appealing for longer trips. Therefore, we recommend that future studies include experiment designs that consider aRP as both a direct and feeder mode within the same choice situation, using a wide range of prices to obtain more comprehensive results.

The strongly negative mode-specific constants associated with the new mode alternatives aRH and aRP indicate a high a priori reluctance to choose these modes. While general openness to new mobility options mitigates this reluctance, it does not eliminate it completely. Given that none of the respondents had prior experience using aRP or aRH, it is unclear to what extent this reluctance is due to unfamiliarity with the modes versus actual differences from existing modes, such as the need to order a ride, uncertainty regarding arrival times, the prospect of spending time with unknown persons, and complete reliance on technology while driving. To address this issue, it would be valuable to conduct a similar survey with individuals who have already used shared autonomous vehicles to determine whether and to what extent these reservations persist.

The fact that some variables describing the choice situations, such as the number of additional passengers in aRP and the type of pick-up point, did not turn out to be statistically significant suggests these factors may not be crucial for mode decisions. However, it could also indicate that the choice experiment was too demanding for respondents. Therefore, we recommend future research to employ a modular experimental design approach, which limits the number of variables presented in each choice situation while using a different set of variables for different situations or respondents.

It is currently unclear whether and how aRP and aRH services would be integrated into the public transport system. For instance, depending on the time of day and location, it might be beneficial to allow fare integration of aRP when used as a feeder mode, or even as a direct mode, if this enables the discontinuation of low-demand public transport lines. Additionally, it is likely that profit-maximizing aRP operators would implement dynamic pricing strategies based on supply and demand. Given this complex environment, we recommend that future research evaluate customer needs and acceptance regarding fare integration and discount cards through qualitative methods. This approach would help in designing an effective and more realistic travel card choice experiment.

5 MATSim integration

This study required a simulation of autonomous ridehailing and ridepooling services, which can be used independently for direct trips or as a public transport feeder. To implement this requirement, the MATSim simulation framework had to be extended in three ways:

1. Enable MATSim to simulate autonomous ridehailing (aRH) and ridepooling (aRP) service
2. Add a mode choice capability using MATSim's discrete mode choice extension
3. Implement an option to use aRH and aRP as feeder modes for public transit

5.1 Integrating aRH and aRP in MATSim

Two distinct approaches were considered for simulating aRH and aRP operations within the MATSim framework. The first approach uses the Demand Responsive Transport (DRT) extension of MATSim (**?**). The DRT module facilitates the simulation of dynamic shared mobility services by managing the routing of vehicles and the assignment of passengers based on pre-defined parameters and optimization strategies within the module. In this approach, the existing dispatching algorithms in MATSim can be used, while we also explored the potential integration of external algorithms through an API, which is detailed in section 6. The second approach uses an external simulator for aRH and aRP fleets, allowing easier integration and testing of new dispatching algorithms. However, this approach was abandoned as proper integration with public transport was not feasible.

5.1.1 MATSim's DRT Module

DRT module is an extension of MATSim's Dynamic Vehicle Routing Problem (DVRP) module. It models shared mobility by dynamically assigning vehicle routes in response to user

requests. The DRT optimizer and dispatcher, core components of this module, account for factors such as vehicle locations, service times, and ride-sharing constraints to generate efficient routing plans. It mirrors how such services operate in real life. When a request is received, the dispatcher is presented with a list of available vehicles. To efficiently handle the requests, the dispatcher algorithm iterates through the list and assigns each request to the nearest vehicle. However, it also takes into account predefined constraints to ensure passenger satisfaction. These constraints include:

1. Limiting overall travel time: The dispatcher ensures that the total travel time for passengers, including those already in the vehicle, those waiting for the vehicle, and the new customer, does not exceed predefined thresholds. This helps maintain a reasonable and efficient travel experience for all passengers.

2. Managing boarding times: The dispatcher considers the expected boarding times for customers waiting for the vehicle and the new customer. It ensures that the boarding times fall within the requested time frame, allowing for a smooth and timely pickup process.

The request is rejected if no suitable vehicle is available to accommodate a request while adhering to the predefined constraints.

5.1.2 Consideration of an external dispatching algorithm

There are two possible methods of integrating the external dispatcher into MATSim. An online approach that involves the creation of an Application Programming Interface (API) for the new dispatching algorithm. This API would be integrated directly with MATSim's DVRP module, effectively replacing the standard DRT optimizer. Here, ride requests are dispatched in real-time, with batches of trip data being sent to the external dispatcher following each replanning phase in MATSim. The dispatcher then assigns passengers to vehicles and dictates vehicle routing, with the instructions sent back to MATSim via the API. The second method is to decouple the dispatching process from MATSim's real-time simulation, an offline approach. Here, during the simulation of trips in an iteration, all ridesharing trips are "teleported," abstracting the actual movement through the network. Post-simulation, the accumulated trip data is processed by the external dispatching algorithm. The resulting travel times, routes, and assignments can then be used to update agents' plans for subsequent iterations.

Several tradeoffs are worth mentioning. The DRT module offers a streamlined integration with the MATSim framework, taking advantage of the existing infrastructure for network, demand modeling, and schedule planning. The inherent optimization algorithms are also well-tested, ensuring reliability and efficiency in simulating ridehailing services. Both the online and offline methodologies afford greater control over the dispatching logic. The online approach allows for dynamic interactions within the simulation environment, potentially leading to more accurate and responsive service modeling. However, it requires a robust API design and could introduce computational overhead. While less computationally demanding, the offline approach may sacrifice the nuanced interaction between agents and the transportation network, potentially affecting the fidelity of service representation. Nonetheless, it allows for complex post-processing of data without the constraints of real-time computation, which can benefit in-depth analyses. Finally, the online approach had to be abandoned due to the technical difficulties of integrating a MATLAB code base with MATSim. Therefore, we settled on using the existing and well-tested dispatching algorithm within the DRT module.

5.2 Mode choice

The surveys conducted to estimate a discrete mode choice model are essential in simulating the envisioned scenarios of future automated on-demand mobility services in Switzerland. Therefore, it is necessary to transfer the parameters from the model into MATSim. This can be achieved using the discrete mode choice (DMC) extension for MATSim (Hörl *et al.*, 2019). The DMC extension enables the integration of traditional mode choice models into MATSim's replanning phase. During this phase, MATSim's inherent scoring capability is deactivated and reconfigured to maintain a singular plan per agent. This approach effectively

transforms MATSim into a sophisticated traffic simulator that supplies detailed route and trip data, such as travel times, congestion levels, and waiting times from iteration to iteration. This information is then fed into the DMC module, where decisions are made based on the observed variability and tradeoffs reflected in the estimated choice model.

The DMC module considers the constraints of individual trips or tours and considers rules regarding mode availability. The DMC module is invoked with a certain probability during the replanning process for an agent, allowing the agent to update the transport modes for all the planned trips based on their specific situation and constraints. This process generates mode choice sets for each trip. To determine the utility of each alternative, utility functions derived from the survey conducted in this study are used to calculate the utility for each mode. Once the utilities are calculated, various selection methods can be employed to choose a mode.

This study uses a multinomial logit selector to obtain the sequence of transport modes used in each tour in the individudal's daily schedule.

5.3 Intermodal public transport

The public transport router in MATSim, based on the Raptor algorithm **?**, plays an important role in this study for routing intermodal public transport trips. In MATSim version 14.0 used in this study, the PT router facilitates public transport routing, considering various access and egress modes. The router determines the least-cost path based on travel time by evaluating all possible modes for accessing and egressing from the public transport service. For this study, the following parameters of access and egress modes are relevant:

- Search distance: This parameter represents the radius of a circle around origin and destination activities within which public transport stops are searched for access or egress.
- Maximum search distance: In cases where fewer than two stops are found within the search distance, the maximum search distance defines the maximum radius for searching public transport stops around the origin and destination activities.
- Search distance factor: This factor ensures that the access/egress modes are not used for much of the trip.
- DRT minimum search distance: This parameter sets the minimum distance at which DRT modes, in this study aRH and aRP, can be considered as an access or egress mode. Its purpose is to prevent these modes from replacing very short walking trips.

The search distance factor and DRT minimum search distance were implemented specifically for this project.

6 Matching algorithm

In the scope of the current project, we have designed a versatile real-time simulation framework for addressing the challenges of capacitated ridepooling. The key components of our framework include:

- Ridepooling Problem Formulation: We have formulated the ridepooling problem as a dynamic deterministic on-demand matching problem, considering tolerance times to enhance the efficiency of the system.
- Dynamic Congestion Implementation: To account for varying traffic conditions, we have incorporated dynamic congestion in our simulation by regularly updating link travel times throughout the simulation horizon.
- Online Optimization: Our framework solves the optimization problem in an online manner, utilizing a combination of heuristics and commercial solvers. This approach en-

sures timely decision-making and optimal resource allocation.

- Stakeholder Objectives and Policies: We have incorporated the multiple objectives of different stakeholders and designed policies that encourage the development of efficient and mutually beneficial solutions. This allows us to consider a holistic approach that accommodates the diverse needs of all parties involved.

- Overall, our modular real-time simulation framework offers a comprehensive solution for addressing the capacitated ridepooling problem, considering real-world dynamics and stakeholders' objectives.

A complete explanation of the algorithm and the components are provided in the following publication: Ghandeharioun, Z. & Kouvelas, A. (2023). Real-time ridesharing operations for on-demand capacitated systems considering dynamic travel time information. Transportation Research Part C: Emerging Technologies, 151, 104115. (Ghandeharioun and Kouvelas, 2023)

We evaluated the effectiveness of our approach using real-world data and conducted experiments to measure the trade-offs between fleet size, total travel time, distance, waiting time, and passengers' delay. To create a more realistic representation of changing congestion patterns, we incorporated dynamic link travel times into our analysis. Additionally, we explored different objective functions to examine how various operational policies affect service performance.

Our results indicate that with our proposed methodology, it is possible to accommodate 97% of taxi rides in Manhattan using only 2,000 taxis capable of carrying up to 5 passengers each, instead of the current 13,000 taxis. These 2,000 taxis can achieve an average pick-up waiting time of less than 2 minutes and an average in-car delay of fewer than 7 minutes. These findings were obtained based on a scenario where the maximum delay time to pick-up a passenger was set to 5 minutes and maximum detour time to 15 minutes. By implementing these changes, we can significantly improve the traffic situation in the network by reducing the number of cruising taxis.

During periods of high demand, we observed high vehicle occupancy, and a smaller fleet size coupled with longer waiting times and in-car delays increased the potential for ridepooling. High-capacity ridepooling services achieved a service acceptance rate ranging from 80% to 98%. However, the fleet size played a crucial role in minimizing the distance traveled by each vehicle. Overall, our research demonstrates that implementing capacitated ridepooling services, optimized in real-time using dynamic data and feedback, can greatly enhance urban transportation systems.

It is important to note that system parameters such as fleet size, pre-specified tolerance times, and service requirements tailored to demand patterns have a significant impact on the quality of the service provided.

Integrating the new algorithm into MATSim, a well-established transportation simulation framework, would be a laborious task that could significantly increase computation time. However, upon careful evaluation, it becomes apparent that the potential contribution of this integration to the core research questions of the current project may be limited. As a result, we decided against pursuing the integration and instead propose allocating additional time for exploring policy scenarios.

MATSim already provides a robust platform for conducting transportation research, offering a wide range of functionalities and established methodologies. The integration of a new algorithm, although potentially beneficial, would require extensive modifications and rigorous testing to ensure compatibility and stability. This process could consume valuable time and resources, diverting attention away from the core research questions at hand.

The integration of the new algorithm in the current work does not yield significant efficiency gains when compared to using the native algorithm of MATSim for answering the research

question. While the new algorithm may bring some operational improvements, these gains are relatively minor. Alternatively, an effective way to achieve similar effects is by simply reducing the ride-pooling fares within the native MATSim algorithm.

Furthermore, it is important to consider the potential impact on computation time. MATSim simulations can already be computationally intensive, and integrating a new algorithm could exacerbate this issue. Longer computation times would not only hinder research efficiency but also impede the exploration of multiple policy scenarios within a given timeframe. Given the limited contribution of the algorithm integration to the core research questions, this trade-off becomes less favorable.

In conclusion, while integrating the new algorithm into MATSim may appear attractive at first glance, the laborious nature of the task and the potential increase in computation time suggest that the benefits may not outweigh the costs. Therefore, we decided to allocate additional time to delve deeper into policy scenarios.

7 Case studies

The objective of the case studies is the evaluate which mode share can be expected for on-demand ride-pooling service depending on location and policy measures. To this end, case studies are simulated in three different regions that differ with regards to their spatial character and therefore the potential of ride-pooling service to pool travel demand. The same type of pull and push policy measures are applied to all case studies to understand potential differences with regards to their objective to increase pooling rates, lower travel times and limit traffic growth.

The objective of the case studies is to evaluate the expected mode share for on-demand ride-pooling services based on different locations and policy measures. To achieve this, simulations are conducted in three distinct regions, each with unique spatial characteristics that influence the potential for ride-pooling. The same type of pull and push policy measures are applied across all case studies to analyze how these measures affect pooling rates, travel times, and traffic growth. This approach aims to uncover potential variations in outcomes and identify which policies seem promising for optimising the effectiveness of ride-pooling within the transportation system.

7.1 Case study regions

Three 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 aRP and aRP is dependent on the spatial context. These include Chur, Fribourg, and Zurich. While all three 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 three 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. In the case of Fribourg, the covered area contains the city of Fribourg plus a 10km buffer. For Zurich, the study region contains the area of the city of Zurich plus a 5km buffer (see also Fig. 17, Fig. 18, and Fig. 19). Please refer to section 7.2.1 for details on how travel demand with origins or destinations outside the covered areas is dealt with in the case studies, while section 7.2.2 contains information on how the modelled travel demand differs between those regions. Information about how the simulation models have been calibrated is available in section 7.2.3.

7.2 Travel demand model

The travel demand model for these study regions is based on a synthesis process that generates synthetic population and travel demand patterns for an average workday in the whole of Switzerland. This process was developed by Tchervenkov *et al.* (2022) and relies

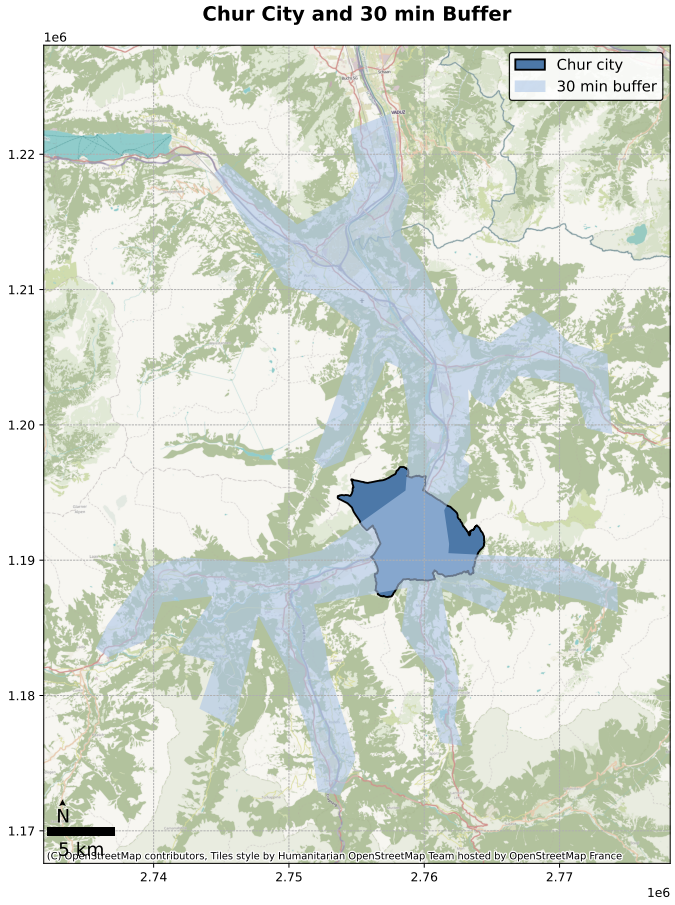


Fig. 17 *Chur case study region*

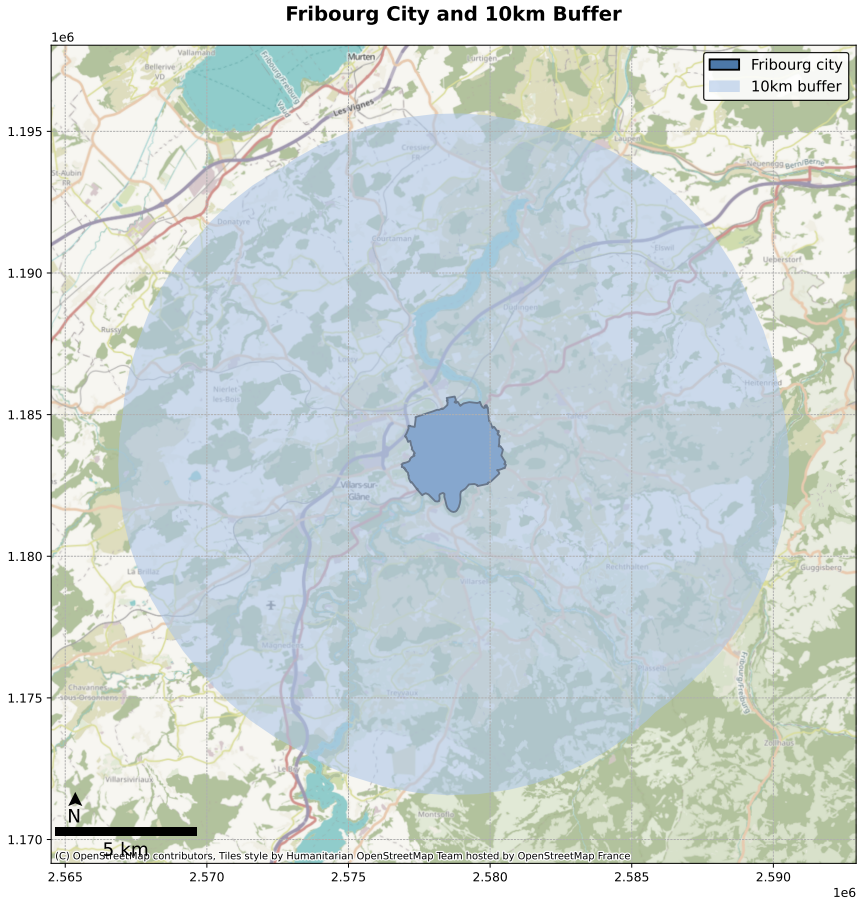


Fig. 18 *Fribourg case study region*

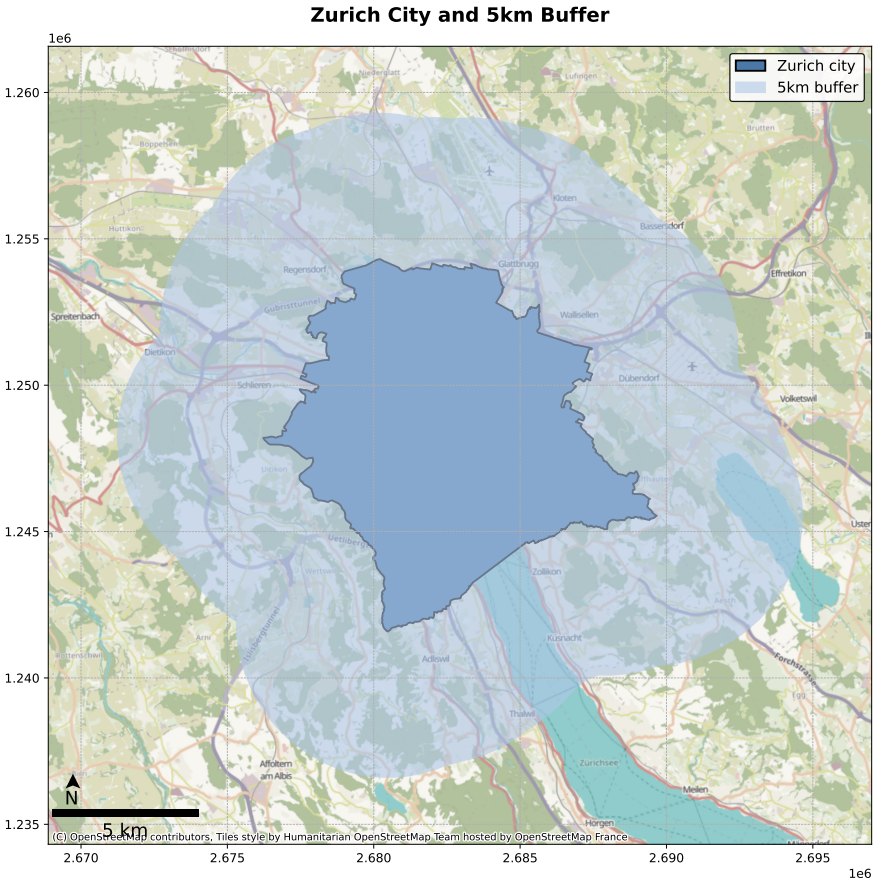


Fig. 19 *Zurich case study region*

on the *eqasim* framework - a pipeline for the generation of synthetic population and travel demand based on straightforward statistical methods and generally available datasets (Hörl and Balac, 2021). The eqasim pipeline considers various factors such as sociodemographics, mobility patterns, transport networks, and facilities specific to Switzerland to create a realistic representation of the population. It uses data from census records, travel surveys, OpenStreetMap, and HAFAS transit data (see Tab. 52 for detailed information on datasets used to create the Swiss travel demand model). The output of this process is a set of simulation files used by MATSim. These files include information on population, households, facilities, network, and transit schedules. The demand generation process involves the following:

- Generating agents for a synthetic population: A synthetic population that represents the population of Switzerland is created using data from the Swiss census.
- Enriching agent activity chains: The synthetic population is further enriched by assigning daily activity chains to each agent. This information is obtained from the national travel survey (Microcensus) data and includes details such as start and end times, travel distances, and modes of transport.
- Assigning locations for primary activities: Agents in the synthetic population are assigned specific locations for primary activities such as home, work, and education. Home locations are assigned based on the raw census information, while the structural survey is used to assign work and education locations based on the observed commuting flows and residential locations.
- Assigning locations for secondary activities: In addition to primary activities, secondary activities are also assigned locations. The locations are determined to maintain the distance distributions observed in the Mikrozensus. The methodology is explained in detail in Hörl and Axhausen (2023).
- Validating the synthetic population: To ensure the accuracy of the generated synthetic population, the next step is to compare the patterns and distributions of its activity chains, distances, and social demographics to the Microcensus data. This validation step helps ensure the reliability of the synthetic population and is documented in (Hörl and Balac, 2021; Hörl *et al.*, 2019b).
- Generating other MATSim scenario elements: Apart from the population, additional scenario elements required by MATSim are generated. These include facilities, transport network data, public transit schedules, and vehicles.

7.2.1 Population cutting

This study focuses on specific regions within Switzerland to analyze the population's travel behaviour. We used a process called "scenario cutting" described in (Hörl, 2020) to obtain the studied regions from a larger Switzerland model. This cutting process considers interactions with the surrounding areas and filters agents at the correct points in time and space. Agents who performed at least one activity within the region and those involved in through traffic are preserved. Whenever an agent entered or left the region, a distinct outside activity marked this event. For example, if an agent's activity chain was (home, work, home) but the workplace was outside of the study area, it would look like (home, outside, outside, home) after cutting the trips. The mode of transportation between the two outside activities was labeled as an "outside mode," which is teleported in a way to ensure the correct activity timings.

To ensure consistency in the simulation, all elements of the scenarios, including plans, network, public transport schedules, and facilities, were adjusted accordingly.

Fig. 20 shows an example of cutting for Zurich, where a buffer around the city was defined. There are three types of trips: Type 1 trips are within the region, Type 2 trips are incoming and outgoing trips where the mode of transport within the region is preserved, and Type 3

Tab. 52 *Datasets for Switzerland travel demand generation*

Data	Year	Access	Source
Microcensus (HTS)	2015	Licensed	BfS
STATPOP (Census)	2012	Licensed	BfS
STATENT (structural business statistics)	2014	Licensed	BfS
Structural Survey	2010, 2011, 2012	Licensed	BfS
Municipality Borders	2008 - 2018	Open	BfS
Statistical Quarters	2017	Open	BfS
Municipality Type	2014	Open	BfS
Spatial Structure	2018	Open	FSO
ARE Gemeindetypologie	2019	Open	ARE
NUTS	2003, 2006, 2010, 2013, 2016	Open	Eurostat
Postal Codes	2019	Open	Swisstopo
Country Codes	2018	Open	BfS
ÖV Güteklasse	2018	Open	ARE
Projections	2019	Open	BfS
Freight GTE	2017	Licensed	BfS
Freight GQGV	2014	Licensed	BfS
Freight Departure Times	2008	Open	Gueterlogistik [a]
Freight Projections	2019	Open	BfS

[a] Fig. 4.10, p.47 in Anforderungen der Gueterlogistik an die Netzinfrastruktur und die langfristige Netzentwicklung in der Schweiz (2014)

trips are trips passing through the region. For Type 3 trips, the trip was divided into inside and outside, with the legs of the Type 3 trips outside the region being teleported.

We compared the number of trip crossings (Type 2 trips) across different buffer distances to determine the appropriate buffer distance from the city boundary for each region. For Zurich and Fribourg, we compared buffer distances of 5km, 10km, and 15km, and for Chur, we used isochrones (lines connecting points with the same travel time) instead of distances to match the topography better. Based on the results of these comparisons, we chose a distance of 5km for Zurich, 10km for Fribourg, and a travel time of 30 minutes for Chur (see also Tab. 53, Tab. 54, and Tab. 55).

Tab. 53 *Zurich crossing shares*

Mode	Crossings	5km	10km	15km
All	Total trips in million	4.35	4.77	6.38
PT	outside -> inside	5%	4%	3%
	inside -> outside	5%	4%	3%
Car	outside -> inside	4%	3%	3%
	inside -> outside	4%	3%	3%
Other	outside -> inside	3%	3%	2%
	inside -> outside	3%	3%	2%
All	Total crossing shares	24%	20%	16%
All	outside -> outside	19%	11%	10%

7.2.2 Travel behaviour parameters

This study uses a discrete mode choice model to simulate the population's behavior, particularly how people choose their transport modes. The eqasim framework, which combines a discrete model choice (DMC) extension with the microsimulation in MATSim, is employed to simulate agents' mode choice decisions.

The mode choice model in this study is based on the multinomial logit model presented in section 4.8. The model includes transport modes such as car, private AV (PAV), public transport (PT), walk, bike, aRH, and aRP modes. PAVs are treated similarly to cars but with a travel time reduction multiplier of 0.65. This value was inspired based on results from a field study in California (Harb *et al.*, 2022): when individuals were driven by a chauffeur

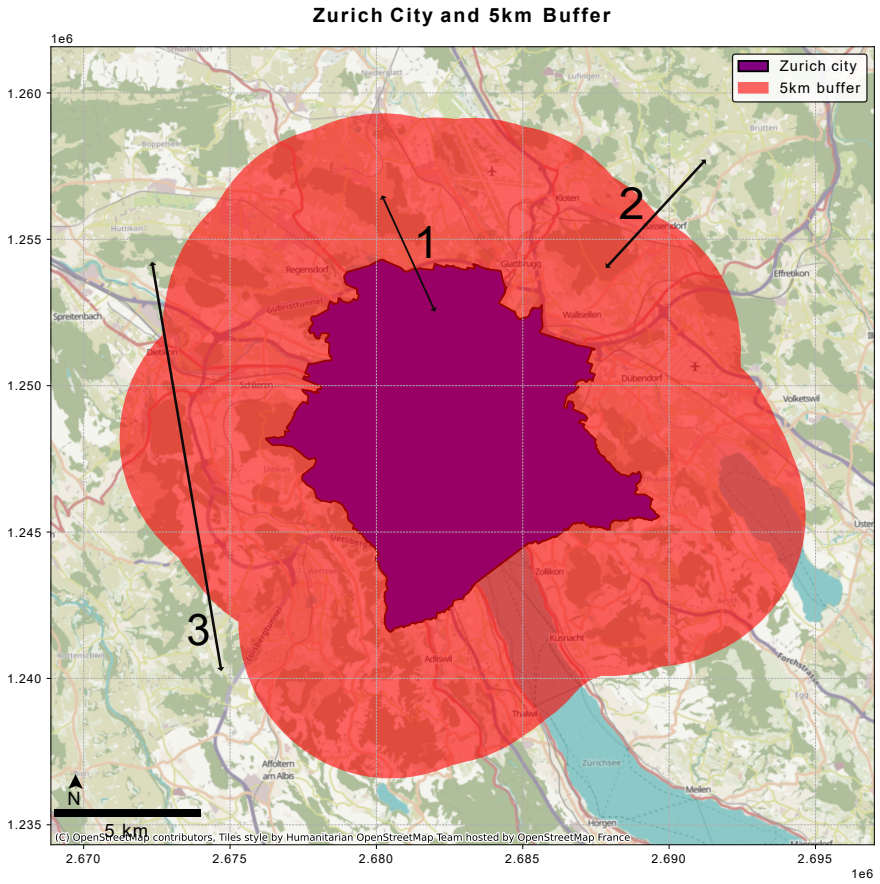


Fig. 20 *Schema representing cutting cases.*

Tab. 54 *Fribourg crossing shares*

Mode	Crossings	5km	10km	15km
All	Total trips in million	0.641	0.807	1.16
PT	0utside -> inside	5%	4%	4%
	inside -> outside	5%	4%	4%
Car	outside -> inside	4%	4%	4%
	inside -> outside	4%	4%	4%
Other	outside -> inside	4%	4%	4%
	inside -> outside	4%	4%	4%
All	Total crossing shares	26%	24%	24%
All	outside -> outside	28%	19%	21%

Tab. 55 *Chur crossing shares*

Mode	Crossings	5km	10km	15km
All	Total trips in million	0.403	0.489	0.692
PT	outside -> inside	4%	3%	3%
	inside -> outside	4%	3%	3%
Car	outside -> inside	3%	3%	3%
	inside -> outside	3%	3%	3%
Other	outside -> inside	4%	4%	4%
	inside -> outside	4%	4%	4%
All	Total crossing shares	22%	20%	20%
All	outside -> outside	27%	28%	21%

instead of driving themselves, the mileage of trips longer than 20 miles increased by 45%. At this trip length, perceived travel time becomes the most important element of generalized cost.

The mode choice model also accounts for various access methods to public transport, including walking as well as intermodal trips using autonomous ride-hailing (aRH), and autonomous ride-pooling (aRP) as access and/or egress mode.

The parameter values are listed in Tab. 56. The parameters for work and leisure trips are based on the model results presented in Tab. 49. For shopping and other trip purpose, the parameter values are derived by taking the ratio of the corresponding value of time for the different modes from the Swiss cost-benefit norm VSS (2009). For example, for shopping the VOT for car trips is 34% less than for commuting. Hence, the in-vehicle travel time parameter for shopping was reduced by 34% compared to commuting. For parameters where this approach is not applicable, the same values were used for all trip purposes.

The constants for aRP and aRH are based on the sum of the constant and the innovation parameter as indicated in Tab. 49. This method ensures that the constant reflects a future situation where the entire population is as willing to use aRH and aRP as those who indicated in the survey to be more likely to test new mobility services compared to the general population.

For intermodal trips, we decided not to differentiate between the disutility of the different types of transfers (aRP,aRP to PT, and between PT). Since the constant of the intermodal alternatives already accounts for one transfer (between aRP/aRH and PT), but each transfer is scored in the MATSim utility function, we reduced for intermodal alternatives the constant's value by the disutility of one transfer. For intermodal trips with aRH, no statistically significant transfer parameter could be estimated. Here, we defined the transfer penalty as 15% lower than in the case of aRP to account for the higher arrival reliability if no additional passengers need to be picked-up or dropped of on the way.

Tab. 56 *Behavioral parameters employed in the case studies*

Mode	Parameter	commuting	leisure	shop	other
All modes	Cost	-0.096	-0.096	-0.096	-0.096
	λ cost-distance	-0.513	-0.513	-0.513	-0.513
Car	Constant	0.000	0.000	0.000	0.000
	In-vehicle travel time	-0.053	-0.043	-0.035	-0.039
	λ 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	-0.045	-0.028	-0.034	-0.040
	λ in-vehicle time-distance	-0.472	-0.472	-0.472	-0.472

Mode	Parameter	commuting	leisure	shop	other
	Transfer time	-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	-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	-0.043	-0.041	-0.041	-0.041
	λ in-vehicle time-distance	-0.181	-0.119	-0.119	-0.119
	Half-fare card	0.446	0.446	0.446	0.446
aRP+PT	constant (incl. innovation)	-0.690	-0.690	-0.690	-0.690
	In-vehicle time ridepooling	-0.043	-0.041	-0.041	-0.041
	In-vehicle time PT	-0.045	-0.028	-0.034	-0.040
	λ in-vehicle time-distance PT	-0.472	-0.472	-0.472	-0.472
	Additional PT transfer	-0.389	-0.389	-0.389	-0.389
	Half-fare card or travel card	0.407	0.407	0.407	0.407
aRP/aRP+PT	Response time	-0.024	-0.024	-0.024	-0.024
	Access / egress	-0.065	-0.065	-0.065	-0.065
aRH	Constant (incl. innovation)	-1.208	-1.208	-1.208	-1.208
	In-vehicle travel time	-0.057	-0.049	-0.049	-0.049
	λ 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
aRH + PT	Constant (incl. innovation)	-1.201	-1.201	-1.201	-1.201
	In-vehicle time ridehailing	-0.071	-0.076	-0.076	-0.076
	In-vehicle time PT	-0.045	-0.028	-0.034	-0.040
	λ in-vehicle time-distance PT	-0.472	-0.472	-0.472	-0.472
	Additional PT transfer	-0.332	-0.332	-0.332	-0.332
aRH/aRH+PT	waiting/response time	-0.023	-0.023	-0.023	-0.023
Bike	Constant	0.152	0.152	0.152	0.152
	Travel time	-0.352	-0.286	-0.232	-0.261
	λ in-vehicle time-distance	-0.800	-0.800	-0.800	-0.800
	high_age	-2.659	-2.659	-2.659	-2.659
On foot	constant	0.590	0.590	0.590	0.590
	travel time	-0.128	-0.105	-0.085	-0.095
	λ travel time time-distance	-0.267	-0.267	-0.267	-0.267
Reference	PT, car, aRP, aRH	28.4	30.3	30.0	30.0
distance [km]	Bike	4.0	4.0	4.0	4.0

$$u_{\text{walk,i}} = \alpha_{\text{walk,i}} + \beta_{\text{tt,walk,i}} \cdot tt_{\text{walk}} \cdot \xi^{TD}_{\text{walk,i}} \tag{43}$$

$$u_{\text{bike,i}} = \alpha_{\text{bike,i}} + \beta_{\text{tt,bike,i}} \cdot tt_{\text{bike}} \cdot \xi^{TD}_{\text{bike,i}} + \beta_{\text{age,bike,i}} \cdot (\text{age>=60}) \tag{44}$$

$$u_{\text{car,i}} = \alpha_{\text{car,i}} + \beta_{\text{tt,car,i}} \cdot_{\text{car}} \cdot \xi^{\text{TD}}_{\text{car,i}} \cdot \texttt{tt}_{\text{car}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{car}} \tag{45}$$

$$\begin{aligned} u_{\text{pt,i}} = \alpha_{\text{pt,i}} + \\ \beta_{\text{ivt,pt,i}} \cdot \xi^{TD}_{\text{pt,i}} \cdot ivt_{\text{pt}} + \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{pt}} + \\ \beta_{\text{tt,pt,i}} \cdot tt_{\text{pt}} + \beta_{\text{hw,pt,i}} \cdot hw_{\text{pt}} + \\ \beta_{\text{tr,pt,i}} \cdot ntr_{\text{pt}} + \beta_{\text{aet,pt,i}} \cdot aet_{\text{pt}} + \beta_{\text{quality,pt,i}} \end{aligned} \tag{46}$$

$$\begin{aligned} u_{\text{aRP,i}} = \alpha_{\text{aRP,i}} + \\ \beta_{\text{ivt,aRP,i}} \cdot \xi^{TD}_{\text{aRP,i}} \cdot ivt_{\text{aRP}} + \\ \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRP}} + \beta_{\text{rt,aRP,i}} \cdot rt_{\text{aRP}} + \\ \beta_{\text{aet,aRP,i}} \cdot aet_{\text{aRP}} \end{aligned} \tag{47}$$

$$\begin{aligned} u_{\text{aRH,i}} = \alpha_{\text{aRH,i}} + \\ \beta_{\text{ivt,aRH,i}} \cdot \xi^{TD}_{\text{aRH,i}} \cdot ivt_{\text{aRP}} + \\ \beta_{\text{cost}} \cdot \xi_{\text{CD}} \cdot cost_{\text{aRH}} + \beta_{\text{wt,aRH,i}} \cdot wt_{\text{aRH}} \end{aligned} \tag{48}$$

$$\xi^{TD}_{\text{i,j}} = \left(\frac{d}{\theta_{distance}}\right)^{\lambda_{TD,i,j}} \tag{49}$$

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

$$\xi^{CD}_{\text{i,j}} = \left(\frac{d}{\theta_{distance}}\right)^{\lambda_{CD,i,j}} \tag{50}$$

where $income$ is the household income and θ_{income} is the average income.

All mode choice models' attributes are obtained by looking up sociodemographic information or examining the agents' plans. Additionally, some attributes are calculated during the simulations. Travel times and costs are provided by the MATSim network router, which dynamically estimates them based on factors such as traffic, vehicle numbers, pricing, and departure time. For cars and PAVs, an additional penalty for parking search time and access/egress walk time of 4 minutes each is included. Wait times and delays for aRH and aRP services are computed according to the methods described in the following section.

Cost model: Different cost models for various transport modes were defined. For cars and PAVs, a distance-based cost approach was used. PT also has a distance-based cost, with a minimum price of 2.50 CHF. Additionally, PT subscriptions affect the cost. Individuals with a "Generalabo" (GA) subscription, which allows unlimited PT usage throughout Switzerland for a month or a year, incurred zero variable 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 modes, the cost comprises the base and distance fare, which were first calculated to ensure cost coverage and then adjusted in various scenarios.

Mode availability rules: Transport mode availability rules were set up to ensure that agents had appropriate mode options based on their sociodemographic or household characteristics. PT, aRH, aRP, and walk were always available to all agents. Agents without a driving license or whose households did not own a car could not use a car. Bike availability depended on whether the household owned a bike. PAV availability was determined by the household's possession of a PAV.

Trip and Tour constraints: A tour is a set of trips starting and ending at home. A tour constraint is applied to ensure that a person who takes a vehicle from home must also return it by the end of the tour. For aRH and aRP trips, a minimum distance limit of 250m was imposed. A shapefile constraint was added for aRP and aRH to ensure that these modes are only chosen for trips within the defined case study regions.

Wait time estimation for aRH and aRP: For realistic decision-making behavior, wait times and additional delays for aRH, and aRP service were estimated and integrated into the choice model. This was done by observing wait times and travel times per zone and time intervals throughout the day. This information was used to inform travellers about expected wait times or delays in their area and during specific times of the day, allowing them to make informed decisions about using the service. During each iteration of the mobility simulation, wait times and travel time information for agents using these services were tracked for each time interval and zone. The mean values were calculated based on all waiting times and delays experienced per zone and time segment. If no waiting was observed in a zone and time interval during a particular iteration, the value from the previous iteration was retained. If no previous value existed, a default wait time of 15 minutes was applied. This study used a square grid size of 850m and a wait time interval of 30 minutes. Travel time delays are aggregated by the time of day and distance. The time interval is set to 30 minutes and distance is divided into 1000 metres bins. The initial delay constraint of $1.3 * traveltime + 5minutes$ is considered when no value is observed. Using a moving window method, these values are smoothened to calculate the average values over every 5 iterations. For more details, please refer to Kagho (2023).

7.2.3 Baseline scenario and calibration

A baseline scenario is defined to represent the current state of the existing transport system. Each region's travel demand model was calibrated to validate the agents' travel behaviour. The primary objective of the initial calibration was to achieve modal shares that closely matched those observed in the HTS data used for validation. Additionally, the aim was to ensure a reasonable distribution of distances traveled per mode.

For the general mode choice calibration, the focus was on car, bike, walk, and PT since these modes are present in the HTS data used for validation. The ASCs for car, bike, and walk modes were adjusted while keeping the ASC for PT at zero, as it served as the reference. Additionally, the lambda value for calculating the elasticity of Euclidean distance on travel time was adjusted for some modes depending on the scenario. The calibration process was applied to trips that start and end within the study regions. Fig. 21, Fig. 22 and Fig. 23 illustrate the modal shares of the calibrated modes with distances segmented into 1km bins, providing insights into how the calibrated modes compare and distribute across different distance ranges. Tab. 57 presents the resulting calibrated parameters.

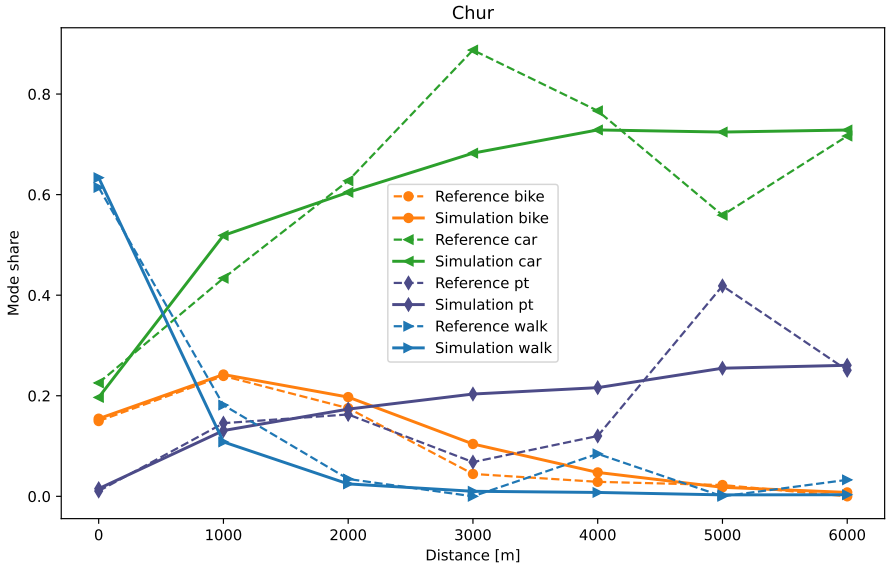


Fig. 21 *Validation of mode share by distance Chur*

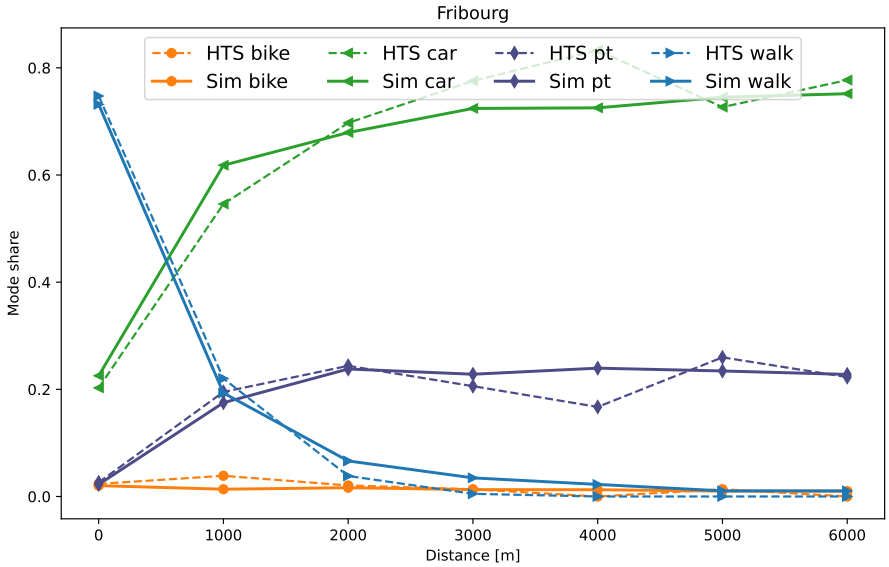


Fig. 22 *Validation of mode share by distance Fribourg*

Tab. 57 *Updated parameters*

	Original value	Chur	Fribourg	Zurich
$\beta_{\text{ASC,car}}$	0.0	0.262	−0.1014	1.7447
$\beta_{\text{ASC,bicycle}}$	0.152	0.9428	2.002	−0.0514
$\beta_{\text{ASC,walk}}$	0.590	3.1781	2.7525	2.0501
$\lambda_{\text{TravelTimeEuclideanDistance,bicycle}}$	−0.8	0.4	−0.3	0.35
$\lambda_{\text{TravelTimeEuclideanDistance,pt}}$	−0.472	−0.672	−0.772	

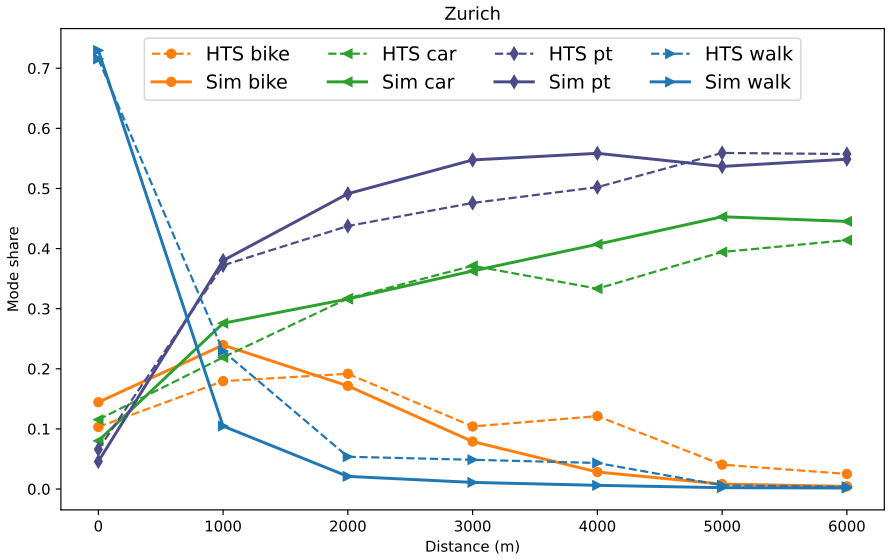


Fig. 23 *Validation of mode share by distance Zurich*

7.3 Intermodal configuration

Route choice: The route choice process is deterministic, meaning that a disutility value is calculated for each mode, and the mode with the least cost is selected for access and egress. In this process, different factors are considered to compute the disutilities for each mode.

The disutility of walking is based only on travel time. The longer the travel time, the higher the disutility associated with walking.

Travel time and cost are considered when calculating the disutilities for aRH (automated ride-hailing) and aRP (automated ride-pooling) services. The cost of using aRP is determined solely based on the per-distance fare to mimic a situation with public transport fare integration for aRP when using it as a feeder from or to a railway station. Additionally, the travel time aRP includes a detour time, estimated by adding a fixed multiplying factor of 1.2 to the direct travel time.

Below are the parameters configured for the intermodal access/egress mode, as defined in 5:

aRH and aRP

- Initial search radius = 3000 m
- Max radius = 10000 m
- Search extension = 2000 m

Walk

- Initial search radius = 1000 m
- Max radius = 2000 m
- Search extension = 200 m

Intermodal constraints

- Minimum distance = 500 m
- Distance factor = 0.3
- aRH and aRP only allowed as a feeder to/from rail connections

These values ensure that aRH and aRP do not compete with walking and should not be used for a large part of the intermodal PT trip, making the trips more sustainable.

7.4 aRH and aRP configurations

- Operating hours: The aRH and aRP operators operate 24 hours a day, providing door-to-door services
- Vehicle size: aRH and aRP vehicles are considered to use the road space more efficiently and, therefore, are configured with a PCU of 0.83 based on the ASTRA 2018/002 (Axhausen *et al.*, 2020).
- Passenger capacity: aRH vehicles can only pick up one passenger, while aRP vehicles can accommodate up to four passengers. Please note that the simulation does not account for individuals who travel in groups, e.g. families due to the lack of behavioral data.
- 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 modelled regions to anticipate the strong morning demand in those areas, with an assumption 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 up with demand.
- Fleet size: The fleet size for both operators is determined based on the scenarios tested and will be described later.
- Base fare: The base fare is set to 2.5 CHF independent on public transport card ownership. For intermodal trips, the base fare was set to 0. The idea behind this pricing scheme is to position aRP as an additional public transport service with an integrated pricing structure.
- Distance-based fare: Distance-based fares for aRH and aRP were determined based on the result of the fleet size optimization described in the next section (see Tab. 59).

7.5 Fleet sizing by cost coverage

Determining the right fleet size for aRH and aRP is a trade off between meeting demand and operational efficiency. It depends on regional factors and traveller behaviour, which are influenced by cost, travel time, and convenience. The pricing of on-demand services comes from vehicle operational costs and demand, with demand itself being a function of service pricing relative to wait and travel times. Therefore, it is essential to establish an optimal fleet size that balances high demand with affordability and reduced wait times.

Following the cost coverage model developed by Bösch *et al.* (2018) and adapted for the purposes of simulation by Hörl *et al.* (2020b), aRH and aRP service metrics are incorporated into a cost calculator within the simulation to determine customer pricing. For aRP, the goal is to cover operational costs, while for aRH, there is an additional target of achieving a 20% profit margin. These prices and factors like travel and wait times influence traveler decision-making in the simulation regarding whether to use the on-demand services.

After 25 iterations, the cost coverage model adjusts the per kilometer price to better reflect actual demand. Various fleet sizes are tested across different regions, considering that the number of aRH versus aRP vehicles can differentially affect service metrics. This prompted a detailed cost coverage simulation across a matrix of selected fleet sizes for specific re-

gions. For Chur, fleet sizes of 800, 1000, and 1200 were tested; for Fribourg, 1800, 2000, 2200, and 2400; and for Zurich, 1000, 1200, 1400, and 1600 for its 10% sample population. The outcomes from these simulations for the three regions are detailed in Fig. 24, Fig. 25, and Fig. 26, showing how fleet size influences the efficiency and operational costs of aRh and aRP services.

The figures show the relationship between fleet size and several key performance indicators (KPIs) for aRP and aRH in the three regions. From these graphs, looking at the aRP stats, one can immediately identify the peak in the number of aRP requests for different aRH fleets shown by the different colors in the legend, after which the demand decreases. Regardless of this peak in demand, as the fleet size increases, so does the fare, while the wait time decreases towards a diminishing return because more vehicles are available. To select a suitable fleet size for the scenarios in this study, there was a need to balance the demand for aRP and aRH while considering the waiting time.

For Chur, for example, a fleet size of 1000 would be optimal for aRP. This size seems to balance the demand (as it's at the peak before decreasing) and the operational cost (as indicated by the distance fare). Additionally, it ensures a lower waiting time, improving user convenience without significantly increasing the fare. While a fleet size of 1000 also seems ideal for aRH, 800 has been selected for scenario testing to provide an advantage over aRP. For the other regions, the selection decision was made in a similar way. For Zurich, the fleet size of 1400 and 1200 for aRP and aRH, respectively, was chosen (remember that this fleet is for a 10% population sample). For Fribourg, 2000 vehicles and 1800 vehicles for aRP and aRH, respectively to maximize the demand. While the ridepooling demand for Fribourg plateaus at a fleet size of 2200, an aRP fleet size of 2000 seems to provide sufficient coverage for the majority of travelers as it is also close to the plateau point, which means the demand can be met with fewer resources as the slight reduction in wait time and another service cost may not justify the additional 200 vehicles.

In all scenarios across pull and push measures are implemented to enhance the competitiveness of on-demand ride-pooling (aRP), leading to an anticipated increase in demand. Consequently, aRP fleet sizes were increased by 20% to accommodate this higher demand, while maintaining consistent fleet sizes across all scenarios within each region for comparative analysis.

Given a base fare of 2.50 CHF, the distance-based fare required to cover all operating costs for on-demand ride-pooling (aRP) is very low in all regions, and effectively zero for aRH. This finding must be interpreted within the context of the case study regions, where cost coverage is calculated at the fleet level rather than for individual trips. Due to the spatial limitations of these regions, short trips are predominant. For very short trips, the base fare of 2.50 CHF exceeds the actual operating costs, while for longer trips, the fare may not fully cover the costs, necessitating higher distance-based charges to ensure operational sustainability. Hence, it is reasonable to assume that a combination of base and distance fares would be applied in reality. Therefore, the price model applied in the scenarios foresees a combination of base and distance-based fares (see Section 7.6.2).

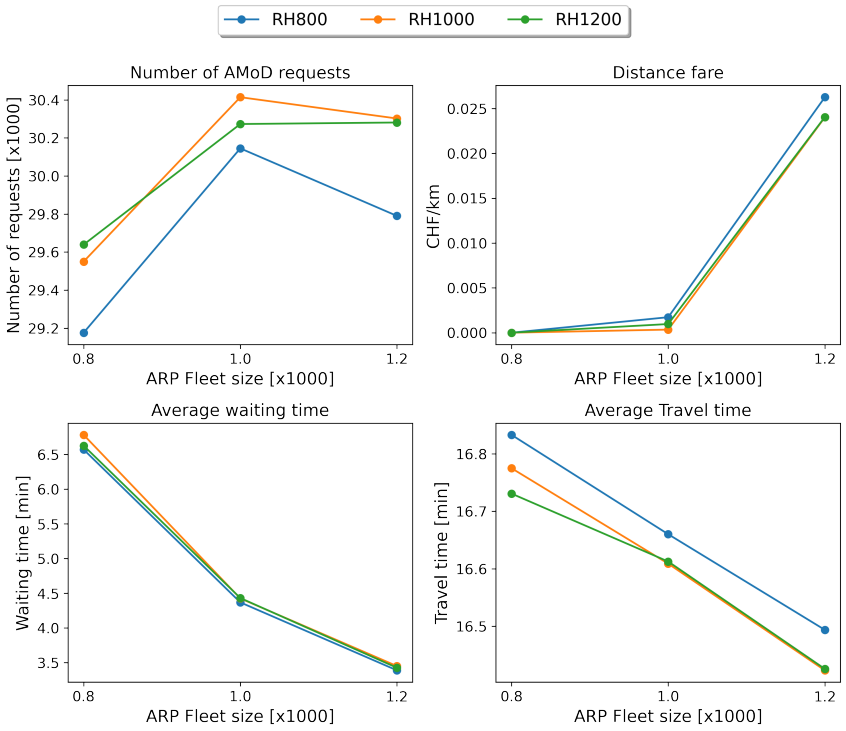
7.6 Policy scenarios

7.6.1 Mobility tool ownership

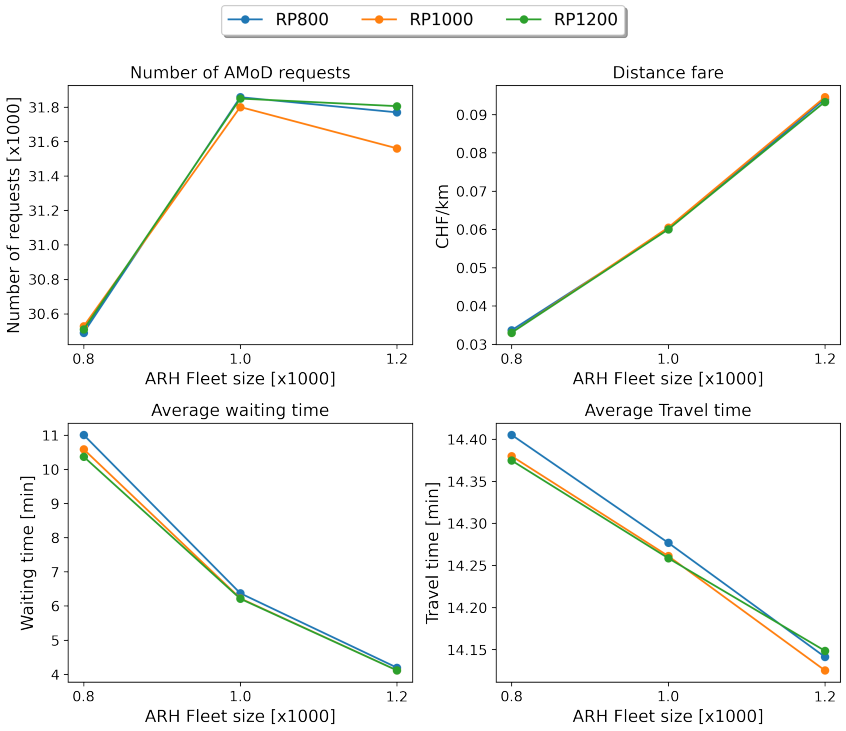
To describe a realistic future situation reflecting the results of the car ownership choice experiment, car ownership was adapted to fit the following control totals:

- 40.4% have a conventional car available,
- 24.2% have a private autonomous vehicle (PAV),
- 35.4% do not have a car available.

To this end, the likelihood of each of those three alternatives was computed for each car-holding individual who is of legal driving age and who lives within the studied region based

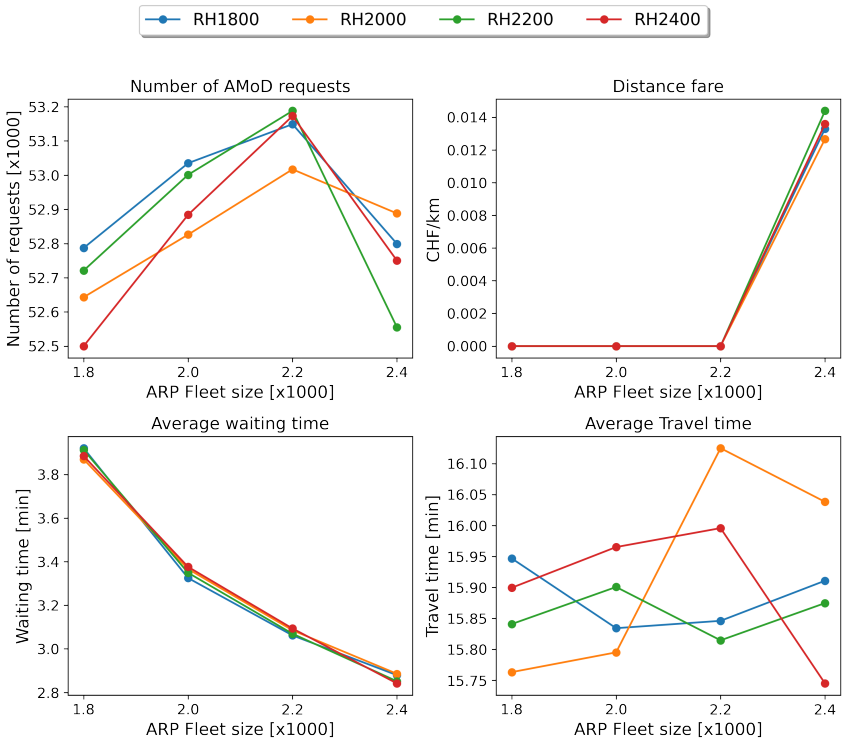


(a) *autonomous Ridepooling (aRP) stats*

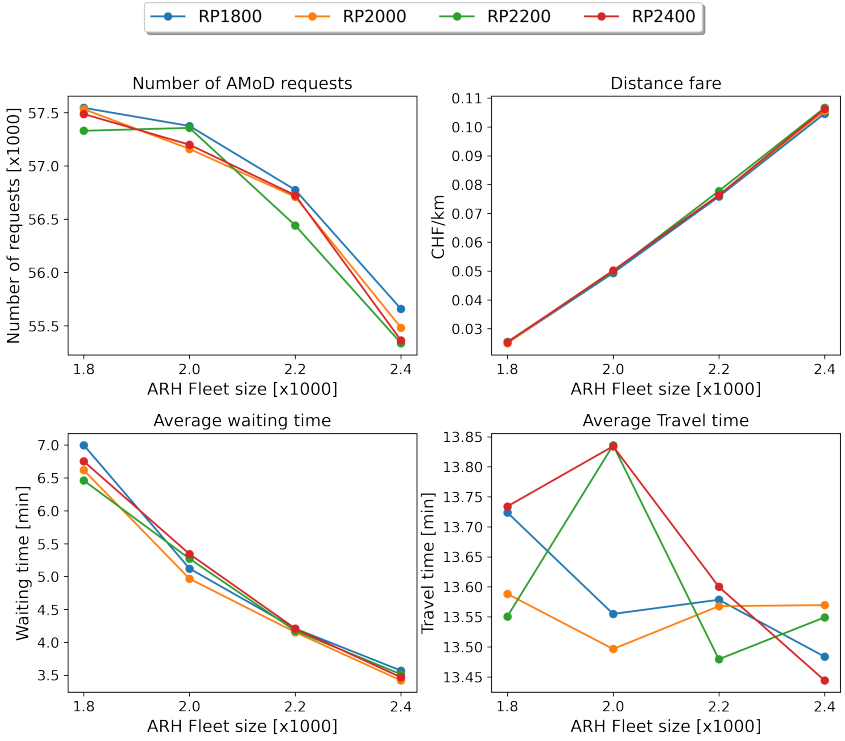


(b) *autonomous Ridehailing (aRH) stats*

Fig. 24 *Fleet sizing for Chur*

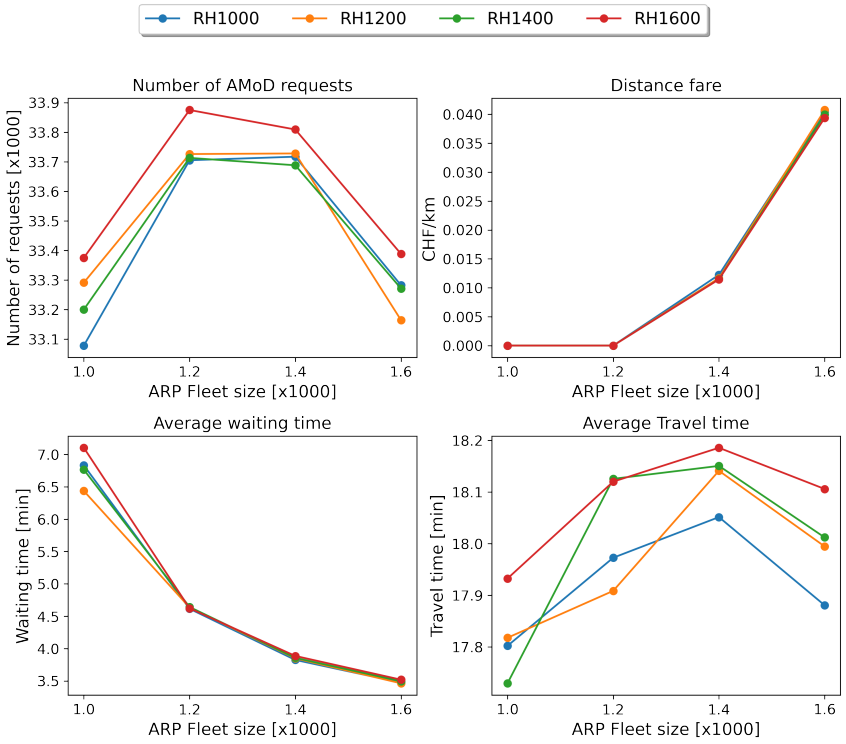


(a) *autonomous Ridepooling (aRP) stats*

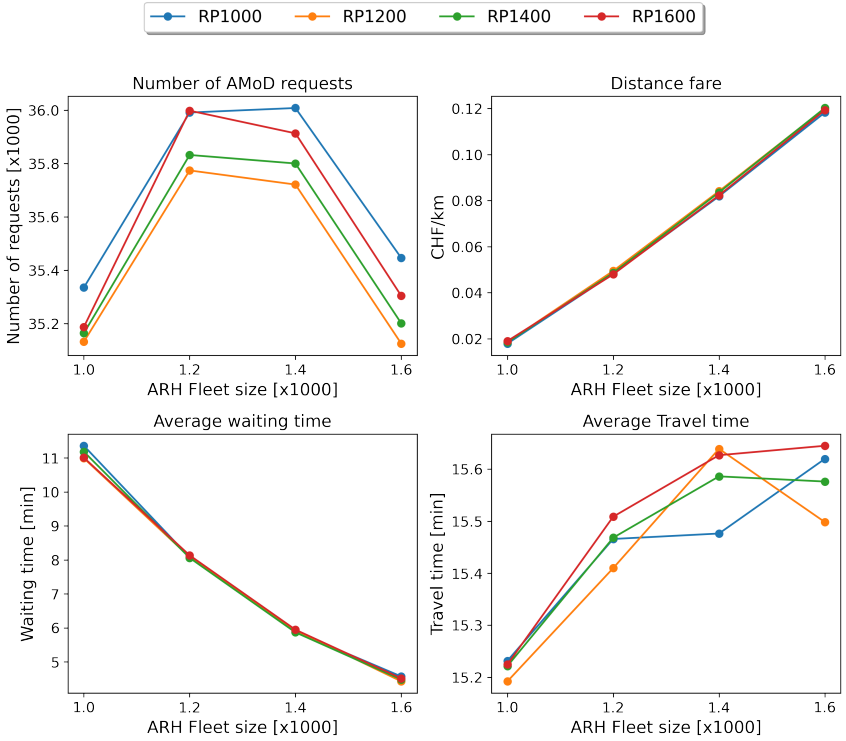


(b) *autonomous Ridehailing (aRH) stats*

Fig. 25 *Fleet sizing for Fribourg*



(a) *autonomous Ridepooling (aRP) stats*



(b) *autonomous Ridehailing (aRH) stats*

Fig. 26 *Fleet sizing for Zurich*

on the results of the corresponding choice model (see Tab. 59). In a subsequent step, car ownership was adjusted for those individuals with the highest likelihood of giving up car ownership. For each of the remaining households, the likelihood of purchasing a PAV was computed, and PAV ownership was assigned to 37.5% of those households based on the computed PAV ownership likelihood. In this way, we ensured that ownership rates, as predefined above, are maintained while preserving the behavioral patterns identified by the choice model.

The model designed to describe the purchase of aRP discount cards was ultimately not used for the case studies. It was found that in the case study regions, the base fare of CHF 2.50 for aRP trips without an additional distance-based fare was sufficient to ensure an economically viable service without any subsidies. As a result, the concept of an aRP discount card became obsolete.

7.6.2 Policy measures

Based on findings from earlier studies, a key concern with the introduction of autonomous vehicles is the potential for increased traffic volume and resulting higher rates of congestion (Hörl *et al.* (2019a)). As travel time is perceived as less negative when motorists are freed from the driving task, traveling by autonomous car becomes more attractive. Additionally, ridehailing and ridepooling services provided by autonomous vehicles offer new travel options for people who do not own a car or hold a driving license. If individuals transition from active modes of transportation or public transport to these new modes, the number of vehicles on the road and overall traffic levels will rise. Additionally, autonomous vehicles traveling without passengers to pick up the next rider or to find cheaper parking will further increase vehicle mileage.

However, if people switch from using their own cars or ride-hailing services to ride-pooling, traffic efficiency could improve due to higher vehicle occupancy. Nevertheless, there is an inherent preference for individual travel modes. This preference is influenced by behavioral parameters derived from the stated preference survey (see Section 4.8) and the typically shorter travel times associated with these modes.

There are different possibilities to enhance the attractiveness of ridepooling through policy measures. With regards to pull measures, ridepooling could be subsidised, similarly as in the case of conventional public transport today. However, it might make sense if subsidies for ridepooling are strategically allocated based on the quality of public transport services in each area. Specifically, subsidies should not be provided for aRP in regions where it would compete with more space-efficient public transport options. Instead, aRP should be supported to supplement or replace public transport in areas where cost coverage is low and service quality is limited. This targeted subsidy approach ensures that ridepooling enhances overall transportation efficiency without undermining existing public transport systems.

Regarding push measures, various road pricing strategies seem suitable to deter the usage of low occupancy vehicles. Implementing cordon pricing in urban areas for private cars and ridehailing vehicles, with an exception for ridepooling, can enhance the attractiveness of ridepooling in congested areas of the urban core. In urban agglomerations, distance-based charging for private cars and ridehailing vehicles can increase the appeal of pooled vehicles by making them a more cost-effective option and reducing the externalities associated with motorised modes of transportation in non-urban areas.

Tab. 58 provides an overview of which pull and push measures define the three policy scenarios applied to each case study region. To avoid that existing public transport users switch to aRP, we foresee a distance-based fare of 0.5 CHF/km in addition to the base fare. However, as a pull measure in, the distance-based fare is discounted in Scenario A based on 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 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 (Hörl *et al.*, 2019). In Chur and Fribourg, travel demand is less concentrated towards the urban core but more spread out across the agglomeration. Therefore, an additional distance-based externality tax is applied, amounting to CHF 0.20 per kilometer for private cars and CHF 0.26 per kilometer for ridehailing vehicles. The lower levy for private cars addresses the situation that average vehicle occupancy is higher for cars as compared to ridehailing 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.

Tab. 58 *Overview of policy scenarios*

	Zurich	Chur	Fribourg
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%	100%
aRP fleet size	1680	1200	2400
aRH fleet size	1200	800	1800

Tab. 59 defines the fare stucture for aRH and aRP as applied policy scenarios for the three case study areas.

The fleet sizes of each scenario are determined based on results of the optimisation described in section 7.5, but increased by 20% to correspond to the expected higher demand for aRP caused by the push and pull measures. The fleet sizes were not optimised again for each policy scenario to ensure comparability between the different scenarios. However, it is expected that fleet operators would adjust the fleet size depending on the implemented travel demand management measures.

Further, more advanced demand management measures have been evaluated to be define further policy scenarios, but we refrained from it due to various reasons. The definition of an economically optimal marginal pricing scheme (see for example (Chakirov, 2016)) with road usage levies varying depending on congestion levels of each link at various times of the day would require an additional optimisation loop and therefore increase the computational demand substantially. A more simplistic scheme with fixed road usage charges depending on link and time of the day was considered; however, it would have required a detailed analysis

Tab. 59 *Fleet sizes and fare structure as applied for the case studies*

Mode	Indicator	Chur	Fribourg	Zurich
aRH	Fleet size base case and policy scenario	800	1800	1200
	Base fare [CHF/trip]	2.5	2.5	2.5
	Distance-based fare estimated [CHF/km]	0.032	0.05	0.045
	Distance-based fare applied [CHF/km]			
	in Scenario 0 and A [CHF/km]	0.26	0.26	0.26
	in Scenario B and C [CHF/km]	0.26	0.51	0.51
				plus cordon tax
aRP	Fleet size base case	1000	2200	1400
	Fleet size policy scenario	1200	2400	1680
	Base fare [CHF/trip]	2.5	2.5	2.5
	Distance-based fare estimated [CHF/km]	0	0	0
	Distance-based fare applied			
	in Scenario 0 and B [CHF/km]	0.5	0.5	0.5
	in Scenario A and C for [CHF/km]			
	... for PT Quality class A or B	0.5	0.5	0.5
	... for PT Quality class C	0.4	0.4	0.4
	... for PT Quality D	0.3	0.3	0.3
	... for aeas withouth PT Quality	0.1	0.1	0.1

of bottlenecks in each scenario and, at the same time, limited the comparability of the findings, leading us to refrain from pursuing this option. Furthermore, we evaluated charging empty rides as a further policy scenario. However, this would have required a computation-efficient aRP and aRH dispatching algorithm that could optimise the positioning of vehicles in alignment with such a charging system, which was not available when we conducted the study. To depict the effect of such a charging scheme with regard to private cars, parking location choice would need to be modelled and simulated. While this would be principally feasible with the MATSim framework (Waraich and Axhausen, 2012), we did not address it for various reasons. There are currently no empirical parameters with regard to the preference of parking location choice for private autonomous vehicles. In addition, the simulation models used in this study do not use such a feature, and extending them to do so would have required substantial efforts to collect the required parking supply data.

8 Results

This section presents the simulation results for the Chur, Fribourg, and Zurich regions. To fully understand the impacts of these automated services, 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 pricing 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

- 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

8.1 Chur

8.1.1 System perspective

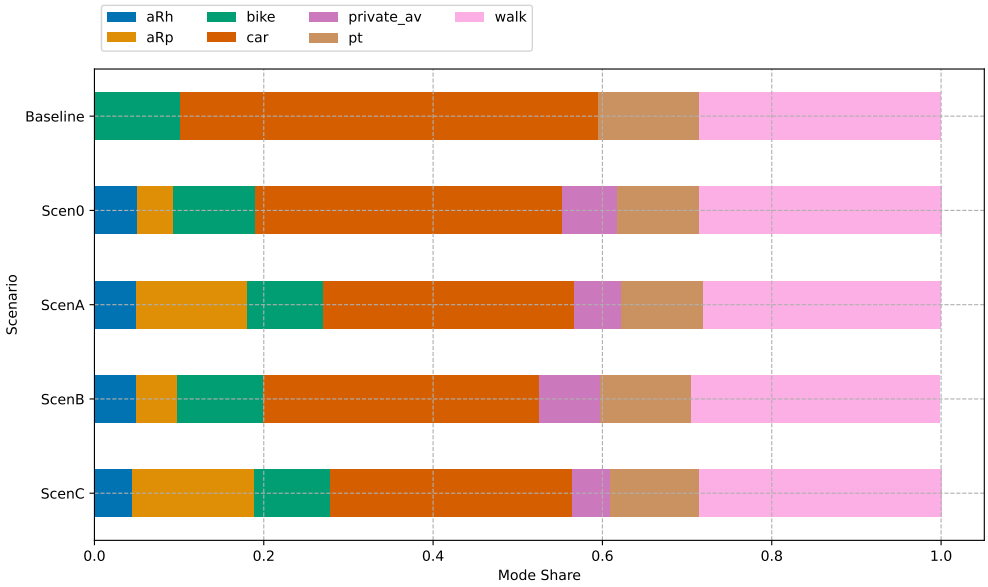


Fig. 27 *Mode share by trip in Chur.*

Figure 27 shows the mode shares on a trip level for different scenarios. People in the studied region around Chur highly prefer the car as the mode of travel, with almost 50% mode share 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%.

The inclusion of aRP and aRH affects considerably motorized means of travel. However, it does not substantially impact cycling and walking, which remain stable at around 10% and 28%, respectively. Regarding the impacts of various policies, the pull policies in Scenarios A and C have the largest impact on the demand for aRP, while aRH demand remains stable, hinting at the low competition between aRP and aRH. On the other side. the push policy in Scenario B shows an increase in mode share of all modes, with only a slight increase in aRP and aRH shares, at the expense of the private car.

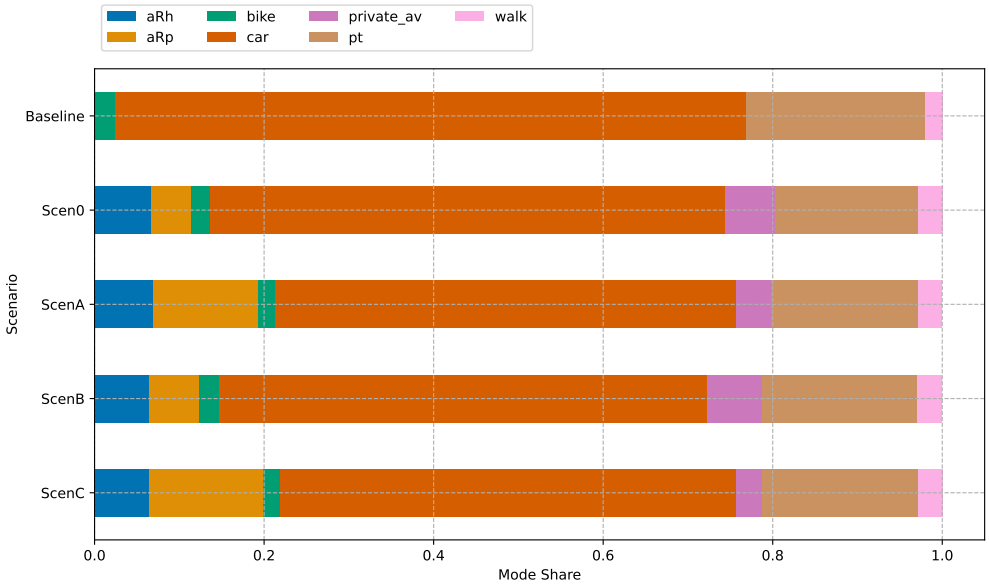


Fig. 28 *Mode share by distance in Chur.*

Fig. 28 shows the mode share by distance. In Scenario 0, 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%. 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, which will be discussed further below.

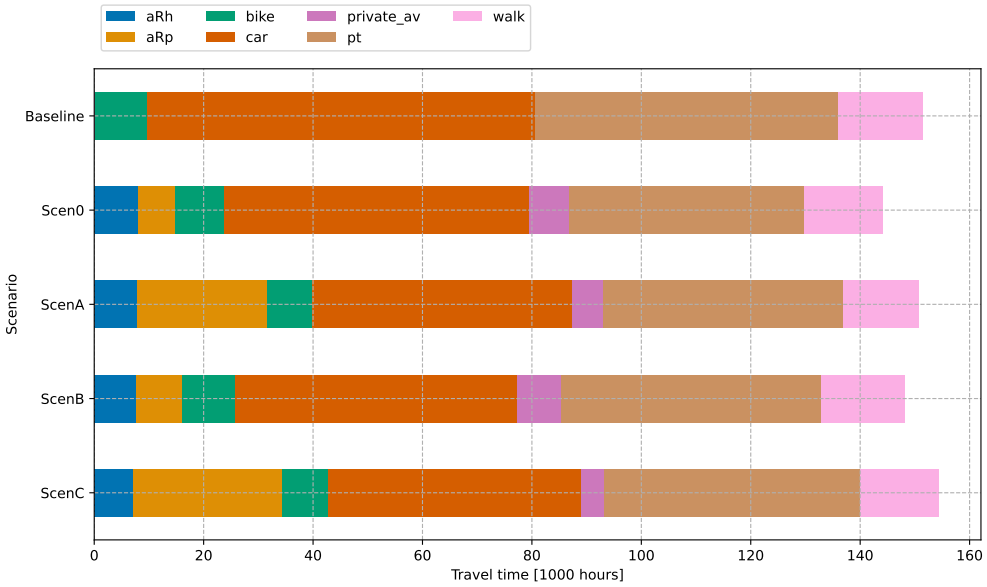


Fig. 29 *Travel time by mode in Chur (Note: not including the waiting time for aRP and aRH).*

From the system perspective, including aRP and aRH services reduces the total travel time for all scenarios, except in the pull and push scenario C, as seen in Fig. 29. The total travel time is reduced due to fewer walking, cycling, and public transport trips and the higher efficiency of automated vehicles. In Scenario C, the total travel time is increased due to more detours for pooled rides. Moreover, it is important to remember that waiting time is also considered as a travel time element for aRP and aRH, but valued much less as compared to public transport as waiting time can be spent at the place from which door-to-door service picks up the passenger.

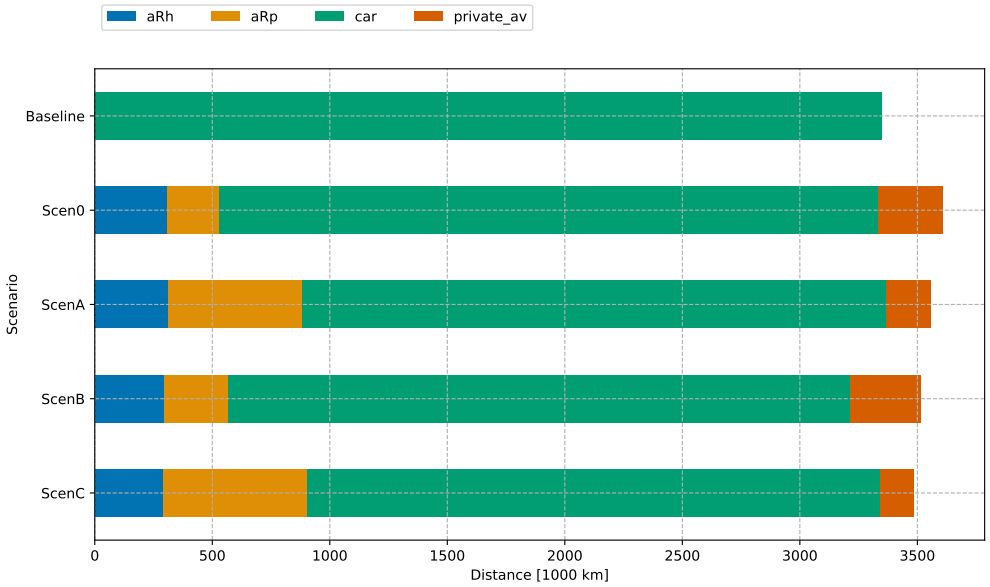


Fig. 30 *Total vehicle distance in Chur.*

Fig. 30 shows the total vehicle distance per transport mode from the perspective of vehicles, not passengers (public transit is not shown as it stays constant between the scenarios). Therefore, the empty distance is also included for aRp and aRp.

The results clearly show that introducing automated services increases the total system vehicle kilometers traveled in all scenarios. This is supported by the findings of previous studies in Switzerland. This increase is slightly reduced in policy scenarios, hinting at increasing pooling rates. Interestingly, the push policy in scenario B has a stronger effect than the pull measures in scenario A.

Assuming that self-driving vehicles require 17% less road space (at the penetration given in the case studies) and utilize the available network capacity more efficiently, the base network utilization increases by 7% in Scenario 0 as compared to the baseline. However, in Scenarios A and B the overall network utilization remains on the level of the baseline scnenario and decreases by 1% in Scenario C. This is primarily because travelers who used to drive by car are using autonomous ride-pooling (aRP) in those scenarios.

8.1.2 Operator perspective

Tab. 60 shows the most important statistics of the aRP and aRH services for different policy scenarios.

Waiting times for aRH and aRP heavily depend on the scenario. In scenario 0, as aRH is cheaper than aRP, it generates higher demand, leading to higher waiting times. Similar behavior with increased waiting times can be observed in the push Scenario B. Conversely, 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.

In general, the share of the distance that the vehicles drive empty is around 25% for both services. The notable exception is the aRP service in Scenarios A and C when the demand for aRP is the highest, and the empty ratio falls to around 12%.

aRP and aRH services are profitable in all scenarios. The highest total profit is in Scenario C, which combines Scenario A and B's push and pull policies. Even though the number of trips stays stable for aRH, the highest profit can be observed in Scenarios B and C, where externality tax is applied to aRH trips. aRP operates with a higher profit in all policy scenarios due to the considerable increase in the number of rides even though the costs for passengers have decreased.

The results show obvious tradeoffs between empty vehicle distance ratio (efficiency perspective), waiting times (user perspective), and profit (operator perspective). Therefore, there is no obvious winner among the tested scenarios.

Tab. 60 *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]	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

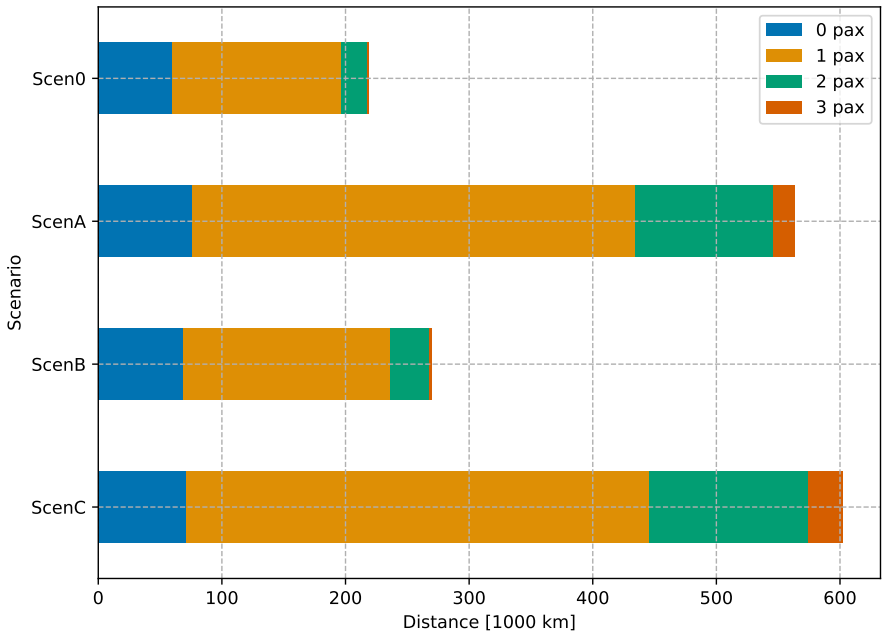


Fig. 31 *Total vehicle distance by occupancy for aRP in Chur.*

Fig. 31 shows the distance driven per occupancy for the aRP service in different scenarios. Scenarios with pull policies A and C positively affect the pooling frequencies with an insignificant increase in the empty distance. The push measures in Scenario B only slightly increase the number of trips with two passengers, which is expected, taking into account the results of the rest of the presented statistics.

8.2 Fribourg

The Fribourg simulations for Scenarios 0 to C with aRP fleet size of 2400 and aRH fleet size of 2200 are presented below.

8.2.1 System perspective

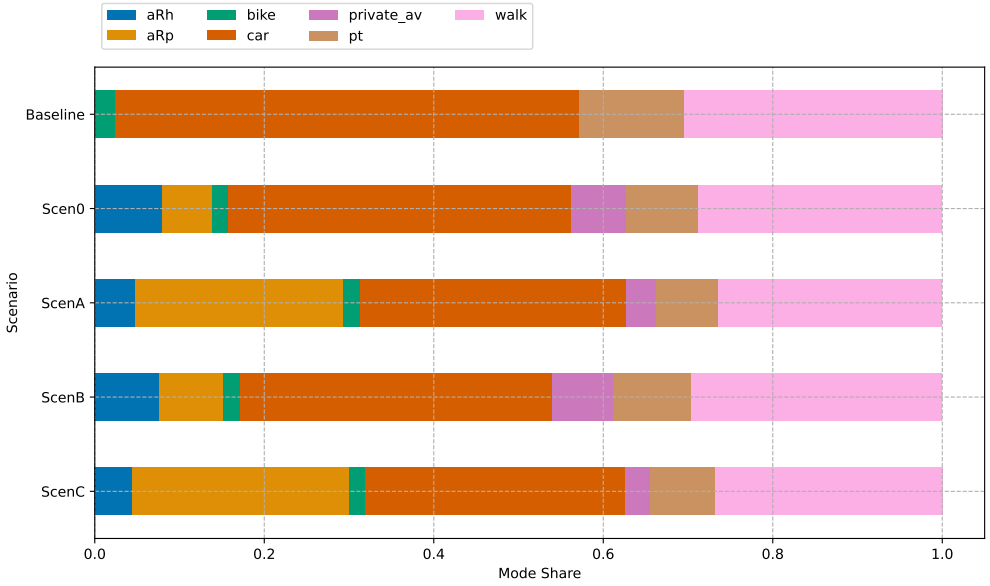


Fig. 32 *Mode share by trip in Fribourg.*

The region of Fribourg is even more car-centric than Chur, with a car mode share of close to 55%. The rest is mostly taken up by walking at close to 30% and public transport at around 12%. Only around 2% of trips are cycling trips, as can also be seen in Fig. 32.

In general, in all Scenarios with automated vehicles, the number of trips with motorized vehicles increases, even when considering public transport. In Scenario 0, the share of aRP and aRH are 6% and 8%, respectively. In scenarios A and C with pull effects, the share of aRH drops to around 4.5% with an increase of aRP to around 25%. The switch to automated modes in all scenarios is mostly at the expense of car and public transport, with a slight effect on walking and cycling.

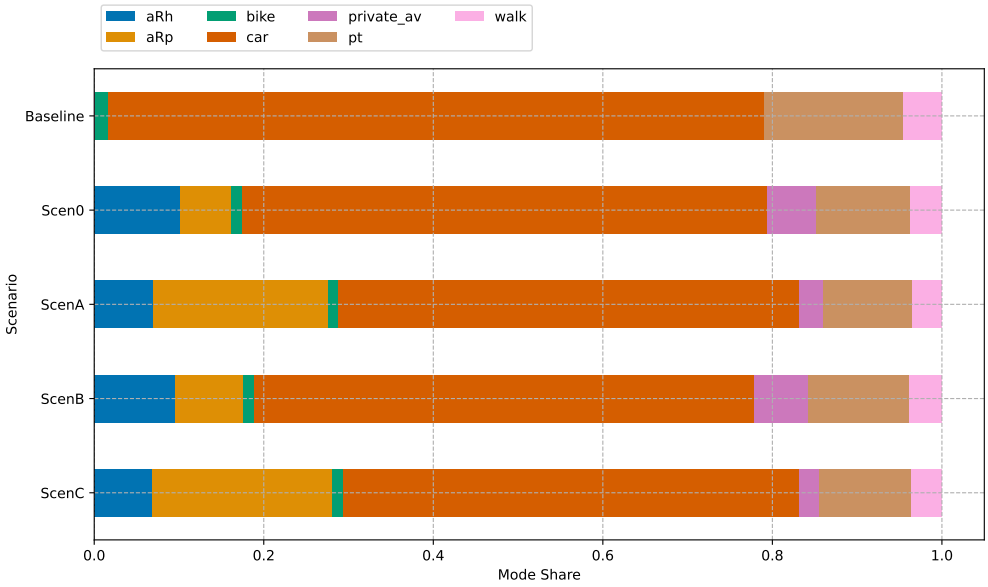


Fig. 33 *Mode share by distance in Fribourg.*

Fig. 33 shows the mode-share in different scenarios waited by traveled distance in Fribourg. The car is the most prevalent mode of transportation here as well. Pull policies in scenarios A and C considerably impact the distances traveled by the aRP mode. What can be seen is that the share of motorized modes remains stable between the scenarios with automated vehicles, however, with an increase over the current state of the demand.

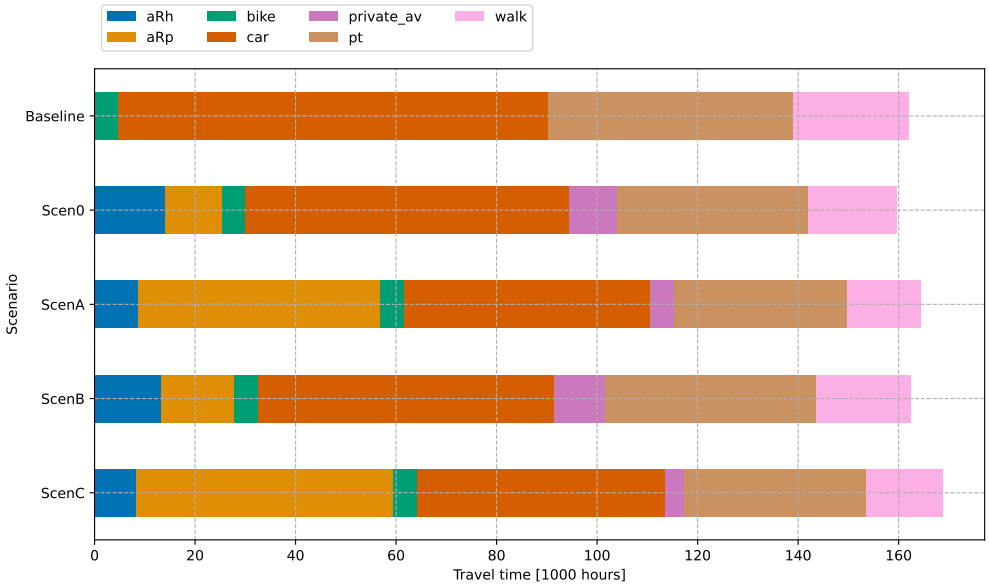


Fig. 34 *Travel time by mode in Fribourg (Note: not including the waiting time for aRp and aRH).*

Fig. 34 presents the time spent traveling in various scenarios for different modes. Scenario 0 exhibits the lowest total travel time and even reduces the travel time compared to the Baseline. Interestingly, the effect is not as strong as the one observed in Chur. Push and pull policies in scenarios A to C due to a switch to a cheaper but slower aRP option increases the total travel time due to pooling detours.

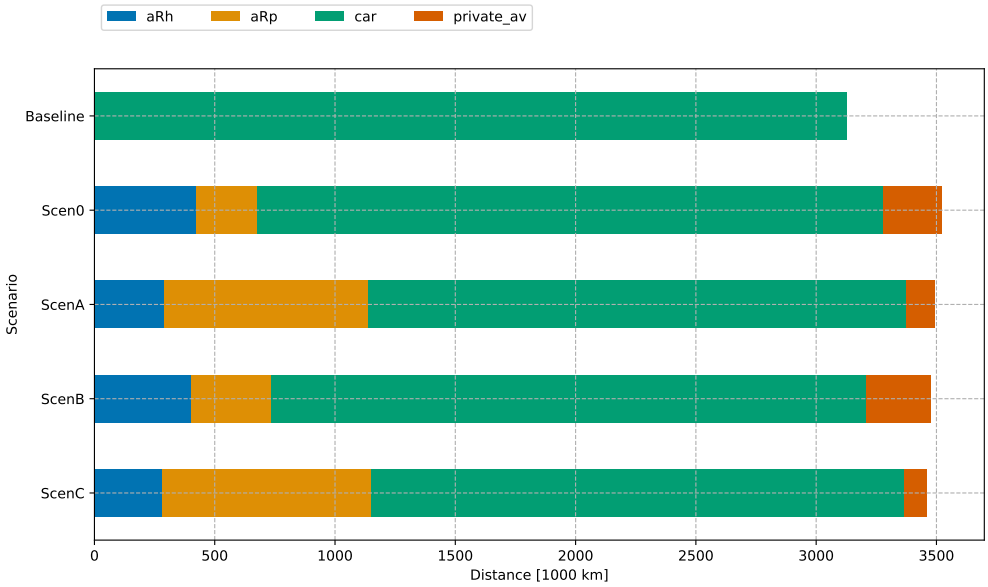


Fig. 35 *Total vehicle distance in Fribourg.*

Fig. 35 shows the total vehicle distance per transport mode from the perspective of vehicles, not passengers. Therefore, the empty distance is also included for aRP and aRH. Vehicle mileage increases with the introduction of shared vehicle fleets. This means pooling in aRP vehicles is insufficient to counteract the empty rides and switch from other non-car-centric modes. In general, in all scenarios, the total vehicle mileage increases by around 10%.

Assuming that self-driving vehicles require 17% less road space (at the penetration given in the case studies) and utilize the available network capacity more efficiently, the base network utilization increases by 7% in Scenario 0 as compared to the baseline. In Scenarios A, B and C, the overall network utilization increases by 4% to 5% as the pull and push measures attract more travelers who used to drive by car to using autonomous ride-pooling (aRP) in those scenarios.

8.2.2 Operator perspective

Tab. 61 shows the most important statistics of the aRP and aRH services for different policy scenarios from the user and operator perspectives.

The average waiting time is below 10 minutes in all scenarios and is generally lower than in Chur. We observe similar trends as in Chur. Pull policies increase the demand for aRP and aRH, with a more substantial effect on aRP, causing much higher customer waiting times. Push effects in Scenario B only slightly change this metric.

The empty distance ratio is above 25% in all scenarios except for aRP in Scenarios A and C, where the demand and pooling rates are the highest, and it falls to around 12%. In those scenarios, the demand for aRP increases to above 150 and 160 thousand, respectively, more than four times the increase over Scenario 0.

Both services are profitable in all scenarios. Again, as in Chur, the highest net income is in Scenario C. In contrast to Chur aRH in Scenario A loses considerable income compared to Scenario 0, as the number of trips is reduced by almost 60%, showing that the pull policy in Fribourg has a much stronger effect than in Chur.

Tab. 61 *Most relevant operational statistics of aRP and aRH in Fribourg.*

Scenario	Scen0		ScenA		ScenB		ScenC	
Vehicle	aRH	aRP	aRH	aRP	aRH	aRP	aRH	aRP
Avg Waiting Time [min]	3.63	2.56	4.80	8.05	3.34	2.68	5.29	9.00
Passenger distance [1000 km)	312.11	225.95	188.18	997.75	293.67	303.69	175.81	1047.75
Total vehicle driven distance [1000 km]	423.76	252.35	289.11	846.32	402.48	333.85	279.16	872.21
Total vehicle occupied distance [1000 km]	312.11	191.77	188.18	739.17	293.67	253.39	175.81	768.87
Total empty vehicle distance [1000 km]	111.64	60.58	100.92	107.15	108.81	80.46	103.35	103.33
Empty ratio	0.26	0.24	0.35	0.13	0.27	0.24	0.37	0.12
Cost [1000 CHF]	134.31	118.90	113.84	221.21	131.42	130.34	112.02	225.89
Revenue [1000 CHF]	222.78	178.11	140.87	502.25	296.91	229.80	185.69	520.88
Net income [1000 CHF]	88.47	59.21	27.03	281.04	165.49	99.46	73.67	294.99
Number of rides	52 052	37 999	32 669	155 596	49 913	47 217	30 410	161 316

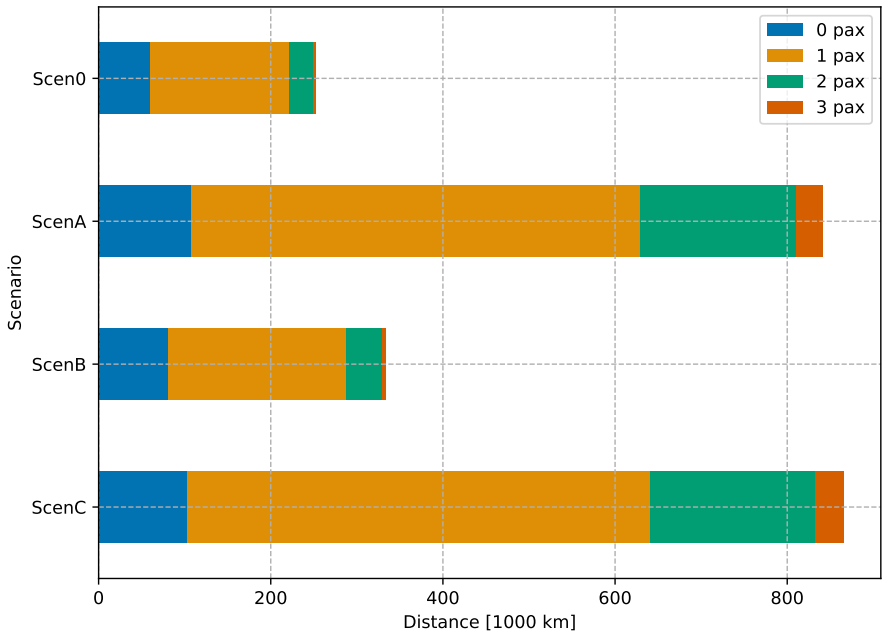


Fig. 36 *Total vehicle distance by occupancy for aRP in Fribourg.*

Fig. 36 shows the distance driven per occupancy for the aRP service in different scenarios. Pull scenarios A and C achieve the aimed effect of increasing the pooling frequencies, and even though the largest share of the distance is with one passenger on board, a considerable increase can be observed for occupancies of 2 and 3. Push policy in Scenario B does not affect pooling significantly, as the pooled distances seem to be followed by the increase in empty distances.

8.3 Zurich

The Zurich simulations for Scenarios 0 to C, using 10% of the population and an aRP fleet size of 1700 and aRH fleet size of 1500, are presented below. The results are not scaled up to 100% but have been left to represent 10% of the population.

8.3.1 System perspective

Zurich is the least car-oriented region studied. Car mode share stands at 36.4%, followed by walking and public transport at 28% and 27%, respectively. Introducing aRP and aRH modes in Scenario 0 impacts all transport modes. Interestingly, the impact is strongest on private cars, whose share falls to 26.7%, followed by public transport, whose share falls to 22.3%. In Scenarios A and C with pull measures, the share of aRP increases at the expense of all modes, including the aRP, which seems to be most affected. However, the push measures in Scenario B do not seem to have a substantial effect, and the mode shares of all modes, even though slightly reduced, stay stable. A possible reason for this is that the mode of trips originating from the cutout region into the cordon was fixed.

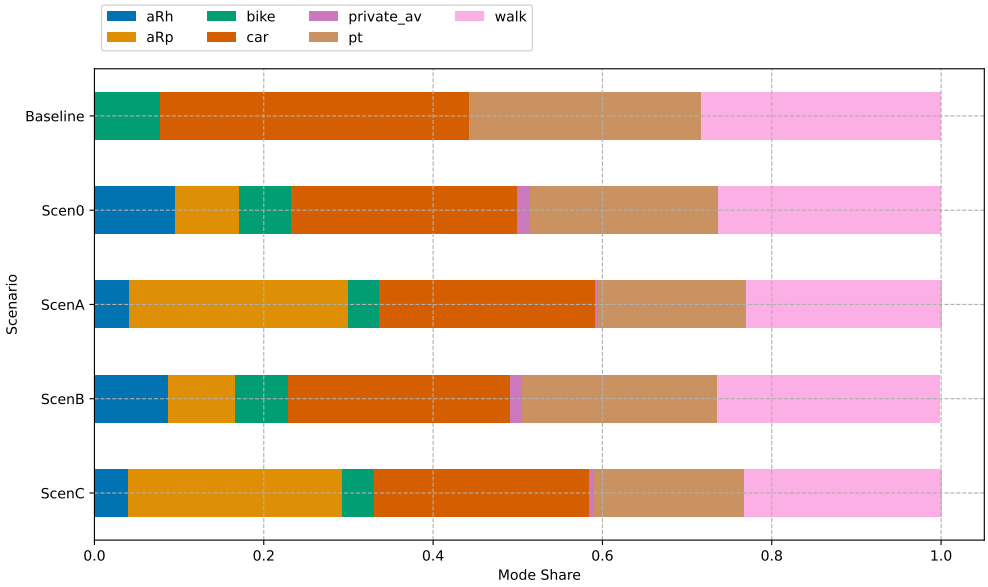


Fig. 37 *Mode share by trip in Zurich.*

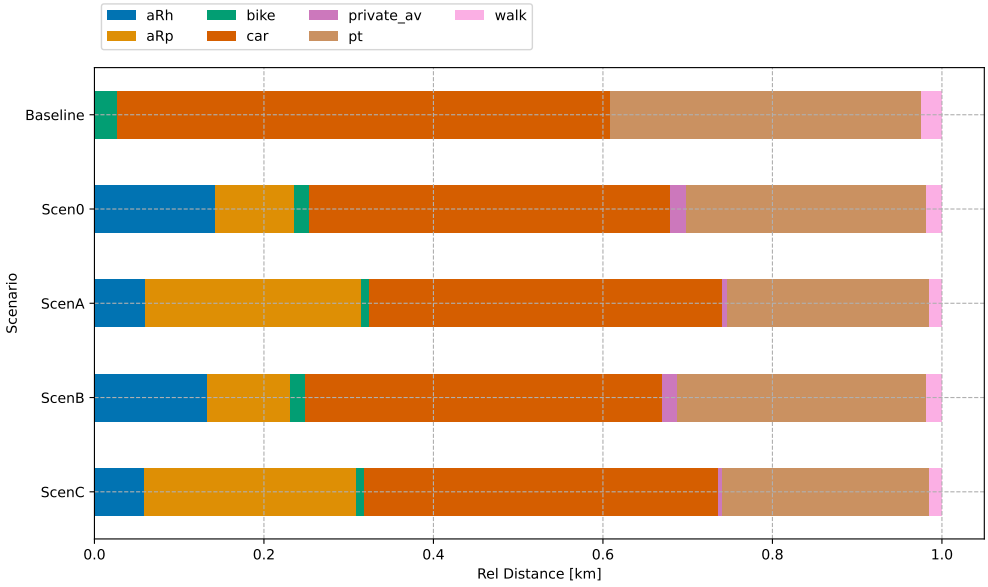


Fig. 38 *Mode share by distance in Zurich.*

Fig. 38 shows the mode-share in different scenarios waited by traveled distance in Zurich. Currently, when measured by distance, the car is again the most prevalent mode in Zurich at close to 60%. Including aRP, aRH, and private AVs in Scenario 0 pushes the motorized distance traveled share to 68%. Pull measures further push the share of motorized travel to 73%, where public transport distance share is affected the most. Also here, push measures in Scenario B do not show a substantial effect.

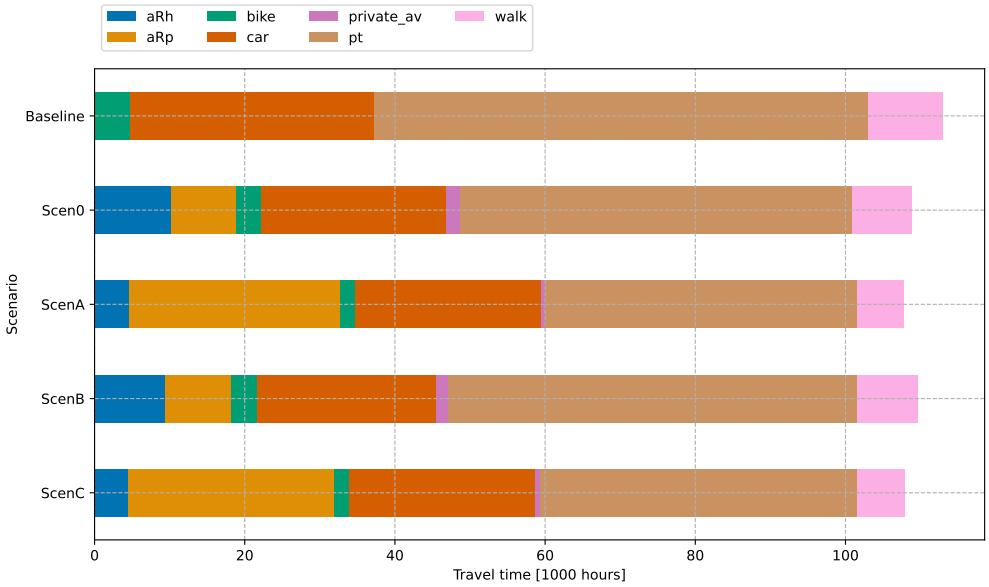


Fig. 39 *Travel time by mode in Zurich (Note: not including the waiting time for aRP and aRH).*

Fig. 39 shows the travel time by mode in Zurich. Due to the inclusion of aRP and aRH services, the total travel time decreases in all simulated scenarios; moreover, at a higher rate than in Chur and Fribourg. This signals that individuals tend to switch from slower modes (especially public transport) to faster aRH and aRP modes.

Assuming that self-driving vehicles require 17% less road space (at the penetration given in the case studies) and utilize the available network capacity more efficiently, the base network utilization increases by 18% in Scenario 0 as compared to the baseline. In Scenarios A and C, the overall network utilization increases even by 27% and 26%, respectively as the pull measures attract primarily more travelers who used public transport to using autonomous ride-pooling (aRP) in those scenarios. In Scenario B, the increase in network utilization amounts to 15% indicating that the cordon pricing helps to motivate a share of car drivers to switch to aRP and public transport.

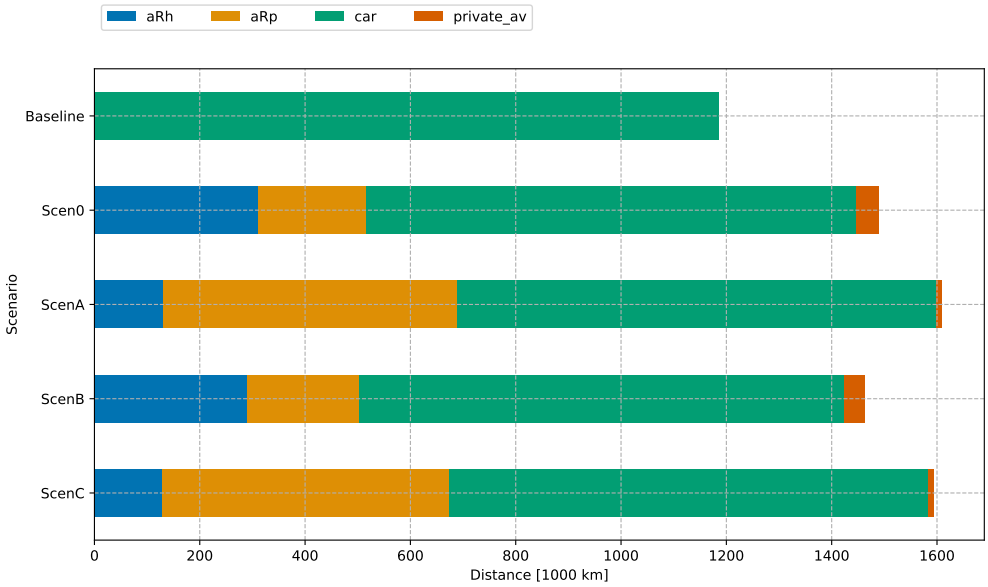


Fig. 40 *Total vehicle distance in Zurich.*

Fig. 40 shows the vehicle distance between the scenarios in more detail by considering the distance all vehicles traveled during one day (also including the empty distance of aRP and aRH vehicles). In scenarios A and B with the pull measures in effect, the total vehicle distance increases by around 33% compared to the baseline scenario, which substantially increases the congestion on the streets, supporting the results of the increases in travel times observed in Fig. 39. In Scenario B, push measures slightly reduce the total vehicle distance traveled, mostly due to the reduction in car trips.

8.3.2 Operator perspective

Tab. 62 shows the most relevant statistics of aRH and aRP from user and operator perspectives in Zurich.

The average waiting time for both simulated services stays stable at 3 to 4 minutes, except for aRP in push scenarios A and C. As in other regions, the large increase (almost tripling) in aRP demand also causes the average waiting time in push policy scenarios to almost double.

The empty ratio is mostly above 25%, while it falls to 16% in push scenarios for aRP where the demand for aRP is considerably increased. The push policy in Scenario B and C seems to have no substantial effect on the empty ratio nor the number of trips for aRP mode.

Both services remain profitable in all scenarios, even though aRH service comes close to cost coverage in Scenario A. The scenarios with the highest total net income are Scenarios B and C - Scenario B because of the cordon charge and C because of the high demand and cordon charge combination.

Tab. 62 *Most relevant operational statistics of aRP and aRH in Zurich.*

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

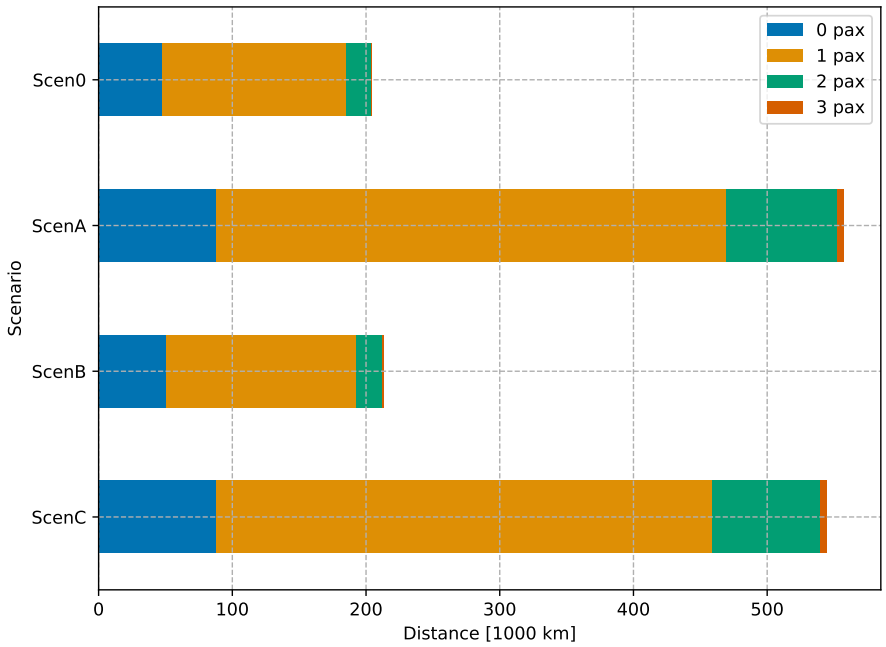


Fig. 41 *Total vehicle distance by occupancy for aRP in Zurich.*

Looking at Fig. 41, one notices a large impact of pull policies on the occupancy of the aRP mode. Even though there is an increase in empty distance, the marginal gain in the kilometers traveled of vehicles with occupancy two and three is higher. Push policy in Scenario B increases the distance traveled of vehicles with occupancy one and two, but at the expense of more empty kilometers traveled.

8.3.3 Discussion

Finally, it is important to discuss the results obtained from the simulations considering the findings from all three studied regions to draw overarching conclusions and necessary future steps.

The findings in all three regions show that mode share on a trip level of autonomous vehicles would be around 20%, which could increase to 40% with pull policy measures in Fribourg and around 35% in Chur and Zurich. This considerable mode-share of AVs also translates to larger vehicle kilometers traveled (VKT), as found previously for Zurich (Hörl *et al.*, 2019a). Zurich, being a more public transport-oriented city than Chur and Friburg, also witnesses the largest 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.

The results indicate that the tested measures are effective in less densely populated areas, enhancing accessibility without increasing network utilization. However, in densely populated urban regions, different measures are needed to achieve similar outcomes in the context of autonomous vehicles.

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

Pooling levels for aRP mode are, in general, low for all three regions, with Fribourg having the largest driven distance with more than one passenger in pull scenarios. The average

vehicle occupancy (including empty trips) ranges between 0.83 persons in Chur without any policy measure and 1.18 for Chur and Fribourg with pull and push measures. The reasons probably lie in the low spatial and temporal density of trips to allow for higher pooling frequencies as well as the lack of modeling group travel and aRP serving pick-up and drop-off points instead providing door-to-door service. These results are comparable to previous findings in Switzerland (Axhausen *et al.*, 2020).

From the user perspective, the average waiting times are consistently below 5 minutes between the scenarios, except for pull scenario C, where aRP has the highest demand in all three regions. As we keep the fleet size constant between the scenarios, this is unsurprising. Therefore, it is expected that some of the individuals who repeatedly do face large waiting times might, in practice, opt-out from using this service in the future, meaning that the forecasted demand in these policy scenarios is overestimated.

In all three regions, the demand for intermodal trips is considerably low. However, we observe a stronger preference for combining aRH over aRP with public transport. Possible reasons are the lack of simulation of longer trips where the transfer penalties could be justified.

8.3.4 Limitations and future research

The agent-based simulations of aRH and aRP services, along with the associated behavioral models, reflect the latest advancements in knowledge and modeling capabilities. However, modeling autonomous vehicles and the related transport services is inherently complex. This technology affects travel demand and supply across multiple, interconnected dimensions, and it is not feasible to address all these dimensions comprehensively. Therefore, it is important to recognize the methodological limitations when interpreting the results. The following limitations are particularly noteworthy:

- The public transport schedules were not adapted in reaction to aRP and aRH offer. The introduction of aRP and aRH services will lead to an decrease in public transport ridership. At the same time, autonomous buses and trams would lead to lower operating cost for public transport and provide opportunities to offer more frequent services to be served with smaller vehicles.

- The fleet size for aRP and aRH was not optimised for the demand in policy scenarios but increased by 20% as compared to the optimal fleet sizes of the base scenario. Compared to the base case scenario, the policy scenarios included several changes affecting demand: an increased distance-based fare, a higher percentage of the population without access to a car, and the introduction of both pull and push measures. Given the high profitability of aRH and aRP operations in all scenario, one would expect other operators to enter the markert or regulators to mandate bigger fleets to ensure better service quality.

- Cost of shared rides not fluctuating according to demand and supply. However, profit-maximizing fleet operators would likely implement demand-responsive pricing structures.

- No pick up and drop off points (pudo): To evaluate whether restricting aRP services to pick-up and drop-off points rather than offering door-to-door service would increase demand and improve pooling rates, future research could utilize the spatial distribution data of aRP demand to develop a pick-up and drop-off network with varying spatial densities.

- Only 10% scenario employed for Zurich case study due to computation time limitations. A higher sharing rate can be expected if a 100% scenario is employed (Kagho *et al.*, 2022).

- Spatially limited scenarios, especially in Zurich: intermodal trips with aRP and aRH are primarily attractive for longer trips due to the high transfer penalty. Therefore, we

expect the share of such trips to increase if scenarios include longer trips.

- No parking traffic simulated, even though it is likely to increase as pAVs can be sent for cheaper parking opportunities in the outskirts. This would result in higher vehicle mileage and congestion levels in and around cities.
- At the assumed cost structure for aRP and aRH services, the case studies showed that aRP and aRH operations can be operated at very competitive prices for customers (i.e., same price or even cheaper than public transport) and would not require no subsidies. At the same time, such vehicle increase traffic levels and more congestion. However, such vehicles also contribute to increased traffic and congestion. Future research should explore how public transport and aRP services can complement each other to enhance accessibility while simultaneously managing traffic levels and reducing congestion.
- The scenarios did not include any effect on destination choice and trip change due to the changing generalized travel cost and availability of new travel modes. With reduced generalized costs and increased availability of individual motorized modes, it is likely that those trips will become longer and more frequent.
- Group travel is not modelled in the simulations due to the lack of behavioral data. However, previous work has shown that by considering group travel, one does observe a substantial increase in pooling rates Kagho and Balac (2023).

9 Recommendations for transport policy and future research

The following policy recommendations and directions for future research are derived from the results of qualitative interviews, the stated choice survey, and the case studies.

AV fleets increase accessibility but also traffic levels In all three case studies, the introduction of aRH and aRP fleets led to a reduction in total travel time between 2% to 4% while the total vehicle distance increased between 5% to 33% as individuals switched from slower modes (especially public transport) to faster aRH and aRP modes. None of the tested policy scenarios reduced vehicle mileage compared to a situation without aRP and aRH services. In the case of Fribourg, traffic levels even increased due to some policy measures leading to higher rates of empty rides. Therefore, a range of policy measures is necessary to increase vehicle occupancy in both commercial and private autonomous vehicles to ensure that the accessibility gains provided by such vehicles do not lead to increased congestion levels and the associated economic and environmental costs.

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. The dispatching algorithm used aimed to serve all requested trips within the service area without prioritizing expected revenue or benefit. The sole economic constraint was that the fleet size should cover the running costs. In this setup, a base fare of CHF 2.50, combined with a minimal distance-based fare of less than 0.05 CHF for aRH and a zero distance-based fare for aRP, proved sufficient to generate the necessary revenue to operate both fleets.

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. Due to the higher activity density, the waiting time and empty driving distance to serve the next trip are smaller. Therefore a profit maximising company would prioritise trips starting or ending in those areas. However, the policy scenarios revealed that demand for ride-pooling and accessibility significantly increases when ride-pooling costs are subsidized based on the quality of current public transport connections. Therefore, a regulation should be implemented that requires

autonomous 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. This approach would allow for the reduction of public transport lines that are not cost-effective. At the same time, lines serving city centres, where space efficiency is crucial, would benefit from limited competition with ride-pooling services. We suggest that future research should assess the levels of availability and reliability required from a user perspective and determine the operational feasibility and associated costs. This will provide a foundation for evaluating the effectiveness of such regulatory schemes. In consideration of the environmental concerns of potential users, regulations and according informational campaigns with regards to the environmental and societal impact of using different types of autonomous vehicles and related services are also recommended.

Mobility pricing Both the distance-based externality tax in the Chur and Fribourg case studies, as well as the cordon pricing in the Zurich case study, resulted in a moderate increase in aRP and aRH usage, ranging from approximately 20% in Zurich to 35% in Fribourg. This shift led to a notable reduction in car usage, consequently decreasing the total vehicle distance traveled, as the increase in shared rides by aRP more than offset the additional mileage of empty trips of aRH and aRP vehicles. However, in scenario B, the total travel time increased slightly in all regions, ranging from 1% in Zurich to 5% in Chur. This indicates that while mobility pricing measures are generally effective in increasing the usage and occupancy of shared vehicles, they need to be better designed to also reduce travel times and thereby enhance accessibility.

In the case studies, the pull measures did not differentiate between time of the day. While the cordon pricing in Zurich targeted a traffic reduction in the city of Zurich, the distance-based externality tax did not include a component of spatial differentiation. Therefore, individuals in the simulations avoided car and PAV usage even during times and along corridors without traffic congestion. However, these results, along with economic theory in mobility pricing literature, suggest that a targeted mobility pricing approach—one that increases usage costs only in areas and at times where congestion occurs—would not only lead to higher usage of shared vehicles but also result in a reduction of overall travel time.

For future simulation studies, we suggest evaluating mobility pricing measures that have been designed in a more targeted manner. 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. In a future situation where most trips are served by autonomous vehicles, charging road usage based on real-time congestion levels seems technologically feasible.

Integrated planning of aRP and public transport Such measures could include implementing road charges based on vehicle occupancy, dedicated lanes for high occupancy vehicles both on motorways but also arterias in urban agglomerations or introducing initiatives to reduce car ownership. The effectiveness of such measures should be tested in future research.

The case studies demonstrated that aRP ridership could be significantly increased by reducing fares in areas with limited or poor public transport service quality. In these areas, the proportion of people with public transport travel cards is currently low, so the fare reduction results in a significant decrease in travel costs for these individuals. If aRP is used as a substitute for conventional public transport with an integrated tariff structure and if sufficient and reliable coverage is ensured through regulatory measures (see paragraph above), it is likely that the proportion of individuals with public transport travel cards in those areas would substantially increase.

At the same time, aRP is more attractive than the current public transport system for existing public transport users in these areas. Consequently, the usage rates for existing public transport services in those areas decrease, worsening the cost recovery ratio. In such a situation, it is important to reconsider how to most effectively provide public transport service

coverage by integrating conventional public transport with on-demand ride-pooling service. These services can range from door-to-door options to line-based approaches, adapting to spatially and temporally varying demand patterns.

Therefore, we recommend that future studies evaluate how different paradigms of service provision and fare integration for public transport and aRP in less dense urban agglomerations and rural areas affect operational costs, ridership, and accessibility. It would also be beneficial to test various service provisions based on the time of day and the spatial configuration of travel demand (e.g., narrow valley versus scattered agglomeration) to determine the most effective strategies for maximising ridership and pooling rates while minimizing operational cost.

High-occupancy vehicle lanes High-occupancy vehicle lanes on motorways can reduce travel times and improve travel time reliability for vehicles with two or more occupants, particularly during peak periods. This, in turn, increases infrastructure capacity and can encourage more people to use shared ride-pooling services. In Switzerland, where motorways typically have only two or three lanes, implementing temporary high-occupancy vehicle lanes seem to be more effective than permanent ones.

Allowing ride-pooling vehicles to use bus lanes elevates its attractiveness but may also affect the operation and reliability of public transport. Future research should explore this trade-off, assessing how many ride-pooling vehicles can be accommodated on bus lanes and at public transport stops to optimize ridership for both modes and improve overall space utilization.

Parking of private vehicles One key advantage of (shared) autonomous vehicles is their potential to reduce the demand for parking spaces. However, the case studies did not account for changes in parking demand or the potential for more space-efficient parking solutions. Additionally, the simulations did not model the impact of private autonomous vehicles potentially driving empty to reach a parking space, possibly in locations with lower parking costs.

Parking provision is currently a crucial policy measure for limiting car traffic in Swiss cities and urban agglomerations. However, the advent of private autonomous vehicles will significantly impair the practicality and effectiveness of existing measures, such as restrictions on on-street parking supply. At the same time, new parking demand will arise from fleets of shared aRH and aRP vehicles, which will vary by time of day and location. The availability of parking spaces for these vehicles will impact both vehicle availability and the mileage covered by empty trips to pick up the next passenger. Therefore, we recommend that future studies explicitly model parking traffic to evaluate the effectiveness and desirability of parking policy measures in addressing these new challenges.

10 Synthesis

10.1 Key insights and conclusion

The results of the qualitative interviews confirm the relevant psychological factors determining the acceptance of ridepooling in autonomous vehicles found in previous research. They can be structured along the technology acceptance model based on the Unified Theory of Acceptance and Use of Technology. The qualitative interviews reveal many relevant factors concerning performance expectancy (perceived usefulness) that determine the acceptance of aRP. These are determinants such as safety concerning technology, waiting time and travel time, environmental considerations, reliability, flexibility, availability, or comfort. Notably, none of these factors are distinctly perceived as a barrier or a driver.

For some factors (time, flexibility, availability, comfort, and environmental considerations), the classification as barrier or driver depends on whether ridepooling is assessed relative to a private car or public transport. For example, a private car is perceived as more reliably available than ridepooling in autonomous vehicles (hence availability is perceived as a bar-

rier); but ridepooling in autonomous vehicles is perceived as more flexibily available than public transport (hence availability is perceived as a driver). For time, flexibility, availability, and comfort factors, this comparison leads to a favourable evaluation of ridepooling in comparison with public transport and an unfavorable perception when compared with a private car. Concerning perceived costs, ridepooling in autonomous vehicles is perceived as more expensive than public transport and as cheaper than a private car. Surprisingly, security was brought up only by a few participants.

From this, we conclude that ride-pooling has the potential to establish itself as a distinct transportation mode, bridging the gap between public transport and private cars, and is likely to attract users from both existing modes. Public transport users may be drawn to ride-pooling for its convenience and coverage, especially in areas with limited service, while private car users might be enticed by the reduced costs and the availability of a shared, on-demand service.

The results of the mode choice model support this conclusion. While travel time is valued more negatively for both aRP and aRH compared to public transport and private cars, the travel time savings offered by these modes relative to public transport, combined with their reduced cost compared to private cars, enable them to attract market share from both existing modes. This suggests that the benefits of aRP and aRH, in terms of efficiency and cost-effectiveness, position them as competitive alternatives capable of drawing users away from both public transport and private cars.

The negative alternative-specific constants for aRP and aRH alternatives indicate a general reluctance among respondents to choose these new modes, which directly affects their anticipated market shares. This reluctance is less pronounced towards ride-pooling as compared to ride-hailing and among individuals who are more open to mobility innovations compared to the general population. It is reasonable to expect that such reluctance will generally diminish over time as users become more familiar with these new travel modes.

However, certain aspects of the travel experience with aRP and aRH, which differ from existing modes, were not fully captured by the variables describing these alternatives, but may partially explain the observed reluctance. For instance, using aRP and aRH typically requires making reservations through an app, increasing the burden to plan and conduct a trip. Additionally, demand and supply for aRH and aRP fluctuate by time of day and location, creating an aspect of planning uncertainty that can only be partially addressed in stated preference surveys. Furthermore, fleet operators are likely to implement dynamic pricing to manage these fluctuations, which could further increase the planning burden for customers.

The mobility tool experiment reveals a general reluctance to relinquish car ownership, even if fleets of shared autonomous vehicles could provide comprehensive personal mobility without a private vehicle. Conversely, respondents exhibited a strong willingness to purchase a discount card for aRP, particularly those who currently use public transport infrequently and do not hold a travel card or only possess a Half-Fare card. While some of this effect observed in the survey may be influenced by framing effects, it underscores the market potential for discount cards for both aRP and aRH.

For fleet operators, such discount cards present an opportunity to stimulate demand by offering diminishing marginal prices, thereby distributing the fixed costs of operating the fleet more broadly. From a transport policy perspective, these discount cards could be beneficial if they encourage car drivers to switch to aRP, thus reducing road space usage. However, to enhance transport efficiency, it would be ideal if conventional public transport remained cheaper than aRP or aRH during peak hours due to its higher space efficiency. Achieving this would likely require targeted mobility pricing measures that not only impact car drives but also users of aRH and aRP.

While MATSim's Demand Responsive Transport (DRT) module provide a robust and computationally efficient environment for the simulation ride-sharing and ride-pooling in MATSim, more complex frameworks allow to test how the operational efficiency can be improved

through smart matching of ride-pooling demand and supply. The versatile real-time simulation framework which has been developed as part of this study allows to account for varying traffic conditions when optimising the allocation of the ride-pooling fleet to the fluctuating demand. It was showed that it is possible to accommodate 97% of taxi rides in Manhattan using only 2,000 ride-pooling vehicles capable of carrying up to 5 passengers each, instead of the current 13,000 taxis. These 2,000 taxis can achieve an average pick-up waiting time of less than 2 minutes and an average in-car delay of fewer than 7 minutes. These findings were obtained based on a scenario where the maximum delay time to pick-up a passenger was set to 5 minutes and maximum detour time to 15 minutes. This shows that there is substantial potential to improve traffic conditions with limited impact with regards to travel time if a city decides to limit single-occupancy vehicles. However, the integration of this new algorithm would be a laborious task that could significantly increase computation time, but likely not lead to new insights as the impact of a higher operational efficiency of aRH and aRP on demand is considered to be limited. Therefore, we decided to not employ the new algorithm for the case studies.

An agent-based approach was used to evaluate the potential impacts of autonomous vehicles in three urban regions in Switzerland: Chur, Fribourg, and Zurich. An agent-based transport model, MATSim, was combined with the mode-choice model estimated from the SP survey data to simulate trade-offs between private (autonomous) car, cycling, walking, public transport, and shared autonomous ride-hailing (aRH) and ride-pooling (aRP) services. Additionally, a mobility tool ownership model was applied to the population to anticipate the change in vehicle ownership, given the widespread availability of shared autonomous services. For each region, the baseline scenario representing the current transport demand and supply was calibrated to match the mode shares observed in each region. An optimal fleet size for aRH and aRP services was then determined to ensure profitability while sustaining high demand and user satisfaction. Finally, the fares for aRH and aRP are designed to mimic the car and public transport fare, respectively. The reason being that aRH is considered privately owned and operated to attract high demand, while aRP is part of the public transport operations.

For each studied region, we simulated three scenarios with policy measures aimed at pulling and pushing individuals towards more sustainable pooled autonomous service. As a pull measure, subsidies for aRP services were offered based on the quality of public transport at the origin or destination in all three regions. As push measures, a distance-based vehicle tax was implemented in Chur and Fribourg, while a cordon tax was applied in Zurich.

The results show that introducing aRP and aRH modes reduces total travel time, increases the share of motorized non-PT modes, and increases total vehicle mileage. In Chur and Fribourg, the most affected mode is the car, while in Zurich, it is public transport. From the operator's perspective, the pooling is rather low where most of the traveled distance is without or with only a single passenger, showing the need for policy measures.

The three policy scenarios show similar effects in all three studied regions. Targeted price reductions for aRP depending on public transport service quality as pull measure increase pooling rates at the expense of increased total vehicle distance, with the most substantial increase in Zurich. Interestingly, for Chur and Fribourg, such a pull policy measure reduces the total travel time, while in Zurich, they increase them, which is probably related to a much higher vehicle distance and hence increased level of congestion. From the aRP and aRH operator perspective, pull policy measures considerably increase the demand, especially for aRP. The highest net income for aRH and aRP services is achieved when both push and pull policies are applied. A distance-based fare for private vehicles and aRH, as tested for Chur and Fribourg does not lead to considerable changes with regards to mode share and only a slight increase in aRP usage and aRP vehicle occupancy. The same applies for the cordon charge that was used as push measure for the Zurich case study.

The findings in all three regions show that mode share on a trip level of autonomous vehicles would be around 20% given the employed assumptions with regards to car ownerhship as well as aRP and aRH fleet sizes an pricing structure. With tested pull policy, this share

could increase to 40% for the Fribourg region and and around 35% in Chur and Zurich. This considerable increase in mode share translates to larger vehicle kilometers traveled (VKT), as found previously for Zurich (Hörl *et al.*, 2019a). Zurich, being a more public transport-oriented city than Chur and Fribourg, also witnesses the largest percentage increase in VKT. Pooling levels for aRP mode are, in general, low for all three regions, with average vehicle occupancy (including empty trips) between 0.74 persons in Chur without any policy measure and 1.17 for Fribourg with pull and push measures. The reasons probably lie in the low spatial and temporal density of trips to allow for higher pooling frequencies and neither modeling group travel nor testing the usage of pick-up and drop-off points instead of door to door service. 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 summary, the research demonstrates that a range of targeted policy measures is essential to make ride-pooling a viable travel option that enhances transport system efficiency while avoiding increased traffic levels and congestion.

10.2 Limitations and future research

Capturing the acceptance of ride-pooling with autonomous vehicles and modeling travel behaviour if autonomous vehicles become widely available is linked with various uncertainties. Notably, none of the participants in the qualitative interviews or choice experiments had experienced traveling with such vehicles. Additionally, modeling autonomous vehicles and their related transport services is inherently complex, impacting travel demand and supply across numerous interconnected dimensions. It is not feasible to address all these dimensions comprehensively. Consequently, it is important to acknowledge the methodological limitations when interpreting the results which is at the same time helpful to derive directions for future research.

While detailed descriptions of methodological limitations are provided towards the end of each chapter, the following offers an overarching summary.

- To verify whether the insights from the qualitative interviews and stated choice experiments align with actual behavior, it would be valuable to conduct similar studies with participants who have firsthand experience traveling in various forms of autonomous vehicles. Participants could be recruited in collaboration with companies that operate these vehicles commercially or through pilot projects.

- In the stated choice survey, only trade-offs between ride-pooling and ride-hailing with public transport and private motorized vehicles were tested. However, depending on the fare structure and potential travel cards, these new modes could also offer competitive alternatives to cycling and walking. Moreover, active transport modes have benefits for environmental impact and public health. Therefore, we recommend that future studies explore the interplay between these new modes and active transportation options, with a focus on how transport policy measures can effectively integrate and leverage their respective advantages.

- The case studies demonstrated that simulating travel behavior with large fleets of shared autonomous vehicles in complex configurations, such as intermodal trips, is feasible. The insights gained highlight both the potential benefits and the challenges that autonomous vehicles present to the transport system. However, it is evident that these simulation results require more detailed analysis to provide a deeper understanding of how autonomous vehicles, and ride-pooling services in particular, could benefit the transport system, society, and the environment. Those insights could also inform iterative refinements and further development of the simulation scenarios which would ultimately allow to derive spatially context-aware policy recommendations.

- The availability of autonomous vehicles will significantly transform transportation and influence land use. These new transport options, including shared and private autonomous vehicles, will not only affect mode choice and vehicle ownership but also

impact destination choice and the types and frequency of activities conducted. To better understand this potential impact, it is useful to consider how mass motorization has historically changed various aspects of daily life and the built environment. Given the complexity of modeling all relevant dimensions to predict future scenarios, a backcasting approach could be valuable. By describing various potential scenarios, one can evaluate their feasibility and desirability using suitable transport models. This approach would help identify the necessary and desirable measures to guide progress towards a preferred development path.

Appendix

I Appendix of Design of choice experiments

Tab. 63 *Prior parameter values for regular/utilitarian trip*

Further variables

	Transfers	Transfer duration	Walking time (access/egress)	Frequency	Reaction time	Pick-up	Additional pax
Car	-		0 | 2 | 4	-			
PT	-1 | 0 | +1 (compared to reference)	2 | 5 + 2 * change in transfers	-3 | 0 | +3 (compared to reference)	-1 | 0 | +1 level (compared to reference)			
RP	-		0 | 2 | 4 | 6		-4 | -2 | 0 | 2 | 4	home | pick up point | pt stop	0 | 1 | 2 | 3
aRH Feeder	0 | +1	0 | 2 | 5 + 2 * change in transfers	0 | 2 | 4	-2 | -1 | 0 level (compared to reference PT)	-4 | -2 | 0 | 2 | 4	home | pick up point | pt stop	0
aRP Feeder	0 | +1	0 | 2 | 5 + 2 * change in transfers	0 | 2 | 4 | 6	-2 | -1 | 0 level (compared to reference PT)	-4 | -2 | 0 | 2 | 4	home | pick up point | pt stop	0 | 1 | 2 | 3
Comment	Relative to reported trip		Pick up point: home: 0 Min point: 2 | 4 Min pt stop: 2 | 4 | 6 Min	Levels >7.5 | 7.5 | 10 | 15 | 20 | 30 | 60 min	Offset values: City: 6 Min Agglo: 8 Min Rural: 11 Min		

Tab. 64 *Prior parameter values for leisure trip*

Leisure trip

Variable	VTTS (CHF/H,CHF)	Utility / Prior	Comment	Source
Cost (1 / CHF)		-1		
TT_{car} (1 / min)	22.05	-0.37 (1 / CHF)		SN 41 822a
TT_{PT} (1 / min)	12.01	-0.20 (1 / CHF)		SN 41 822a
TT_{RH} (1 / min)	10.21	-0.17 (1 / CHF)	15% less than PT → 12.6 CHF / h	Own estimate, literature
TT_{RP} (1 / min)	10.81	-0.18 (1 / CHF)	10% less than PT → 12.6 CHF / h	Own estimate, literature
TT_{Walk} (1 / min)	22.79	-0.38 (1 / CHF)	2.2x TT_{PT}	SN 41 822a
Transfer (number)	2.49	-2.49	12 Min (PT)	SN 41 822a
Tranfer duration	9.32	-0.16 (1 / CHF)		
Frequency (per step)	4.33	-0.36	5 Min Step	SN 41 822a
Reaction time	24.02	-0.40 (1 / CHF)	2.2x TT_{PT}	Hörk et al. 2019, relative to TT_{PT}
Additional passenger RP	-	0.1* Pax*$TT_{(a)RP}$	Interaction term with TT_{RP}	Own estimate
Pickup point	(0, -2, -1)	(0, -2, -1)	(@home, pick-up point, PT stop)	Own estimate

Tab. 65 *Utility levels and choice probabilities at average attribute levels (regular/utilitarian trip of 20 min duration)*

	Car					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.289	-2.235	-1.946	-2.235
RP	-2.400	-0.288	-0.803	-2.554	-2.040	-2.842
PT & RP	-2.800	-0.336	-1.760	-3.026	-1.602	-3.362
aRH	-3.000	-0.360	-0.875	-2.062	-1.548	-2.422
aRP	-3.200	-0.384	-0.899	-1.973	-1.459	-2.357
PT & aRH	-3.100	-0.372	-1.796	-2.817	-1.393	-3.189
PT & aRP	-3.300	-0.396	-1.820	-2.874	-1.450	-3.270

	PT					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.473	-2.147	-1.153	-2.627
RP	-2.400	-0.288	-0.803	-2.250	-1.735	-2.538
PT & RP	-2.800	-0.336	-1.760	-2.961	-1.537	-3.297
aRH	-3.000	-0.360	-0.875	-1.747	-1.233	-2.107
aRP	-3.200	-0.384	-0.899	-1.611	-1.096	-1.995
PT & aRH	-3.100	-0.372	-1.796	-2.746	-1.322	-3.118
PT & aRP	-3.300	-0.396	-1.820	-2.802	-1.378	-3.198

	Car			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	64.7%	75.5%	36.8%	57.4%
RP	35.3%			
PT & RP		24.5%		
aRH			30.6%	
aRP			32.6%	
PT & aRH				22.1%
PT & aRP				20.4%

	PT			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	47.8%	66.2%	21.9%	45.9%
RP	52.2%			
PT & RP		33.8%		
aRH			36.8%	
aRP			41.2%	
PT & aRH				28.1%
PT & aRP				25.9%

Tab. 66 *Utility levels and choice probabilities at average attribute levels (regular/utilitarian trip of 40 min duration)*

	Car					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.579	-4.863	-4.284	-4.863
RP	-2.400	-0.288	-0.803	-6.892	-6.377	-7.180
PT & RP	-2.800	-0.336	-1.760	-5.297	-3.873	-5.633
aRH	-3.000	-0.360	-0.875	-4.962	-4.447	-5.322
aRP	-3.200	-0.384	-0.899	-4.338	-3.823	-4.722
PT & aRH	-3.100	-0.372	-1.796	-4.758	-3.334	-5.130
PT & aRP	-3.300	-0.396	-1.820	-4.617	-3.193	-5.013

	PT					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.473	-3.510	-2.517	-3.990
RP	-2.400	-0.288	-0.803	-6.406	-5.892	-6.694
PT & RP	-2.800	-0.336	-1.760	-5.167	-3.743	-5.503
aRH	-3.000	-0.360	-0.875	-4.332	-3.817	-4.692
aRP	-3.200	-0.384	-0.899	-3.709	-3.195	-4.093
PT & aRH	-3.100	-0.372	-1.796	-4.616	-3.192	-4.988
PT & aRP	-3.300	-0.396	-1.820	-4.474	-3.050	-4.870

	Car			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	91.0%	68.3%	35.9%	38.1%
RP	9.0%			
PT & RP		31.7%		
aRH			22.7%	
aRP			41.4%	
PT & aRH				29.2%
PT & aRP				32.8%

	PT			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	93.7%	82.0%	41.7%	56.1%
RP	6.3%			
PT & RP		18.0%		
aRH			20.7%	
aRP			37.6%	
PT & aRH				20.7%
PT & aRP				23.3%

Tab. 67 *Utility levels and choice probabilities at average attribute levels (regular/utilitarian trip of 60 min duration)*

	Car					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.868	-7.490	-6.622	-7.490
RP	-2.400	-0.288	-0.803	-11.352	-10.838	-11.640
PT & RP	-2.800	-0.336	-1.760	-7.557	-6.133	-7.893
aRH	-3.000	-0.360	-0.875	-7.862	-7.347	-8.222
aRP	-3.200	-0.384	-0.899	-6.799	-6.285	-7.183
PT & aRH	-3.100	-0.372	-1.796	-6.699	-5.275	-7.071
PT & aRP	-3.300	-0.396	-1.820	-6.470	-5.046	-6.866

	PT					
Altern. $\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.473	-4.873	-3.880	-5.353
RP	-2.400	-0.288	-0.803	-10.466	-9.951	-10.754
PT & RP	-2.800	-0.336	-1.760	-7.362	-5.938	-7.698
aRH	-3.000	-0.360	-0.875	-7.013	-6.498	-7.373
aRP	-3.200	-0.384	-0.899	-5.711	-5.197	-6.095
PT & aRH	-3.100	-0.372	-1.796	-6.390	-4.966	-6.762
PT & aRP	-3.300	-0.396	-1.820	-6.255	-4.831	-6.651

	Car			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	98.4%	59.9%	35.2%	22.8%
RP	1.6%			
PT & RP		40.1%		
aRH			16.9%	
aRP			47.9%	
PT & aRH				34.7%
PT & aRP				42.5%

	PT			
Altern. $\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	99.6%	91.3%	62.2%	65.9%
RP	0.4%			
PT & RP		8.7%		
aRH			8.3%	
aRP			29.6%	
PT & aRH				16.1%
PT & aRP				18.0%

Tab. 68 *Utility levels and choice probabilities at average attribute levels (leisure trip of 20 min duration)*

	Car					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.216	-1.821	-1.605	-1.821
RP	-2.400	-0.288	-0.672	-2.371	-1.987	-2.659
PT & RP	-2.800	-0.336	-1.707	-2.853	-1.481	-3.189
aRH	-3.000	-0.360	-0.744	-1.780	-1.395	-2.140
aRP	-3.200	-0.384	-0.768	-1.651	-1.267	-2.035
PT & aRH	-3.100	-0.372	-1.743	-2.653	-1.282	-3.025
PT & aRP	-3.300	-0.396	-1.767	-2.707	-1.336	-3.103

	PT					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.587	-2.133	-1.026	-2.613
RP	-2.400	-0.288	-0.672	-2.091	-1.707	-2.379
PT & RP	-2.800	-0.336	-1.707	-2.804	-1.432	-3.140
aRH	-3.000	-0.360	-0.744	-1.544	-1.160	-1.904
aRP	-3.200	-0.384	-0.768	-1.371	-0.987	-1.755
PT & aRH	-3.100	-0.372	-1.743	-2.598	-1.226	-2.970
PT & aRP	-3.300	-0.396	-1.767	-2.651	-1.280	-3.047

	Car			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	69.8%	79.7%	39.5%	63.4%
RP	30.2%			
PT & RP		20.3%		
aRH			28.7%	
aRP			31.9%	
PT & aRH				19.0%
PT & aRP				17.6%

	PT			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	44.2%	62.9%	18.6%	42.6%
RP	55.8%			
PT & RP		37.1%		
aRH			37.7%	
aRP			43.7%	
PT & aRH				29.8%
PT & aRP				27.6%

Tab. 69 *Utility levels and choice probabilities at average attribute levels (leisure trip of 40 min duration)*

	Car					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.432	-3.999	-3.567	-3.999
RP	-2.400	-0.288	-0.672	-6.660	-6.276	-6.948
PT & RP	-2.800	-0.336	-1.707	-4.940	-3.568	-5.276
aRH	-3.000	-0.360	-0.744	-4.492	-4.108	-4.852
aRP	-3.200	-0.384	-0.768	-3.806	-3.422	-4.190
PT & aRH	-3.100	-0.372	-1.743	-4.420	-3.049	-4.792
PT & aRP	-3.300	-0.396	-1.767	-4.267	-2.896	-4.663

	PT					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.587	-3.333	-2.226	-3.813
RP	-2.400	-0.288	-0.672	-6.199	-5.814	-6.487
PT & RP	-2.800	-0.336	-1.707	-4.842	-3.471	-5.178
aRH	-3.000	-0.360	-0.744	-4.021	-3.637	-4.381
aRP	-3.200	-0.384	-0.768	-3.319	-2.934	-3.703
PT & aRH	-3.100	-0.372	-1.743	-4.309	-2.938	-4.681
PT & aRP	-3.300	-0.396	-1.767	-4.155	-2.784	-4.551

	Car			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	95.0%	78.2%	44.4%	50.8%
RP	5.0%			
PT & RP		21.8%		
aRH			18.9%	
aRP			36.7%	
PT & aRH				23.0%
PT & aRP				26.2%

	PT			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	93.5%	79.7%	37.3%	52.7%
RP	6.5%			
PT & RP		20.3%		
aRH			21.1%	
aRP			41.6%	
PT & aRH				22.1%
PT & aRP				25.2%

Tab. 70 *Utility levels and choice probabilities at average attribute levels (leisure trip of 60 min duration)*

	Car					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
Car	0.000	0.000	-0.649	-6.178	-5.529	-6.178
RP	-2.400	-0.288	-0.672	-11.047	-10.663	-11.335
PT & RP	-2.800	-0.336	-1.707	-7.024	-5.653	-7.360
aRH	-3.000	-0.360	-0.744	-7.205	-6.821	-7.565
aRP	-3.200	-0.384	-0.768	-6.033	-5.649	-6.417
PT & aRH	-3.100	-0.372	-1.743	-6.187	-4.816	-6.559
PT & aRP	-3.300	-0.396	-1.767	-5.944	-4.573	-6.340

	PT					
Altern.$\{\bar{k},k\}$	$-\alpha_{\{\bar{k},k\}}/\beta_{cos}$	$\alpha_{\{\bar{k},k\}}$	$\alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} - \alpha_{\{\bar{k},k\}}$	$\bar{V}^*_{\{\bar{k},k\}} - \alpha^*_{\{\bar{k},k\}}$	$\bar{V}_{\{\bar{k},k\}} \equiv \bar{V}^*_{\{\bar{k},k\}}$
PT	-4.000	-0.480	-1.587	-4.533	-3.426	-5.013
RP	-2.400	-0.288	-0.672	-10.234	-9.850	-10.522
PT & RP	-2.800	-0.336	-1.707	-6.878	-5.506	-7.214
aRH	-3.000	-0.360	-0.744	-6.571	-6.186	-6.931
aRP	-3.200	-0.384	-0.768	-5.194	-4.810	-5.578
PT & aRH	-3.100	-0.372	-1.743	-5.949	-4.578	-6.321
PT & aRP	-3.300	-0.396	-1.767	-5.777	-4.406	-6.173

	Car			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
Car	99.4%	76.5%	49.1%	39.5%
RP	0.6%			
PT & RP		23.5%		
aRH			12.3%	
aRP			38.6%	
PT & aRH				27.0%
PT & aRP				33.6%

	PT			
Altern.$\{\bar{k},k\}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$	$P_{\{\bar{k},k\}}$
PT	99.6%	90.0%	58.3%	63.1%
RP	0.4%			
PT & RP		10.0%		
aRH			8.6%	
aRP			33.1%	
PT & aRH				17.1%
PT & aRP				19.8%

II Appendix of MATSim Results

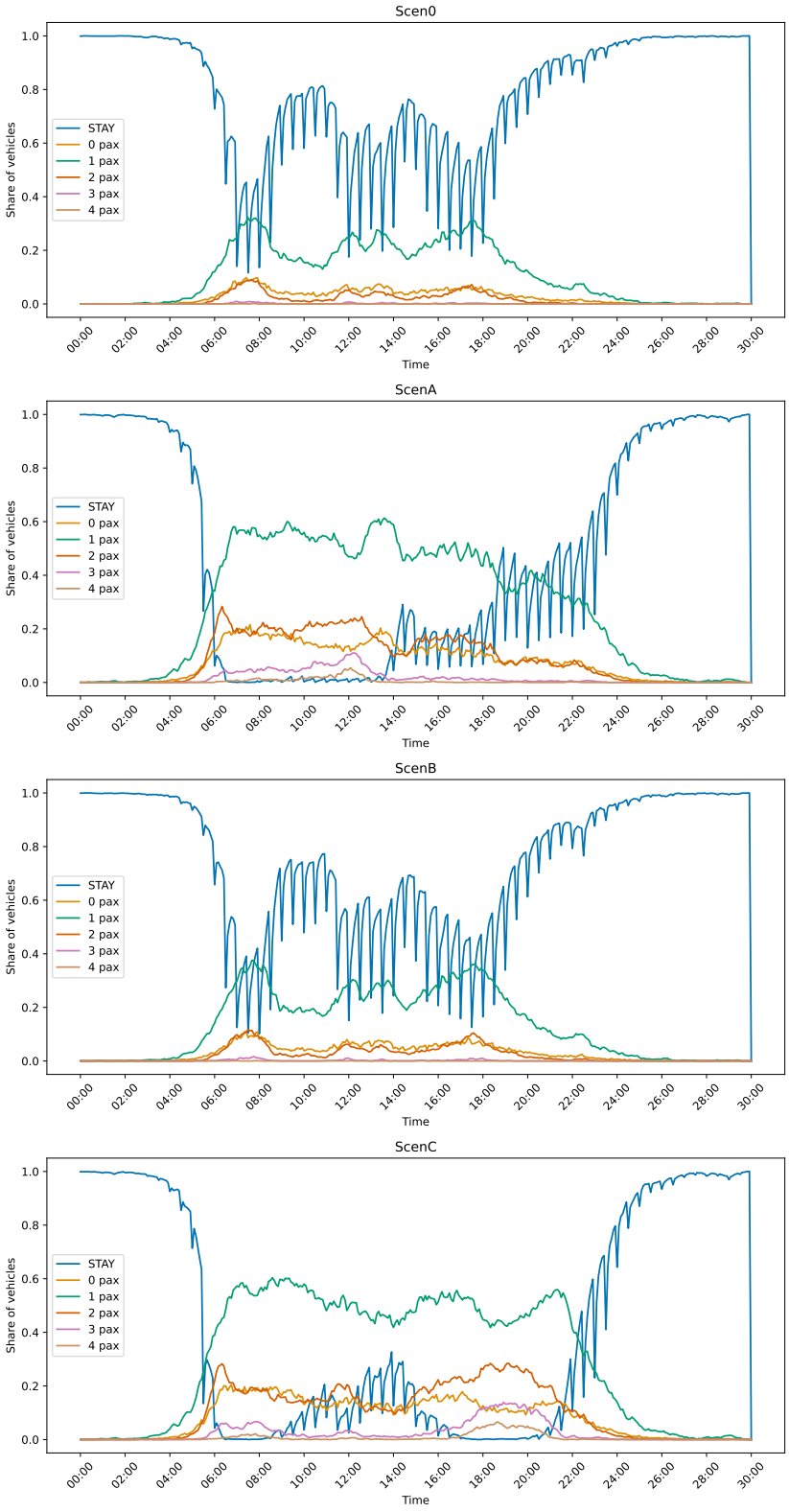


Fig. 42 *Vehicle occupancy per hour for aRP in Chur.*

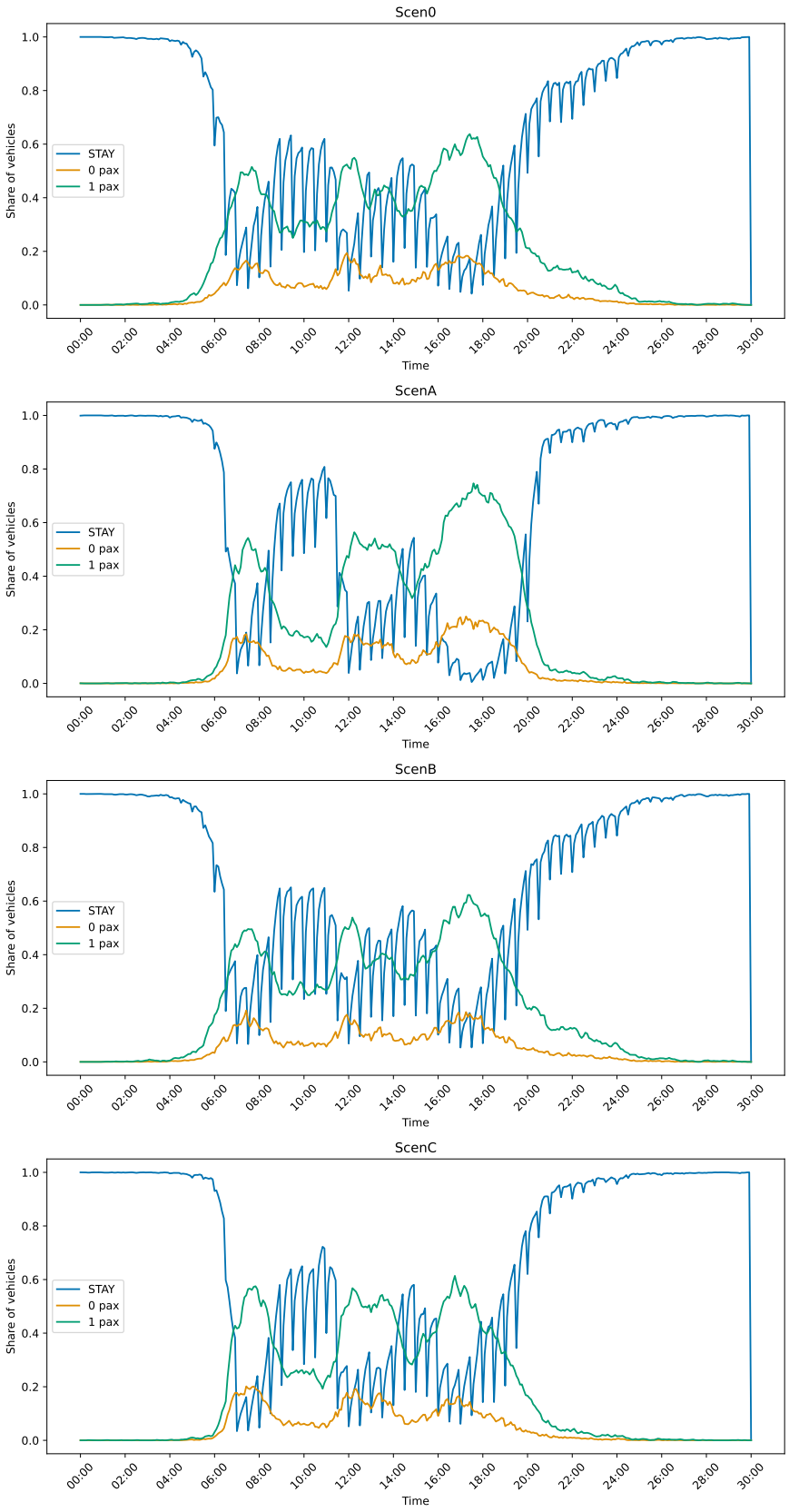


Fig. 43 *Vehicle occupancy per hour for aRH in Chur.*

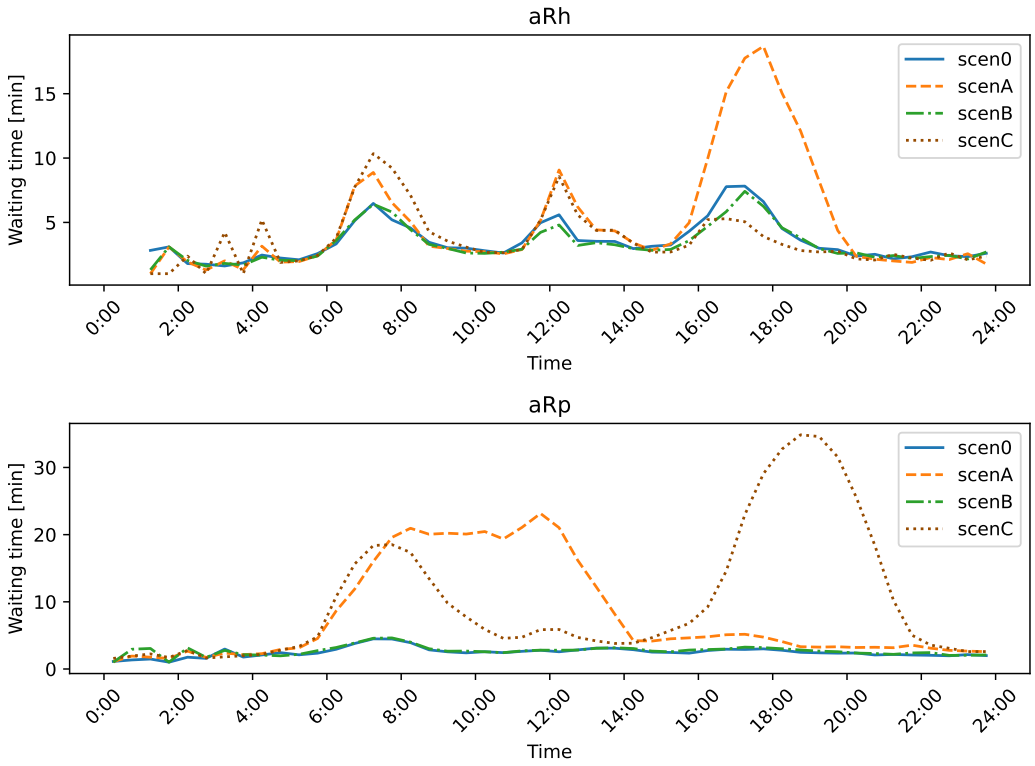


Fig. 44 *Average waiting times for aRP and aRH in Chur.*

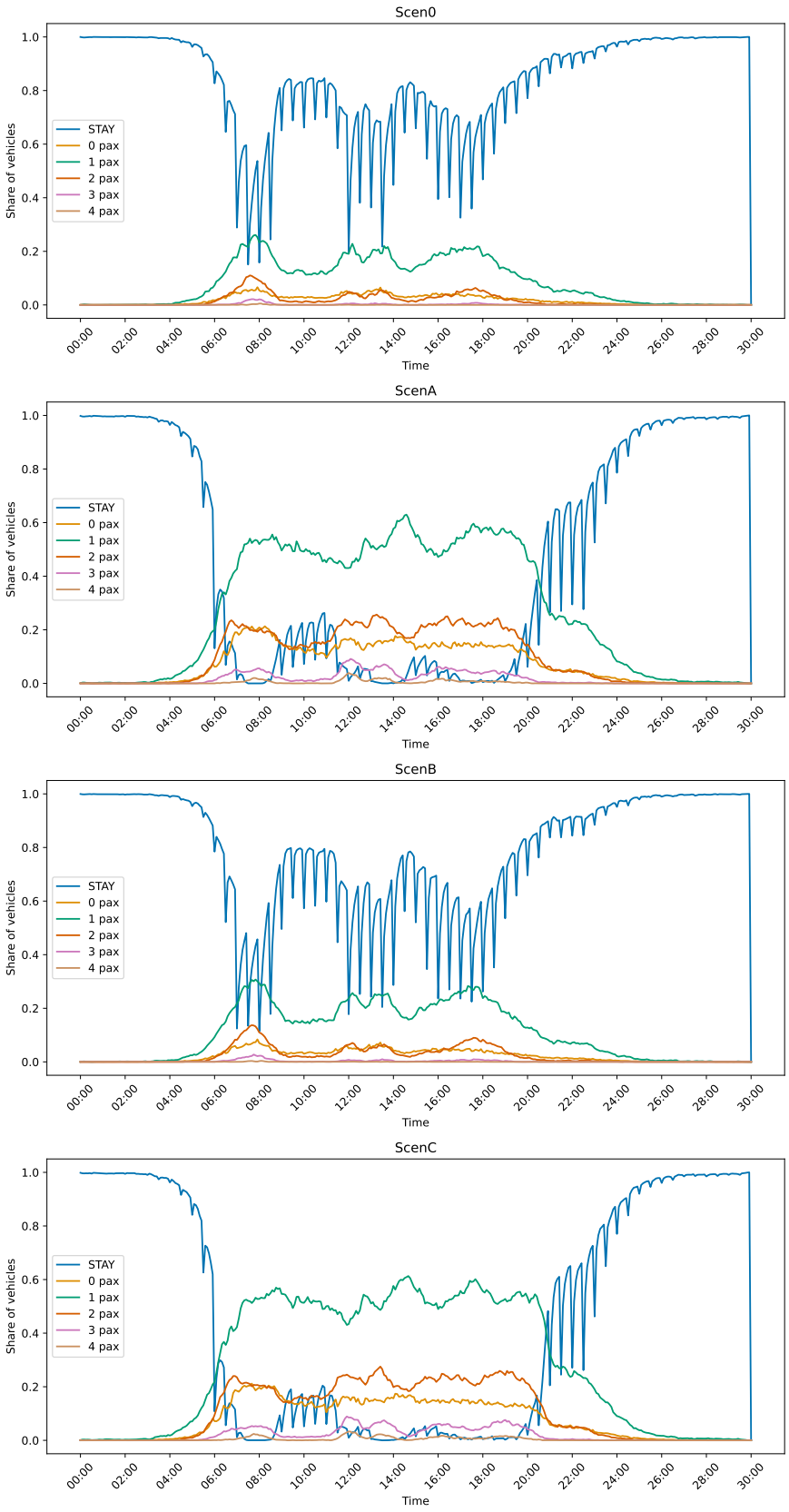


Fig. 45 *Vehicle occupancy per hour for aRP in Fribourg.*

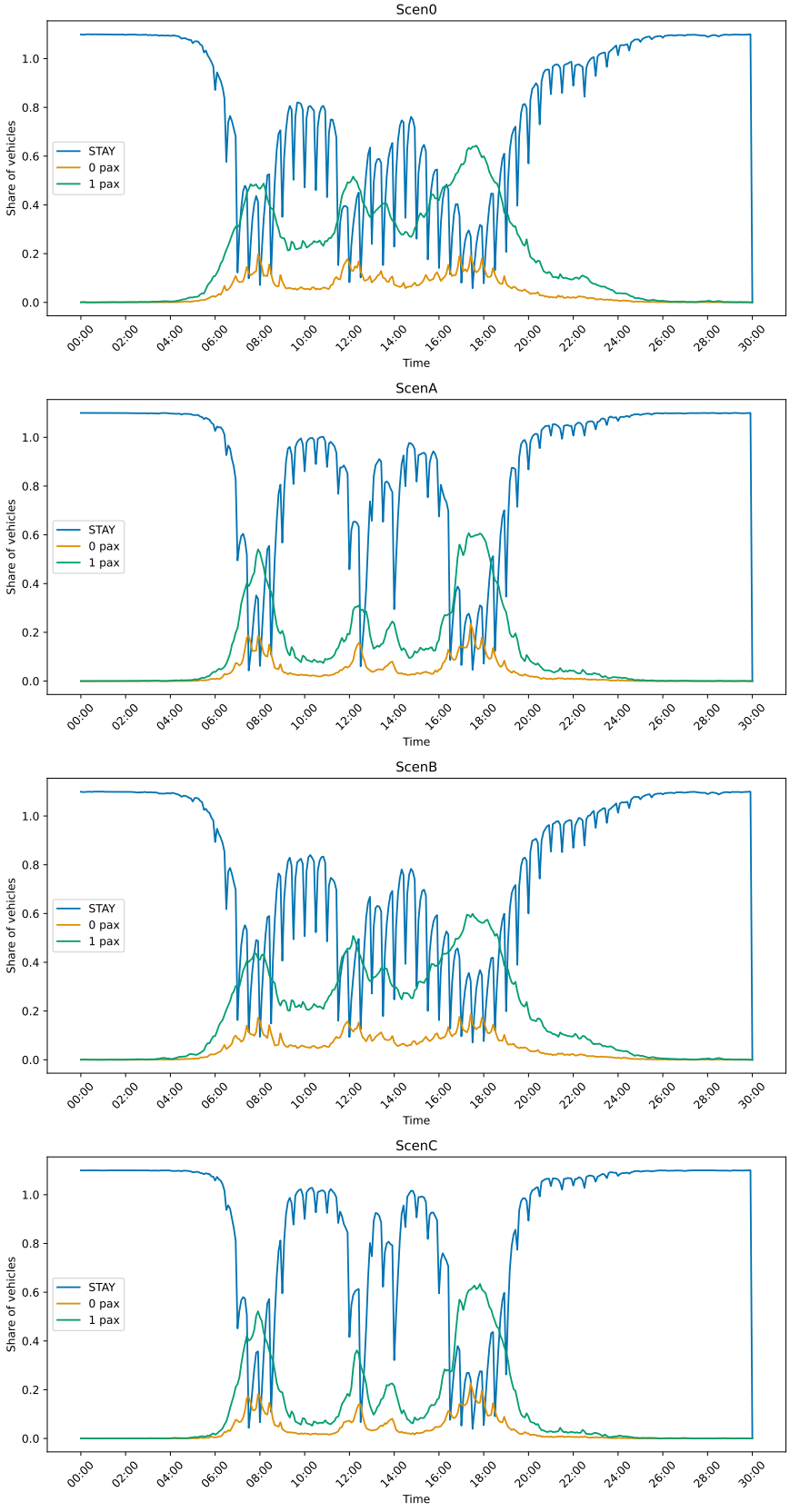


Fig. 46 *Vehicle occupancy per hour for aRH in Fribourg.*

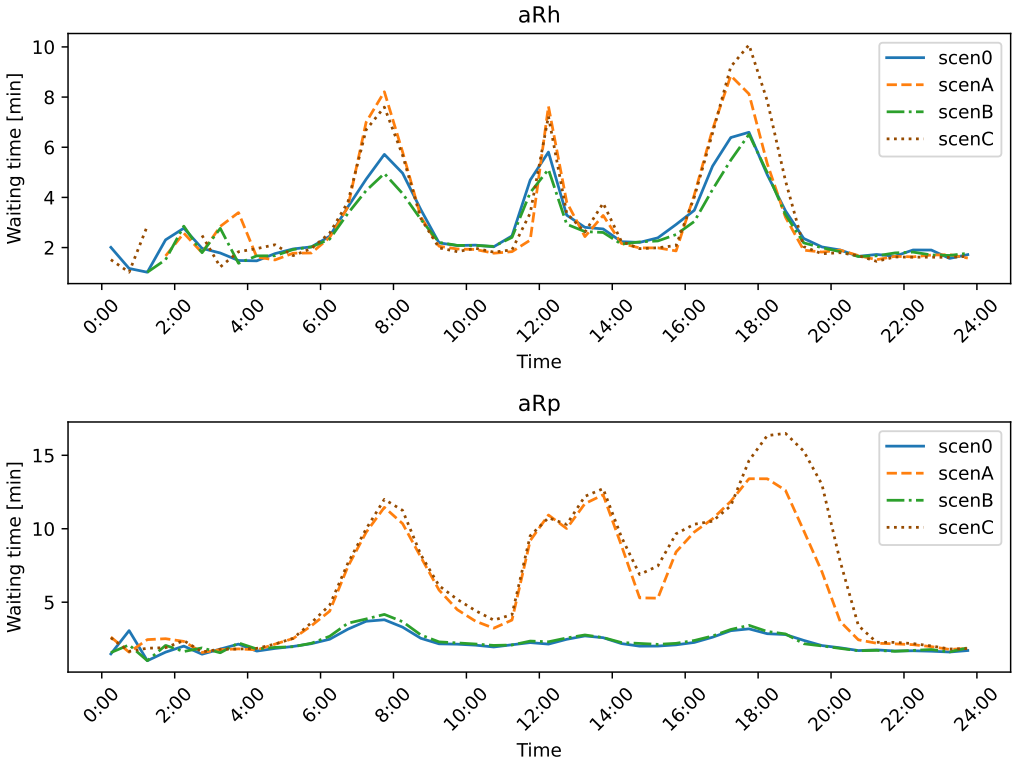


Fig. 47 *Average waiting times for aRP and aRH in Fribourg.*

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Project closure

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FORSCHUNG IM STRASSENWESEN DES UVEK

Version vom 09.10.2013

Formular Nr. 3: Projektabschluss

erstellt / geändert am: 27.8.2024

Grunddaten

Projekt-Nr.:	MB4_20_01A
Projekttitel:	Pooling and its behavioural implications
Enddatum:	15.9.2024

Texte

Zusammenfassung der Projektresultate:

Bisher wurde die Akzeptanz von Ridepooling-Angeboten mit autonomen Fahrzeugen im Schweizer Kontext nicht untersucht.
Zudem war das Wissen zum Verkehrsverhalten und den verkehrlichen Wirkungen von solchen Angeboten lückenhaft.

Um die fördernden und hemmenden Faktoren bei der Nutzung von autonomen Fahrzeugen zu bestimmen, wurden qualitative Interviews durchgeführt. Diese zeigen auf, dass viele Faktoren wie Sicherheit in Bezug auf Technik, Warte- und Fahrzeiten, Umweltaspekte, Zuverlässigkeit, Flexibilität, Verfügbarkeit oder Komfort die Akzeptanz bestimmen. Bemerkenswert ist, dass keiner dieser Faktoren eindeutig als Hindernis oder Treiber wahrgenommen wird. Gleichzeitig wird Ridepooling als teurer als der öffentliche Verkehr (ÖV) aber günstiger als die Nutzung eines privaten Personenwagen (PW) wahrgenommen. Sicherheitsbedenken hingegen werden nur von selten als mögliches Hemmnis genannt.

Um zu verstehen und zu quantifizieren, wie sich Ride-Hailing- (aRH) und Ride-Pooling-Dienste (aRP), die von autonomen Fahrzeugflotten angeboten werden, auf das Reiseverhalten auswirken, wurde eine Stated Preference-Befragung (SP Befragung) in der deutsch- und französischsprachigen Schweiz durchgeführt.

Die Ergebnisse zeigen, dass die Reisezeit sowohl für aRP als auch für aRH im Vergleich zum ÖV und zum PW negativer bewertet wird. Die Reisezeitersparnis, die diese Verkehrsmittel im Vergleich zum ÖV bieten, in Kombination mit ihren geringeren Kosten im Vergleich zum PW, ermöglichen es ihnen, Marktanteile von beiden bestehenden Verkehrsmitteln zu gewinnen.

Das Wahl-Experiment hinsichtlich der Verkehrsmittel zeigt eine generelle Abneigung, auf den Besitz eines Autos zu verzichten, selbst wenn Flotten von gemeinsam genutzten autonomen Fahrzeugen eine umfassende persönliche Mobilität ohne eigenes Fahrzeug ermöglichen könnten. Umgekehrt zeigten die Befragten eine hohe Bereitschaft, eine Rabattkarte für das ÖV-Angebot zu erwerben, insbesondere diejenigen, die derzeit nur selten den ÖV nutzen und keine Fahrkarte oder nur ein Halbtax besitzen.

Ein agentenbasierter Ansatz der Verkehrsnachfragemodellierung wurde verwendet, um die potenziellen Auswirkungen von autonomen Fahrzeugen in drei städtischen Regionen der Schweiz zu bewerten: Chur, Fribourg und Zürich. Für jede untersuchte Region simulierten wir fünf Szenarien: den aktuellen Zustand des Systems, die Einführung autonomer Fahrzeuge und drei Szenarien mit verkehrsplanerischen Massnahmen, die darauf abzielen, Einzelpersonen zu einem nachhaltigeren, gepoolten autonomen Dienst zu bewegen.

Aus der Perspektive des gesamten Verkehrssystems zeigen die Ergebnisse, dass die Einführung von aRP- und aRH-Angeboten die Gesamtreisezeit verkürzt, den Anteil des konventionellen ÖV verringert und die Gesamtfahrleistung steigert. Die drei angewandten verkehrsplanerischen Massnahmen zeigen in allen drei untersuchten Regionen ähnliche Auswirkungen. Die Bündelungsrate steigt erheblich auf Kosten einer höheren Gesamtfahrleistung, wobei der Anstieg in Zürich am stärksten ist.

Die Pull-Massnahmen (Vergünstigung von aRP je nach ÖV-Güteklasse) erhöhen die aRP Nachfrage erheblich und verringern in Chur und Freiburg die Gesamtreisezeit, während sie diese in Zürich erhöhen. Die Push-Massnahmen (Cordon-Pricing für PW in Zürich und leistungsabhängige Strassennutzungsgebühr in Chur und Fribourg) reichen nicht aus, um das durch die neuen Angebote ausgelöste Verkehrswachstum wesentlich einzudämmen.

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Zielerreichung:

Alle Projektziele wurden erreicht:
a) Untersuchung der fördernden und hemmenden Faktoren bei der Nutzung von aRP für die Schweiz
b) Quantifizierung des Reiseverhaltens im Zusammenhang mit aRP und aRH-Angeboten, durch die Entwicklung und Umsetzung einer neuen, pivot-basierten Stated Preference Befragung
c) Implementierung der Umfrageergebnisse in ein agentenbasiertes Verkehrsnachfragemodell der Schweiz und Verknüpfung des Entscheidungsmodells mit betrieblichen Merkmalen, z. B. Flottengrösse, Preisgestaltung, Wartezeit, Zugangs- und Reisezeit und Fahrzeugbelegung.

Folgerungen und Empfehlungen:

Ohne flankierende Massnahmen erhöht die Einführung von autonomen Fahrzeugen und deren Einsatz im aRH und aRP die Verkehrsleistung im Strassenverkehr. Die Ergebnisse zeigen zwar auf, dass verkehrsplanerische Massnahmen dazu beitragen können, das Wachstum einzudämmen und die Pooling-Quoten zu erhöhen. Es fehlt aber eine auf Simulationsstudien abgestützte Vision, die aufzeigt, wie autonome Fahrzeuge eingesetzt werden können, um gesamtgesellschaftliche Ziele, insbesondere in Bezug auf die Nachhaltigkeit erreicht werden können.

Die Erfassung der Akzeptanz von Fahrgemeinschaften mit autonomen Fahrzeugen und die Modellierung des Reiseverhaltens sowie die Simulation von Szenarien mit grossen aRP- und aRH-Flotten, ist mit verschiedenen Unsicherheiten verbunden. In diesem Zusammenhang empfehlen wir die folgenden Stossrichtungen für die zukünftige Forschung:

- Durchführung von qualitativen Interviews mit Personen, die im Rahmen von Pilotprojekten eigene Erfahrung bei der Nutzung von autonomen Fahrzeugen im Ridepooling-Betrieb machen konnten.
- In künftigten Stated Preference-Experimenten sollen auch Entscheidungssituationen umfassen, welche aRP und aRH im Kontext von heute mit dem Velo, E-Bike oder S-Pedelec zurückgelegten Wegen untersuchen. Zudem sollte auch die Wirkung von verkehrsplanerischen Massnahmen, die zu einer Erhöhung der Pooling-Rate führen sowie die Mobility Pricing untersucht werden.
- In zukünftigen Simulationsstudien sollte die Auswertung detaillierter erfolgen. Darauf basierend sollten vielversprechende verkehrsplanerische Massnahmen iterativ weiterentwickelt und mit weiteren Simulationen überprüft werden. Um die notwendigen und wünschenswerten Massnahmen im Sinne einer nachhaltigen Verkehrsentwicklung zu identifizieren, erscheint die Anwendung eines Backcasting-Ansatzes als sinnvoll.

Publikationen:

Im Rahmen der Projekts wurden folgende Publikationen veröffentlicht, respektive zur Veröffentlichung eingereicht.

Stefanelli, A., Haiderer, N., Studer, N., Schaffner, D., Erath, A., & van Eggermond, M. (2022). Pool More, Drive Less: An In-Depth Qualitative Investigation of Barriers and Motivators of Ride-Pooling in Autonomous Vehicles. The Association for Consumer Research Conference, Denver. https://irl.fhnw.ch/handle/11654/34089

Ghandeharioun, Z. & Kouvelas, A. (2023). Real-time ridesharing operations for on-demand capacitated systems considering dynamic travel time information. Transportation Research Part C: Emerging Technologies, 151, 104115. (Ghandeharioun & Kouvelas, 2023)

Erath, A. (2023). How autonomous electric vehicles will affect the Swiss transport system. What we already know and what we can't know yet [Präsentation]. NSL Colloqium 'Transport planning: Where do we go now?', ETH Zurich. ETH Zürich. https://irl.fhnw.ch/handle/11654/38879

Kagho, G., Balac, M., Erath, A., van Eggermond, M., Axhausen, K. (2025), Simulation of policies for automated ride-hailing and ride-pooling services, submitted for the 104th TRB Annual Meeting of the Transportation Research Board.

Weitere Publikationen der Projektergebnisse sind geplant.

Der Projektleiter/die Projektleiterin:

Name: Erath Vorname: Alexander

Amt, Firma, Institut: FHNW, Hochschule für Architktur Bau und Geomatik, Institut für Bauingenieurwesen

Unterschrift des Projektleiters/der Projektleiterin:



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Beurteilung der Begleitkommission:

Beurteilung:

Das Forschungsprojekt behandelt im Kern die Untersuchung von hypothetischen Entscheiden von Verkehrsteilnehmenden bezüglich ihrer Verkehrsmittelwahl im Alltag. Zur Auswahl steht den Verkehrsteilnehmenden - neben den bekannten Fortbewegungsarten - eine neue Verkehrsoption in Form von kollektiv genutzten autonome Fahrzeugen.
Die Effekte hinsichtlich der Wahl von autonomen Fahrzeugen auf das Gesamtverkehrssystem wurden untersucht.
Die Forschungsstelle hat diese Fragestellung umfangreich mit einer Literaturanalyse, qualtiativen Interviews, der Durchführung und der Auswertung einer Stated Preference-Befragung sowie der Umsetzung von agenten-basierten Simulationsstudien in drei Regionen aus Sicht der Forschung qualitativ hochstehend bearbeitet. Für Praxisempfehlungen erfolgte eine Anwendung der Ergebnisse in Fallstudien.

Aufgrund der Ergebnisse aus diesen grundlegenden Arbeiten konnten neue Erkenntnisse in Bezug auf die Akzeptanz eines neuen Verkehrsmittels, dessen Einfluss auf das Verkehrsverhalten und die Wirkung von grossen Flotten mit geteilten autonomen Fahrzeugen gewonnen werden.

Die Ergebnisse zeigen auf, dass autonome Fahrzeuge gerade im Betrieb als Ridepooling-Angebote das Potenzial bieten, bestehende Angebotslücken im ÖV zu schliessen. Gleichzeitig wurde aber auch aufgezeigt, dass eine Einführung von autonomen, geteilten Fahrzeugen ohne flankierende Massnahmen zu Mehrverkehr führt und den ÖV auch dort konkurriert, wo dieser aufgrund der höheren Flächeneffizienz Vorteile bietet.

Der Bericht dokumentiert die durchgeführten Arbeiten ausführlich. Die Zusammenarbeit mit der Forschungsstelle war aus Sicht der Begleitkommission immer konstruktiv zielführend. Die Verzögerung beim Projektfortschritt wurden stets gut begründet und sind auf die hohe Komplexität der Forschungsarbeit zurückzuführen.

Umsetzung:

Die Arbeit zeigt auf, dass Flotten von geteilten, autonomen Fahrzeugen ein grosses Potenzial haben bestehende ÖV-Angebotslücken zu schliessen und auch den Besetzungsgrad von Fahrzeugen im Strassenverkehr zu erhöhen. Die Ergebnisse der Simulationsstudien weisen darauf hin, dass verschiedene Pull- und Pushmassnahmen dazu beitragen, negative Begleiterscheinungen bei der Einführung solcher Angebote, wie zum Beispiel Mehrverkehr und direkte Konkurrenzierung bestehender, flächeneffizienter ÖV-Angebote einzudämmen.

Um besser zu verstehen, welche verkehrsplanerischen Massnahmen und Auflagen, z.B. hinsichtlich der Konzessionierung von geteilten autonomen Fahrzeugflotten das Verkehrssystem als Ganzes optimieren, bedarf es aber weiterer, tiefer gehenden und auf die jeweiligen lokalen Verhältnisse abgestimmte Simulationsstudien.

weitergehender Forschungsbedarf:

Die BK teilt die Einschätzung des Forschungsteams bezüglich des weiteren Forschungsbedarfs:
- Durchführung von qualitativen Interviews mit Personen, welche bereits Erfahrungen mit autonomen Fahrzeugen betriebene Ridepooling-Angebote gesammelt haben.
- Weiterführende Stated Preference Befragung zum Verkehrsverhalten mit autonomen Fahrzeugen in Konkurrenz zu Velo und E-Bike sowie Mobility Pricing und verkehrsplanerischen Massnahmen, die zu einer Erhöhung der Pooling-Rate führen.
- In zukünftigen Simulationstudien sollte die Auswertung und die Weiterentwicklung von Massnahmen zur Optimierung des verkehrlichen Gesamtsystems iterativ erfolgen. Hinsichtlich der Erreichung von Nachhaltigkeitszielen im Kontext von autonomen Fahrzeugen bietet sich ein Backcasting-Ansatz an.

Einfluss auf Normenwerk:

Mit der Ausschreibung der Arbeit und deren Durchführung wurde kein Einfluss auf das Normenwerk beabsichtigt.

Der Präsident/die Präsidentin der Begleitkommission:

Name: Ohnmacht Vorname: Timo

Amt, Firma, Institut: Hochschule Luzern - Wirtschaft, Instititut für Tourismus und Mobilität

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

