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Autonomous Mobility-on-Demand in a Rural Area: Calibration, Simulation and Projection based on Real-world Data

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Abstract

In a pilot project, the operation of autonomous vehicle(s) (AV) in an Mobility-on-Demand (MoD) system without fixed routes is tested on public streets in Kelheim Germany, for the first time. The autonomous service is launched in September 2022 and is integrated into an existing service with human-driven vehicles. This work presents agent-based model for the Kelheim county that is calibrated based on real demand data from the MoD operation. The model is used for demand prediction and impact assessment of several configurations of the AV service. The results suggest that the conventional service is not negatively affected but rather complemented by the AV service. Furthermore, the results show that with the expansion of the AV fleet planned in 2023, the corresponding service area should also be extended. This could lead to a higher efficiency in the AV operation compared to the conventional service. Similar to other findings in the literature, it is observed that the electric AV mainly replace trips with sustainable transport modes. In future, the results will be validated and the mode choice model will be further improved with the help of real AV demand data that will become available during the course of the project.

Keywords: Autonomous Vehicles; Mobility-On-Demand; Demand-Responsive Transport; Transport Simulation; Agent-based Simulation; Rural Mobility

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Acronyms

AMoD Autonomous Mobility-on-Demand. 3

ASC alternative-specific constant. 5, 6

AV autonomous vehicle(s). 1, 2, 5, 6, 9, 10, 11, 12, 13, 14, 15

DRT Demand responsive transport. 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14

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MATSim	Multi-Agent Transport Simulation. 2, 3, 4, 7
MiD	Mobilität in Deutschland. 6
MiT	Mobilität in Tabellen. 6
MoD	Mobility-on-Demand. 1, 2, 3, 6, 11, 12, 13, 14, 15
pt	public transport. 3, 5, 11, 12, 13, 14
SUMO	Simulation of Urban Mobility. 3

1. Introduction

MoD systems have been a focus point of transportation research over the past years, as they fit into the thriving of the sharing economy and have the potential to change the system and the mobility of its users (Narayanan et al., 2020). From an operator's perspective, automated driving could be the major lever in terms of profitability and market power (Litman, 2019; Hörl et al., 2019; Reck and Axhausen, 2019; Bösch et al., 2018). In the past years, many pilot projects tested and investigated the usage of AV for MoD services on public European streets (Technische Universität Hamburg, 2021; Berliner Verkehrsbetriebe, 2022; EasyMile SAS, 2022). However, to the best knowledge of the authors, none of these projects involved a service that was operating without fixed routes. In 2021, the German government passed a law, that made the operation of autonomous vehicles without fixed routes on public European streets possible for test purposes, for the very first time. The project KelRide (Landkreis Kelheim, 2022a) aims to integrate AV that operate freely within a given service area, i.e. do not follow a fixed route, into an existing MoD service in the city of Kelheim, Germany. One focus point is to improve resistance of AV to bad weather and allow for a year-round and highly reliable service. Another important objective is to integrate the service into the public transportation system in an efficient way. In order to understand the impact of the MoD service on the mobility of the population as well as on the transport systems as a whole, a simulation model of the entire region is set up. This model is used in decision making for designing and adopting the service over the course of the project. As an example, after its introduction in September 2022, the autonomous part of the fleet will be expanded from two vehicles to five in summer 2023. The present study uses the model for a case study to address the question whether and how the corresponding service area should be adjusted as an accompanying measure.

Thus, following a short overview on the state of practice in MoD modeling in Section 2, Section 3 presents the development of an activity and agent based transport model for the region of Kelheim, using trajectories generated based on mobility phone data and the simulation software Multi-Agent Transport Simulation (MATSim). The model is then further enriched by representing the human-driven MoD service in the city of Kelheim, named KEXI, which is calibrated based on real demand data from the KelRide project. On this basis, a case study on the introduction and the service design of an autonomous part of the KEXI service is conducted in Section 4 with particular focus on the service area to be established in the future of the project. Finally, Section 5 discusses results and provides an outlook on future work with the developed transport model.

2. State of Research

To the knowledge of the authors, there exists no open source transport model that includes a MoD service, for which the demand reaction is calibrated based on real data. In the following, we provide an overview of existing models and research in the field of MoD, which we will also refer to as Demand responsive transport (DRT).

2.1. Existing DRT models in rural and suburban areas

One of the special features of this research is the focus on a rural area, where the populaton density is typically is low. This subsection tries to give a brief overview of already existing DRT models in rural areas.

Scheier et al. (2021) created a traffic model including MoD vehicles serving a wide rural area near Braunschweig, Germany using the simulation software Simulation of Urban Mobility (SUMO). In their study, the authors find an improved subjective travel experience when implementing compartment buses while at the same time, compared to a fleet of conventional buses, a 10% cost increase can be expected (Scheier et al., 2021).

In a pilot project applying a ride-hailing bus service to the Oberharz region of Germany for six months Sörensen et al. (2021) analyzed gathered demand data. It is concluded that without choosing the DRT service area carefully the service might act as a direct competitor for the existing public transport (pt). By considering existing pt when introducing DRT service areas though, ride-hailing services could operate as feeder lines for rural pt lines or even long distance trains. Such connected operation bears the chance of keeping the existing services intact. It may even attract more demand in general but also makes adaptions for the existing pt necessary (Sörensen et al., 2021).

Liu et al. (2017) conduct simulation experiments on the demand reaction to different price levels for an autonomous DRT system in the six-county region of Austin, Texas. They find mode shares of the autonomous DRT system of up to 50% for low prices and observe that long-distance travelers prefer the service over private cars. The authors also state that pt operators might have difficulties to survive in the region, if an autonomous DRT system is introduced.

In a study, where a ride-hailing service with calibrated prices is transferred to the rural region of Vulkaneifel, Germany, Kaddoura et al. (2021) found that such service can make up for about 16% of all trips when introduced. Just as for Liu et al. (2017), they use MATSim as simulation framework. When comparing their findings for the rural area to more urban settings, they observe a significantly increased average distance travelled by DRT vehicles, which can be explained by (a) the size of the served area and (b) a modal shift analysis. Whereas results for the urban areas suggest no clear share of a certain mode from which passengers shift to the MoD service, for the Vulkaneifel scenario passengers are mainly drawn from modes bike, ride and pt (Kaddoura et al., 2021). Apart from the modal shift analysis, a recent study observing the same rural region focused on DRT pre-booking (Lu et al., 2022a). It demonstrates that efficiency of the DRT operation in the Vulkaneifel region can be greatly improved with the help of pre-booking. As a result, the cost to operate the DRT system can be reduced.

2.2. Simulation of autonomous DRT

As stated in the previous subsection, there already exist numerous studies regarding existing DRT models in rural areas. This subsection aims to give a brief summary of already existing models using an Autonomous Mobility-on-Demand (AMoD) fleet. With AMoDeus Ruch et al. (2018) set a base for investigating and analyzing simulated autonomous DRT models. It was developed using multiple scenarios including one that contains taxi data of the San Francisco area. Due to its open source approach it aims to be easily applicable to other use cases (Ruch et al., 2018).

In order to investigate the effects of a large-sized AMoD fleet Hörl (2020) found that with a number of 7000 vehicles the fleet has a modal share of 31%. Here, passengers are attracted from the modes bike, pt and car. While a general reduction of circulating vehicles can be observed, the overall driven vehicle kilometers increase heavily when modeling the autonomous DRT fleet (Hörl, 2020). Similar findings have been made by Marczuk et al. (2015) when simulating an AMoD fleet, which substitutes private car trips in the Central Business District of Singapore, with the mobility simulation software SimMobility. Depending on the simulated fleet size, road congestion increases due to empty trips of fleet vehicles whereas waiting times can be decreased significantly (Marczuk et al., 2015).

Coretti Sanchez et al. (2022) present another framework for the agent-based simulation and assessment of fleet behavior of autonomous shared mobility systems. Similar to the AMoDeus framework however, there is no mode choice model included. Thus, demand reactions to different operation strategies and service configurations can not be investigated.

2.3. Investigation of Service Area Expansion / Configuration of DRT

The previous subsections have shown that MoD services highly depend on the area they are serving. Therefore, multiple studies with the aim of developing methodologies to determine somewhat ideal service areas have been conducted. Bischoff et al. (2018) have developed a simulation-based methodology to identify the optimal service area of a DRT system. The method gradually modifies the service area while monitoring the results of an objective function (e.g. profitability, vehicle occupancy). An optimal service area, based on the objective function defined by the user, will be returned in the end. This approach has been applied in the follow-up studies by Kaddoura et al. (2020b) and Kaddoura et al. (2020c), where other aspects of DRT configuration, such as pricing, are also considered.

In a study investigating potential DRT service areas for the Greater Manchester region, United Kingdom, Wang et al. (2014) investigated correlations between demand level in different service areas and several socio-economic parameters. They find that areas with a low population density, a low share of inhabitants working from home, low car ownership and high level of deprivation are associated with a higher DRT demand. They state that their findings on the correlation of population density and the demand are in line with earlier research (Nutley, 1988; Koffman, 2004) and speculate that rural areas might experience even higher demand levels, if deprivation is maintained. In contrast, more recent studies suggest that operators tend to serve areas of high population density, where ride-sharing is facilitated, waiting times can be maintained at a low level with less mileage and thus the operation tends to be more profitable or efficient(Bischoff et al., 2018; Schlenther et al., 2020; Bischoff and Maciejewski, 2016a; Liu et al., 2017).

Wagner et al. (2015) state similar findings for car-sharing services using geographically weighted regression models.

For the study at hand, possible service areas were already predefined within the project based on both technical and qualitative constraints such as the feasibility for measuring the environment and driveability of the roads due to steepness. However, future investigations might involve automated processes for expanding the service area.

3. Methodology

The transport model presented in this paper is developed within the open-source simulation framework MATSim (Horni et al., 2016b). MATSim has already been applied to cities and regions of multiple types in various countries including the United States of America (Pozdnoukhov et al., 2016; Liu et al., 2017), Chile (Kickhöfer et al., 2016; Zwick, 2017), France (Hörl et al., 2019), Sweden (Márquez-Fernández et al., 2021) and Germany (Ziemke et al., 2019; Kaddoura et al., 2020a).

3.1. MATSim

A typical MATSim simulation relies on a model of transport supply as well as an initial traffic demand, which is described by a synthetic population composed of so-called agents who hold several options for their daily plans. A plan consists of activities that can vary in their type and duration, and so-called legs between them, which are associated with a transport mode the agents travels with. At the beginning of the simulation, agents choose one plan, which they perform in the physical mobility simulation. After a complete day is simulated, all executed plans get evaluated and assigned a utility score. Some of the agents are then allowed to adapt one of their plans and the mobility simulation is performed again. This cycle typically is repeated until a user-equilibrium is approximated (Horni et al., 2016a).

The scoring of plans is done by the so-called Charypar-Nagel Utility Function, which is described in Equation 1. The total utility S_{plan} for a plan is defined as the sum of all activity utilities $S_{act,q}$ plus the sum of all travel (dis)utilities $S_{trav,mode(q)}$ (Charypar and Nagel, 2005).

$$S_{plan} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,mode(q)} \tag{1}$$

$$S_{trav,q} = C_{mode(q)} + \beta_{trav,mode(q)} * t_{trav,q} + \beta_m * \Delta m_q + (\beta_{d,mode(q)} + \beta_m * \gamma_{d,mode(q)}) * d_{trav,q} + \beta_{transfer} * x_{transfer,q} \tag{2}$$

As some of the parameters will be of importance in the following sections, a closer look on the travel (dis)utility will be taken (see Equation 2): For each leg q the travel (dis)utility $S_{trav,q}$ is calculated by a mode-specific constant $C_{mode(q)}$ (also known as alternative-specific constant (ASC)), added to the time $t_{trav,q}$, change in monetary budget Δm_q, distance $d_{trav,q}$, and transfers $x_{trav,q}$ spent traveling. Further, each parameter is multiplied by a marginal utility β, which indicates whether the parameter has a positive or negative influence on $S_{trav,q}$. Due to varying cost parameters per transport mode, for the distance travelled $d_{trav,q}$, additionally to the marginal utility of distance $\beta_{d,mode(q)}$, a mode-specific monetary distance rate $\gamma_{d,mode(q)}$ multiplied by the general marginal utility of money β_m is taken into account (Nagel et al., 2016).

3.2. Transport Model Generation

The DRT service operates within the municipality of Kelheim, which represents the most populated city within the eponymous district of Landkreis Kelheim (i.e., Kelheim county). For the generation of the transport model, we refer to the Landkreis Kelheim as the study area within this subsection. It is depicted by the blue line in Figure 1a. As it represents the area of operation for the DRT service, the city of Kelheim can be understood as the focus area for the model application in Section 4.

For the Kelheim model, the person transport demand is generated based on mobile phone trajectories and region-type specific behavioral survey data (Neumann and Balmer, 2020; infas et al., 2019, 2017; infas et al., 2018). The demand is derived from a Germany-wide transport model that depicts a typical non-week-end day by cutting out all agents that have at least one activity in the area of interest, i.e. the Kelheim county as shown in Figure 1a. This means, the model respects for long-haul travelers between Kelheim and any other location in Germany. As within the Germany-wide model the population is represented at a sample size of 25%, which is done for computational reasons, this applies to the resulting Kelheim demand model as well, resulting in 42,455 agents.

In addition to the trips made by people, we also account for long-haul freight traffic, which is generated by extracting relevant trips from the German-wide traffic model created by Lu et al. (2022b). This freight model includes both domestic and international trips. The trips are generated based on data from the German Federal Ministry for Digital and Transport (BMDV) and calibrated against freight traffic count data from the German Federal Highway Research Institute (BASt). To extract freight trips that are relevant to the Kelheim model, all freight trips that travel within, originate from, terminate in, or pass through the region are kept. After the extraction process, 20,528 daily long-haul freight trips remain, which corresponds to 5,132 trips in the 25% scenario.

As for the modeled transport supply, the road network is generated based on OSM data (OpenStreetMap, 2021). While it is modeled in full detail within the investigation area, i.e. surrounding the Kelheim county (see blue line in Figure 1a, where the roads are shown in black), it consists of all major roads in Germany. The road capacities are aligned with the demand sample size, i.e. set to 25%. The pt supply is modeled based on General Transit Feed Specification data from Brosi (2022) and covers most parts of Bavaria[1].

Summarizing, the resulting Kelheim transport model[2] consists of all conventional transport modes such as car as a driver, car as a passenger (referred to as ride), pt, bike and walk. The modes ride, bike and walk are modeled as so-called 'teleported modes', meaning agents are not physically moved on the network. This goes along with the assumption that these modes do not cause congestion effects and helps to improve computation time significantly. See Horni and Nagel (2016) for further explanation.

3.3. General Calibration

The calibration of the model is performed in two steps. First, a general calibration is undertaken in order to represent the transport system without DRT service. In a next step which is explained in Section 3.4, we calibrate the demand reaction to the introduction of the DRT service using real demand data. This serves as the basis for investigating effects of supply changes in the DRT system, including AV, as performed in Section 4.

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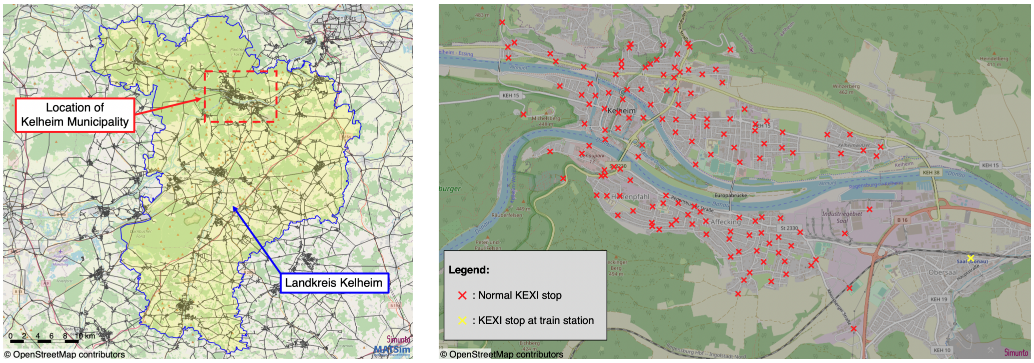
[1] the data is published under the Creative Commons license CC BY 4.0, see `https://creativecommons.org/licenses/by/4.0/`. No changes were made.

[2] see `https://github.com/matsim-scenarios/matsim-kelheim` for the computer code and more information



(a) Road network

(b) KEXI stop locations

Fig. 1: Modeled transport infrastructure: general road network and stop network for the MoD service KEXI

For the calibration of the base model without KEXI (cf. Sec. 1), a combination of data sources was used in order to derive the modal split for the general population as well as for trips in specific distance groups. The aggregated mode share over all trips is given by Mobilität in Deutschland (MiD) (infas et al., 2019) for the study area of Kelheim. In depth information about different distance groups was not available for this specific area. Instead, Mobilität in Tabellen (MiT) (infas et al., 2017; infas et al., 2018) data was used for that purpose. MiT provides modal split data by distance groups for seven generalized statistical region types (*RegioStaR 7*). For the study area we have used data for the region type *Kleinstädtischer, dörflicher Raum einer Ländlichen Region* (Small towns, village area of a rural region)[3].

To calibrate the model, the ASC (cf. $C_{mode(q)}$ in Equation 2) is set for each mode, such that the overall mode share matches the survey data (infas et al., 2019) as closely as possible. The purpose of the ASC is to capture the average effect on utility of all factors that are not directly included in the model. Thus, it is a free variable and can be used to fine-tune the model and resulting modal share. The results of the calibrated scenario are shown in Figure 2a. The largest offset for the modal split between simulation and survey data is observed for car, where the model value is 0.9% higher.

Additionally, to fitting the modal split, it is also important that travel times in the model are close to actual travel times observed in reality. To validate this, we compared 500 randomly selected trips within the study area and compared them to computed travel times from the online API HERE[4]. Figure 2b shows the results.

3.4. Real demand data analysis and DRT Calibration

The DRT service in Kelheim consists of two major parts: the conventional vehicles and autonomous shuttles (or AV). Both conventional vehicles and the autonomous shuttles are operated under the name of KEXI[5]. The conventional vehicle DRT service (conventional KEXI) covers most areas in Kelheim city. The autonomous DRT service (autonomous KEXI) was introduced to the service in September 2022 under the framework of the KelRide project, which is when this study was written (Landkreis Kelheim, 2022b). As the conventional KEXI service was already in operation, we generate the DRT service in our simulation framework based on the actual real world setup.

Currently, for the conventional KEXI service, three human-driven minivans provide an on-demand service in the city of Kelheim, Monday to Saturday, from 6:00 to 22:00. The service is stop-based, which means passengers will be picked up at one stop and delivered to another stop. The stops are indicated by the crosses in red and yellow in Figure 1b. The yellow dot is a special KEXI stop located at the train station Saal an der Donau. Here, passengers can transfer to regional trains and bus services. When a passenger travels between any two red stops, a flat rate of 2 Euro

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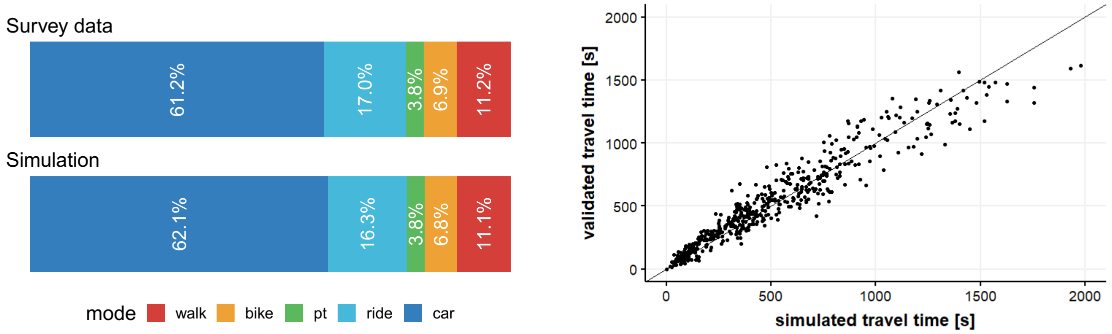
[3] for more information on the system of regional statistical typologies, see `https://www.bmvi.de/SharedDocs/DE/Artikel/G/regionalstatistische-raumtypologie.html`

[4] `https://developer.here.com/`

[5] `https://kexi.de/en/`



(a) Modal split in the survey data vs. simulation results

(b) Travel times: simulated vs. routed with online API

Fig. 2: Calibration of the general transport modal: Modal split and travel times

is charged. When a passenger travels from or to the yellow stop, the fare is 3 Euro. In the simulation, each stop is assumed to take one minute, regardless of the number of passengers boarding and deboarding.

The goal of the DRT calibration, i.e. of the conventional KEXI service, is to match the number of rides realized by the simulated service to the average number of rides in the real demand data (see red line in Figure 3b), which was provided by Via[6]. The provided data includes 6 months of service starting from July 2021 until January 2022, shown in Figure 3a. As, in the simulation, we model a typical weekday, the data is filtered accordingly. This means that out of the aforementioned time span we only look at Tuesday, Wednesday and Thursday and neglect all holidays. After filtering suitable dates, the number of rides on each day is counted, so an average number of rides can be calculated. The same process is done for the average Euclidean distance as well as the mean travel time. Based on the real world demand data, there are on average 119 customers choosing to use the conventional KEXI service per day. The average Euclidean distance of the travel demands is 2.1 km (stop to stop) and the average travel time is 503 seconds.

It needs to be pointed out that in our case study, while we are using a 25% sample of the population, the DRT services (both conventional KEXI and autonomous KEXI) are simulated at 100% in terms of demand and supply. This is because the actual scale of the DRT service in Kelheim is very small – with only 3 minivans and 2 autonomous vehicles, it is not possible to sample down the fleet size with somewhat logical results. Nevertheless, by adjusting the travel cost parameters (i.e., the mode-specific constant $C_{mode(DRT)}$ and marginal utility of travel time $\beta_{trav,mode(DRT)}$, for a more detailed explanation on the terms see Section 3.1), we can still match the full number of DRT rides – and not 25% of it as for other modes. The service quality is also compared against real world data. For mode choice experiments, this means that we treat the other modes as an infinite reservoir. In consequence, such experiments will remain valid as long as the mode shares of these other modes do not change by a lot.

During the calibration process, we have noticed that the number of DRT rides fluctuates within a certain range. Unlike larger scenarios, such as Bischoff and Maciejewski (2016b), where hundreds or even thousands of passengers are served by DRT vehicles every day, this scenario is very small, and fluctuation in the number of rides is relatively large compared to the target value. This does not mean the MATSim mode choice model does not provide realistic simulation results, as a similar fluctuation in number of rides can also be observed in the real world data, see Figure 3b. To account for the aforementioned fluctuation, average values of multiple parallel simulations with different random seeds are used. According to the t-distribution (Student, 1908) and based on the real world KEXI demand data, we determine the number of parallel simulation runs per investigated case to five. This leads to an accurate estimation of the number of conventional KEXI rides per day. More specifically, this means that for the calibrated KEXI case with conventional vehicles only, at a confidence level of 90% the obtained average number of rides (out of 5 simulation runs) lays inside the interval of ±6 rides of the target value (i.e. the error is within a range of 5%).

After the calibration, we end up with an average number of 120 conventional KEXI rides per day in the simulation, which is a good representation of the reality (in average 119 trips per day, cf. 3b). The average Euclidean distance

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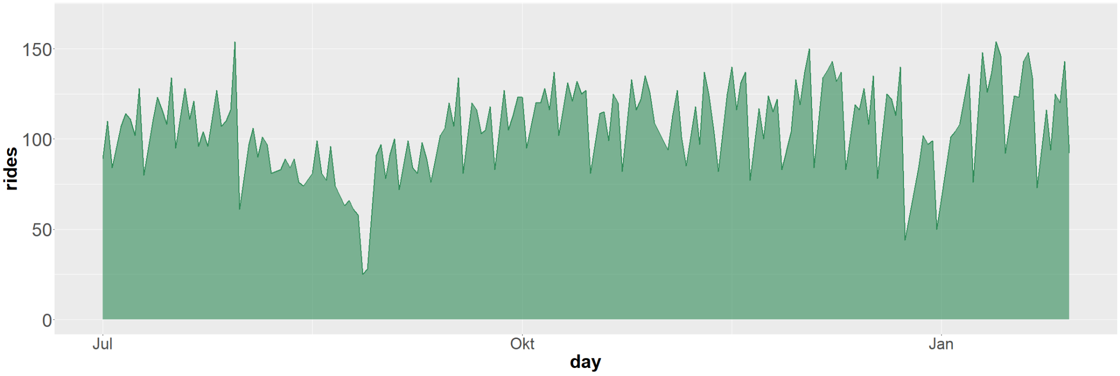
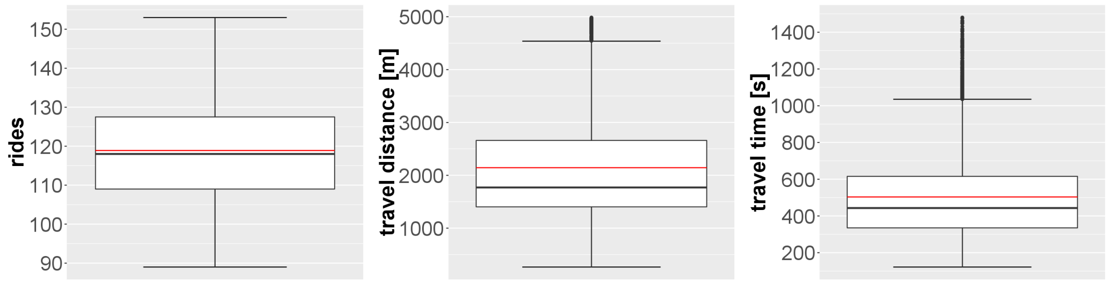
[6] `https://ridewithvia.com/`



(a) demand over time



(b) rides per day (c) travel distances (stop to stop) (d) travel times

Fig. 3: Statistics of real data on the conventional KEXI service for the time span July 2021 until January 2022. The red lines in the box plots display the mean value, while black lines inside the boxes display the median.

(i.e. between pick-up and drop-off) of conventional KEXI trips in our simulation is 2.34 km, and the average travel time is 467 seconds. These values are also reasonably close to the real demand data. The results of 5 parallel runs under the calibrated parameters are summarized in Table 1. The average values for real world data are represented in the table as target values, see Figures 3b, 3c and 3d for their distributions.

Table 1: DRT Calibration results for the conventional KEXI service, to be compared to real data shown in Figure 3

Runs	Nr. of rides	Mean Euclidean trip distance [m]	Mean travel time [s]
Run 1	121	2453	489
Run 2	120	2184	453
Run 3	127	2317	453
Run 4	124	2331	487
Run 5	108	2402	454
Average	120	2338	467
Target	119	2100	503

4. Application to a case study

The autonomous KEXI will be introduced in Kelheim based on a multi-stage plan. First, two autonomous shuttles are introduced and serve a small area in the town center. This stage is in operation since September 2022. The service is then expected to be expanded to five vehicles and potentially to a larger service area in 2023. In this case study, we simulate the autonomous KEXI service in combination with the already existing conventional KEXI service and its performance, both for the fixed introduction plan and for possible expansion plans.

4.1. Introducing autonomous shuttles to the DRT service

The setup of autonomous shuttles in the simulation is based on the actual plan in the KelRide project. Just as the conventional KEXI service, the autonomous KEXI provides a stop-to-stop service with a subset of the same stop locations. The operation of the autonomous shuttles is funded by the German Federal Ministry of Transport and Digital Infrastructure as part of the KelRide project and thus the rides are free of charge for users. Based on plans for the actual vehicle authorizations, the maximum speed of the autonomous shuttles is set to 18 km/h. The AV will only operate from 9:00 to 16:00, in order to avoid congested streets at peak hours and low demand in night operation. At the same time, the conventional KEXI service remains in parallel operation.

At the first stage, two AV are put into service. The service area covers Kelheim's old town and parts of an industrial area across the bridge called Donaupark (see the purple area in Figure 4). The first stage has just been put in service in September 2022. We refer to this scenario as the Base Case.

The KelRide project also includes the plan to increase the fleet size of the autonomous KEXI service in summer 2023 from two vehicles to five vehicles. The present study shall provide insights whether the service area for the autonomous shuttles should be adjusted as an accompanying measure. Therefore, we simulate the service extension in two stages: In a first policy case ”Fleet 2023”, we only increase the fleet size. In three more policy cases, the service area is expanded, additionally. With the help of detailed road mappings and pictures as well as based on historical demand data from the human-driven service, the KelRide project team has identified a shopping center North-West of the old town, depicted in blue in Figure 4, to be a) a major point of attraction and b) technically the easiest area to connect. Possible candidates for further expansion cover living areas north (Bauersiedlung) and south (Hohenpfahl) of the river arms. The area Bauersiedlung connects to the aforementioned shopping area. While the Hohenpfahl area consists of steep, narrow roads that present a big hurdle for the AV, it is densely populated and connects well to the basic service area and is thus regarded here, as well.

We summarize the setups of all the simulations for the autonomous shuttle service in Table 2 and Figure 4. Analogously to the calibration process for conventional KEXI, we simulate each setup with 5 parallel runs under different random seeds.

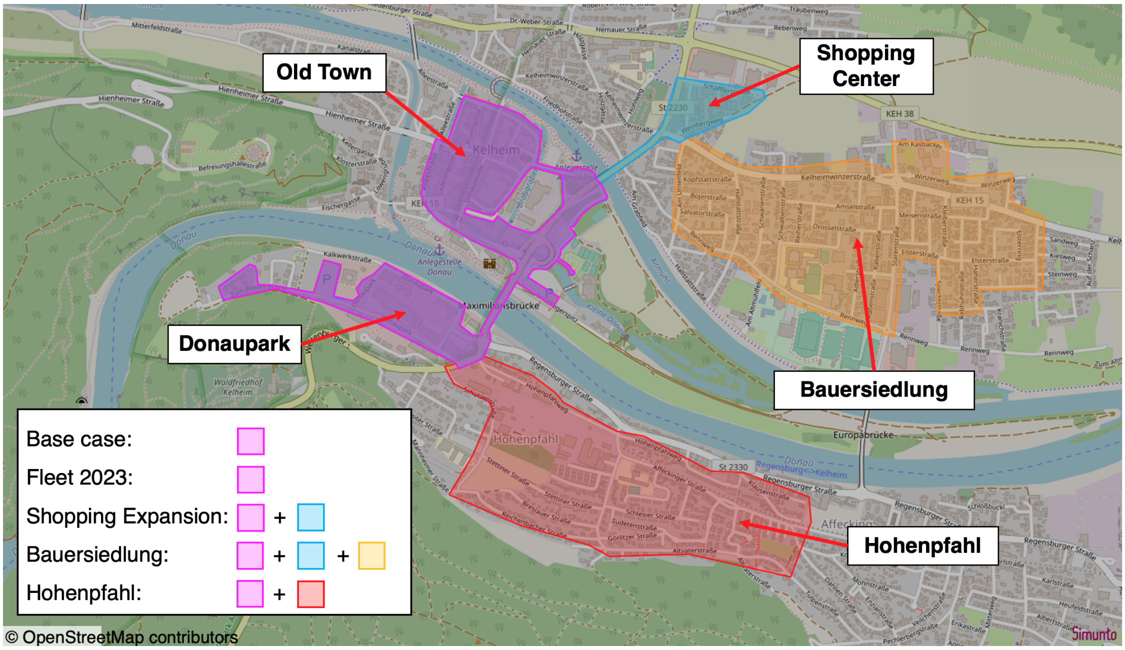


Fig. 4: Potential service areas for AV operation

Table 2: Summary of case studies for the autonomous shuttle service.

Case study	Nr. of AV	AV density $[veh/km^2]$	AV Service Area (see Fig. 4)
Base Case	2	5.43	Kelheim old town and Donaupark
Fleet 2023	5	13.57	Same as **Base Case**
Shopping Expansion	5	11.56	**Base Case** + shopping center
Bauersiedlung	5	4.57	**Shopping Expansion** + Bauersiedlung
Hohenpfahl	5	5.39	**Base Case** + Hohenpfahl

4.2. Results

The simulation results are summarized in Table 3. It shows data for both the autonomous and the (unchanged) conventional part of the KEXI service. Since we perform 5 parallel runs for each setup, the results shown in the table are average values. We will take a look at the number of rides, waiting time, the Euclidean distance of trips (stop to stop) and the in-vehicle travel time. In addition, we also include vehicle distance statistics into our analysis.

Table 3: Demand statistics for the case studies

Case	Number of rides per day / per veh-h	Mean waiting time [s]	Mean trip Euclidean distance [m]	Mean travel time [s]	Mean Euclidean speed [m/s]
Autonomous KEXI					
Base	41 / 2.9	199	634	268	2.37
Fleet 2023	51 / 1.5	180	620	272	2.28
Shopping Expansion	65 / 1.8	247	838	395	2.12
Bauersiedlung	103 / 2.9	428	1205	579	2.08
Hohenpfahl	104 / 3.0	397	1154	573	2.01
Conventional KEXI					
Base	120 / 2.5	397	2394	470	5.09
Fleet 2023	119 / 2.5	388	2385	451	5.29
Shopping Expansion	126 / 2.6	398	2355	455	5.18
Bauersiedlung	123 / 2.6	383	2370	452	5.24
Hohenpfahl	125 / 2.6	380	2398	450	5.33

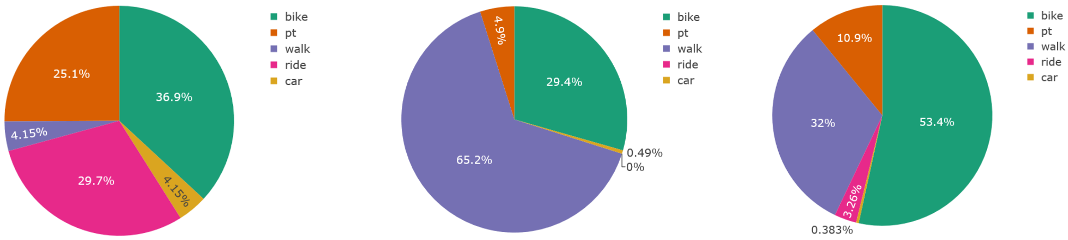
From Table 3, it can be observed that the number of rides with AV grows with increasing fleet size and extending service area. This result is intuitive. One driving aspect of this is that, with more vehicles operating, vehicle density increases and waiting times decrease. Another aspect is that, with an extended service area, the service is eligible for more trips, covering more origin-destination-relations. The conventional KEXI operation, on the other hand, remains relatively stable throughout all cases. This means the autonomous shuttles and conventional vehicles are serving different types of trips, and they are not competing with each other. This is also logical: the autonomous shuttles mainly serve short distance trips due to the service area constraints and the low speed limit. For longer distance trips and trips to the train station, taking a conventional KEXI vehicle will be the more suitable choice. The fact that the demand for the conventional KEXI service is not negatively affected could also be interpreted as that the overall demand for DRT services is not saturated.

In the Base Case, around 40 trips per day are expected for the autonomous KEXI service in average, which corresponds to 20 rides per vehicle per day or 2.9 rides per veh-h. During the operation, passengers are constantly using the autonomous shuttles throughout the service hours, and it is very seldom that both vehicles are idling. On the other hand, the autonomous shuttles only carry no more than one passenger during most of the time, which means that the vehicle capacity is not fully utilized. In order to increase the utilization of the AV, more or stronger incentives are needed. However, this is not easy to achieve. Currently, the autonomous shuttles are already free to ride, and, together with the conventional KEXI service, it is assumed to be the most comfortable way to travel. Therefore, a higher utilization of the autonomous shuttles by the local residents is unlikely, under the setup of the Base Case.

If the fleet size of the autonomous shuttles increases from two to five without expanding the service area, the average waiting time decreases and the demand increases by roughly 10%. That means, while the vehicle density rises by a factor of 2.5, the average number of rides per vehicle is roughly halved. These results can be interpreted as that the demand potential in the AV service area of the Base Case is not far from a saturation point. This suggests that, if vehicle occupation is supposed to be maintained, the service area needs to get expanded with the planned fleet expansion.

An expansion to the shopping center in the North increases the number of AV rides by about 27% and the mean waiting time by roughly 37% compared to "Fleet 2023". Yet, the average number of trips served by each autonomous shuttle is still lower than in the Base Case. This means the vehicle utilization rate is not very high under this setup. In fact, based on additional experiments, we observe that three autonomous shuttles can maintain the same service quality and serve a comparable demand (mean waiting time goes up by 4% while the (realized) demand goes down by 15%). However, the project plan is fixed to bring five AV on the streets. This suggests, that there is capacity left which could be used to expand the service area even further and thus reach a higher share of Kelheim's population.

When we compare the extension plan for the two candidate residential areas (i.e., Bauersiedlung and Hohenpfahl), it can be observed from the simulation results that the inclusion of the two candidate areas leads to a similar number of rides per day. Compared to the other setups, the number of rides with autonomous shuttles is significantly increased. Furthermore, with one of the residential areas included in the service area of the autonomous shuttles, the vehicle utilization rate is similar to the Base Case. Note that the Hohenpfahl case does not include the northern shopping center while the Bauersiedlung case does include it.



(a) Conventional - Base Case (b) AV - Base Case (c) AV - Hohenpfahl

Fig. 5: Original modes of transport for trips undertaken with the conventional and the autonomous KEXI in different case studies.

To understand the impact of the introduction of AV and the service area expansion on the transport system in more detail, we investigate the modal shift and the spatial relation of trips undertaken with the service and compare to the conventional KEXI. Figure 5 supports the suggestion that the different segments of KEXI serve different demand segments. The charts display the original mode of transport that agents were using on trips, for which they use the conventional or the autonomous KEXI service after both have been introduced, i.e. in the Base Case. Figure 5a and 5b refer to the Base Case with 2 AV in the smallest area, and Figure 5c refers to the Hohenpfahl case with five AV.

For conventional KEXI trips, more than half of the trips come from ride and pt. In contrast, Figure 5b shows that roughly two thirds of the trips undertaken with the autonomous shuttle service replace walk trips, when operated only in the old town and in Donaupark. The results are very similar when the fleet is increased to five vehicles and the service area remains the same. For both simulation cases (Base Case and Fleet 2023), the origin and the destination activity lie within the service area for only about 10% of the trips undertaken with the AV (i.e. inner trips), while roughly 60% have both activities outside. To support the understanding of this, it needs to be pointed out that the simulation accounts for the agent's ability to walk into and out of the service area, prior and after the ride. Interpreting these observations leads to the suggestion that in these cases, the major use case for the autonomous MoD service in the simulation is to speed up walk trips that are rather long. Regarding the average waiting time of about 3 minutes and the service being free of charge, this is plausible.

Figure 5c demonstrates that the share of walk trips replaced by the autonomous KEXI can substantially be reduced by expanding the service area. While here the results are shown for Hohenpfahl, the mode shares are comparable for the Bauersiedlung case. By investigating all policy cases, including Shopping Expansion, we observe that the service area expansion mainly attracts former pt and bike riders in the simulation. The larger the area expansion, the more trips are attracted from these modes, especially from bike. In comparison, considerably fewer trips are attracted from walk. When introducing the AV into the residential areas, about 3% of the trips are attracted from ride. Overall, it needs to be pointed out that the simulation results suggest that the autonomous MoD service does not replace car trips in a substantial manner and thus does not contribute to reducing the carbon footprint of the transport system. According to Kaddoura et al. (2020b) and Diebold et al. (2021), a minimum fare or a flat fare can substantially change the modal shift effect of DRT services and reduce the share of trips cannibalized from walk and bike. However, by increasing the user price, the overall demand could significantly decrease. The authors also find in their case study on the city of Berlin, that a larger service area leads to more switches from car trips. In contrast, we observe that the share of trips withdrawn from ride (i.e. car passengers) rises from Base Case to Hohenpfahl. Thus, no cars are pulled off the streets by the AV service. This may be explained by the fact that even in the Hohenpfahl case, the service area is limited to less than half of the city area.

In addition to the demand side, vehicle distance statistics also provide some insights into the performance of the DRT system. Table 4 summarizes the vehicle distance statistics of the conventional and autonomous KEXI service in different scenarios. Similar as for the demand statistics in Table 3, the distance statistics of the conventional KEXI vehicles do not vary significantly among different setups. This further confirms the fact that the operation of AV has limited impact on the conventional KEXI service.

Table 4: Vehicle distance statistics for the case studies

Case	Total distance [km]	Total passenger distance [km]	Total empty distance [km]	Average vehicle distance [km]	Passenger distance ratio	Empty ratio
Autonomous KEXI						
Base	59.0	48.4	18.2	29.5	0.82	0.31
Fleet 2023	67.5	60.8	15.3	13.5	0.90	0.23
Shopping Expansion	101.2	109.4	20.9	20.2	1.08	0.21
Bauersiedlung	200.1	251.8	36.9	40.0	1.26	0.18
Hohenpfahl	184.0	251.2	28.4	36.8	1.37	0.15
conventional KEXI						
Base	569.7	550.3	151.7	189.9	0.97	0.27
Fleet 2023	571.1	531.9	146.5	190.4	0.93	0.26
Shopping Expansion	593.8	561.6	164.2	197.9	0.95	0.28
Bauersiedlung	572.4	546.7	147.6	190.8	0.96	0.26
Hohenpfahl	596.5	549.8	162.1	198.8	0.92	0.27

When it comes to the autonomous part of the fleet, it can be observed that the total fleet distance increases as we enlarge the fleet size and expand the service area. Comparing the Base Case and Fleet 2023 case, the extra driven distance is apparently caused by the extra demands. The average distance per vehicle, on the other hand, decreases as we increase the fleet size of AV from two to five. With the inclusion of the shopping center (Shopping Expansion case), the total fleet distance further increases, but the average distance per vehicle still remains below the Base Case. In the Hohenpfahl case and Bauersiedlung case, we see a leap in the total fleet distance. This is caused by the combined effect of an increase in the number of trips and in the average distance of trips. The inclusion of one of the residential areas not only attracts more agents to use the service, it also enables longer trips by autonomous shuttles because the service area gets significantly larger. In both Hohenpfahl and Bauersiedlung case, the average vehicle distance becomes greater than in the Base Case.

To evaluate the efficiency of a DRT system, we also look at two ratios: passenger distance ratio (i.e., the total passenger travel distance divided by the total fleet distance) and the ratio of empty kilometers to the total fleet kilometers. A larger passenger distance ratio indicates a higher occupancy of the DRT vehicles. It is worth pointing out that the passenger distance ratio can be greater than 1 because of the ride-sharing. According to survey data, the average person occupation ratio of private non-work-related car trips in Germany is 1.5 and for the region type that is relevant for Kelheim it is 1.4 (infas et al., 2018). For work-related trips and thus for the overall average, a slightly lower value can be expected (Umweltbundesamt, 2019). A model-based estimate by the German Federal Ministery for Transport and Transport and Digital Infrastructure concluded to a value of 1.46 (Deutscher Bundestag, 2018). This can serve as a benchmark when evaluating the efficiency of the DRT system in terms of vehicle kilometers traveled. For the larger service areas, the passenger distance ratio approaches those values from below.

The empty ratio refers to the proportion of the total travel distance that the vehicle is not carrying any passengers. The empty drives in the DRT system are mainly caused by pick up trips and strategic empty vehicle relocations, which help to provide a better service quality (lower waiting times) (Schlenther et al., 2020; Lu et al., 2021). On the other hand, every kilometer driven without a passenger is not profitable for the service operator, who is thus generally interested in keeping the empty ratio rather low.

The conventional service performs more efficient in terms of the passenger distance ratio and the empty ratio compared to the autonomous KEXI service, in Base Case. With Fleet 2023 however, the both service segments approach each other when it comes to the results of these two performance indicators: The conventional service performs better at the passenger distance ratio but worse regarding the empty ratio, both by 0.03. For all cases including a service area extension, the passenger distance ratios of the conventional part are lower and the empty ratio higher.

By comparing the autonomous shuttle services under different scenarios, we can find out that the total empty distance actually reduces when the fleet size is increased from two to five while maintaining the same service area. Then, as the service area gets expanded, the total empty distance increases again. But meanwhile, the empty ratio keeps decreasing. A similar trend can be found in the passenger distance ratio as well, but the trend is opposite to the empty ratio. In the Hohenpfahl case, the AV fleet reaches the highest passenger distance ratio of 1.37 and the lowest empty ratio of 0.15. This means the vehicles are most efficiently used in terms of travel distance under this scenario.

5. Discussion and Outlook

Despite their reduced speed, the AV can achieve a higher efficiency in terms of rides per vehicle hour – if a vehicle density of roughly 5 veh/km^2 is maintained. Regarding the passenger distance ratio and empty ratio, the AV service is more efficient than the conventional service for expanded service areas. The reason for this might be multi-folded: even for all the expansion plans, the AV service area is significantly smaller in all variants of the case study and the service is free of charge, which might induce a higher demand density than for the conventional service. Moreover, AV density is higher than the conventional vehicle density in the corresponding service areas, for all regarded cases. However, as the operational costs for AV are expected to be considerably less than for human-driven transport services (Hörl et al., 2019) due to non-existing driver wages, the results could be interpreted as another indicator that vehicle automation might be a major lever to improve pt service quality and make it more cost-efficient at the same time. In future parts of the KelRide project, a total cost of ownership computation will be conducted on the autonomous KEXI service which shall provide more insights in this topic.

Furthermore, the results suggest that due to the different configurations of the conventional and the autonomous MoD services, they do not stand in competition with each other. However, it remains to be investigated whether this holds true if the AV service is spatially further expanded and/or associated with a user fee or improved in terms of vehicle speed. In the current and the projected setups for 2023 however, the autonomous fleet is expected to complement the existing conventional service and increase the overall KEXI ridership significantly. Another reason for the fact that the introduction of AV into the service does not cannibalize trips from the conventional service could be, that the overall market potential for MoD is not saturated. This could be investigated in future simulation studies, by steadily increasing fleet sizes and observing the demand reaction.

In the simulation, the autonomous MoD service mainly replaces walk and bike trips. Although the AV have an electric drive, this worsens the carbon footprint of the transport sector, because walk and bike do not require (as much) electric energy production and less material. However, this emphasizes, that new mobility technologies like MoD need to be non-fossil, as otherwise direct emissions would add on top. In future parts of the KelRide project, these results shall be validated and compared to survey data gathered from AV riders after an initial introduction phase has passed. There are two limitations of the methodology of this study that are relevant to mention in this context:

1. The population is modeled at a 25% sample while the MoD supply and demand, the number of conventional KEXI vehicles and rides during calibration and the number of AV in the policy cases, were modeled based on 100% of the real numbers. This is done because the numbers for KEXI vehicles in reality are so low, that we can not sample them down by 25% in a meaningful way. This means that within the model, agents are 'forced' to use the KEXI service who normally would not use it (due to better alternatives, willingness to pay, etc.). As a consequence, the modal shift in the policy cases should be interpreted with caution. However, this method allows us to maintain a realistic ratio of the MoD supply to its demand density. By doing so, waiting times, vehicle occupancy, the pooling rate and the level of demand are estimated more realistically.
2. This transport model does not account for induced traffic. While the aim of the MoD services is to increase the mobility of people, induced traffic can be regarded from different perspectives. With the AV service being free of charge, fake or just-for-fun rides are likely, worsening the carbon footprint for no purpose. If, however, e.g. elderly people are enabled to take additional trips (for any purpose, even leisure), this can be regarded as a positive effect on the overall mobility of people, while still having a negative effect on the ecological effects of the transport sector. Based on the fact that the simulation suggests that the autonomous service mainly replaces walk and bike trips, one could expect that especially elderly people, who are not able to conduct many bike and walk trips anymore, profit from this service.

However, as shown in Section 2 as well as by Narayanan et al. (2020), the findings that autonomous MoD attract users from sustainable transport modes to a high proportion are found in many simulation studies over multiple scenarios and regions.

As briefly mentioned in Section 4.2, the modal shift towards MoD services is highly influenced by their pricing scheme. As Kaddoura et al. (2020b) show, a minimum fee can significantly reduce the share of trips cannibalized from walk and bike and increase the share of replaced pt and car trips. Similarly, Liu et al. (2017) state that higher distance-based user fees allow for more private cars to be replaced per AV. In the context of the present study and the aforementioned implications, this could be applied to the autonomous KEXI service, if the goal is to improve the carbon footprint. However, a decrease in the demand would be expected and without accompanying measures (such as tolls etc.), the results in Kaddoura et al. (2020b) suggest that the service would still have a high share of replaced pt trips. Furthermore, Kaddoura et al. (2020b) find that an expansion of the DRT service area helps to withdraw more car users. Liu et al. (2017) similarly state that especially for long distance trips, autonomous MoD are preferred over private cars. In the present study, the larger expansion cases Bauersiedlung and Hohenpfahl rather show an increase in the share of users that were car passengers before (cf. mode ride in Figure 5). However, these service areas still only cover less than half of Kelheim city. Thus, it seems plausible that almost no car trips are replaced. For the conventional service that serves the entire city plus a nearby rail stop, the results are better but also show that the share of trips withdrawn from conventional pt are higher.

The simulation results on the modal shift of the (conventional) KEXI service are backed up to some extent by real world evidence: Diebold et al. (2021) conducted user surveys for an MoD service in Hamburg, Germany and found that the introduction of a flat price of one Euro significantly increased the share of trips withdrawn from individual motorized transport (i.e. what we consider as car and ride) to 28% and also helped to improve the reliability of the service. More recently, the same researchers from the Technical University of Hamburg have conducted more surveys on MoD services in rural and suburban areas of Hamburg within a large real lab project and report that the ridership is withdrawn from motorized individual transport was 23% in a suburban setting (city of Ahrensburg at the border of Hamburg) and up to 46% in rural settings. Our model results lie in the middle of this range, see Figure 5a. In a more general sense, the simulation results are further backed up by Erhardt et al. (2022), who scraped data on the two largest transport network companies in San Francisco from their Application Programming Interfaces and compared them with automated passenger count data on transit use and more. They find that transport network companies, i.e. MoD service providers, are responsible for a net decline of about 10% in bus ridership. Our model also suggests a significant cannibalisation of conventional pt trips.

Thus, it is important for policy makers to understand MoD services as a part of pt. On the one hand side, they can improve the mobility of people through flexibilization and a higher cost-effectiveness compared to conventional pt, especially in rural areas. On the other side, there is need for regulation of the service configurations (i.e. the service areas, user prices, waiting times, etc.), especially with regard to the ecological challenges of the transport system.

While the study at hand investigates different potential candidates for the expansion of the AV service area that were determined based on technical and qualitative constraints from partners of the KelRide project, there exist methods for automated exploration of service areas changes in the simulation (see Section 2.3). Future research might investigate further configurations of an autonomous MoD service in the region of Kelheim, varying e.g. the user price, the fleet size, the vehicle speed and/or the service area. As an example, the Kelheim transport model that is developed and presented here, was already used in a sensitivity study that dealt with fleet size estimation for the expansion of the automated MoD service to other parts of the Kelheim city, i.e. beyond the city boundaries. More future work with this model is planned in the context of operation under bad weather conditions. This shall contribute to the goal of improving service reliability for the MoD service.

6. Conclusion

This work presents an open source activity- and agent-based transport model for the district of Kelheim, Germany. Additionally to conventional modes of transport, the transport model consists of a MoD service, that is calibrated based on the analysis of real data. To the knowledge of the authors, the usage of real demand data for the calibration of an open source MoD model is new in the research field. The model is then applied to a case study that investigates impacts of the introduction of AV into the existing conventional MoD service, as well as plans for fleet and service area expansion.

The results suggest that the automated and the conventional service segments do not compete with each other, but rather serve different demand segments. This can be associated to their different configurations: the conventional service operates in a larger area, allowing longer trips for customers who are charged a flat price, while the autonomous service is for free and operates in a limited area. As a consequence, the autonomous segment operates in the simulation at a higher efficiency, i.e. lower mileage per passenger, lower ratio of empty kilometers and higher number of rides per vehicle-hour, but serves less demand than the conventional segment. These findings should be transferable other regions including (larger) cities.

In the context of an AV fleet expansion that is planned in the real world implementation, the simulation results strongly suggest that the corresponding service area should be expanded as an accompanying measure, if the service efficiency is to be maintained. The simulation results further suggest that the autonomous segment of the MoD service does not replace car trips. In best cases, car passengers take advantage of the more flexible system (no coordination with private driver needed). Mostly, trips with eco-friendly transport modes are replaced, which should result in a negative carbon footprint. These results are in line with other findings in the literature. To address this issue, different service configurations could be implemented, e.g. the service could charge a user fee and be further expanded spatially.

In the future, the results of the case study, particularly the travel time, travel distance and demand level statistics of the autonomous MoD service, will be validated, and the simulation will then be recalibrated with the help of real data that will become available during the course of the KelRide project. Further planned applications of the developed transport model include the investigation of MoD operation under bad weather conditions.

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