# From today's ride-sharing services to future mobility concepts: A simulation study for urban and rural areas

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## Abstract

This study explores today's and future ride-sharing services by combining real-world user data with state-of-the-art methods of agent-based simulation. First, an existing ride-sharing service in Berlin, Germany, is implemented in an agent-based model and real-world user data is used to calibrate the model. Then the service is extended and transferred to other regions in Germany (Gladbeck, Vulkaneifel) and to a future scenario where the ride-sharing mode is operated by autonomous vehicles and the service is integrated into the regular (schedule-based) public transit system. The simulation experiments reveal ride-sharing potentials for two different perspectives: From the operator's point of view, urban areas with high population densities (Berlin inner-city center, Gladbeck) are found to be most promising since travel demand can be served more efficiently compared to low-demand areas. From the users' point of view, high potentials are observed in areas (and times) with rather poor schedule-based public transit provision (rural Vulkaneifel district, Spandau, entire Berlin area including outskirts) where the on-demand mobility concept is an attractive alternative to the existing modes of transportation. In the today's scenario, ride-sharing trip shares are rather low, whereas, in the future scenario, there is a strong mode shift effect to the ride-sharing mode and the overall road traffic increases strongly. In the urban area, most users switch from schedule-based public transit to ride-sharing, whereas, in the rural area, most users switch from car to ride-sharing. Yet, in all cases, there are undesired mode shift effects, e.g. from bicycle and walk to ride-sharing. For the today's situation, a profitable service is only observed in some of the simulation experiments. In contrast, in the future scenario, a profitable service is found for all simulated services.

# 1 Introduction and problem statement

App-based on-demand mobility services, also referred to as demand responsive transit (DRT), ride-hailing or ride-sharing, have become very common in the last decade. In some cities or regions, these services play an essential role in mobility provision. In Germany, big players such as *UBER* and *Lyft* (Schaller, 2018) are not allowed to operate the way it is known from other countries. If they are available in a city, their services and prices are rather similar to conventional taxis or limousine services. Yet, there are several App-based DRT services in Germany, typically in the form of a cooperation with the local public transport company and with the approval of the city administration for a limited service area. Most of these services are primarily focused on cities or on inner parts of a city, e.g. *BerlKönig* in Berlin (BVG, 2021), *MOIA* in Hamburg (Zwick et al., 2020) and Hannover or *myBUS* in Duisburg. Also without direct cooperation with public transport companies, various companies have operated on-demand mobility services in different cities, e.g. *CleverShuttle* (Knie et al., 2020), *allygator/door2door*, and *MOIA*. Some of these ride service companies, e.g. *CleverShuttle*, operated competitively in one city, e.g. in Berlin, while in other cities, e.g. Leipzig, they had cooperative agreements with the respective local transit operator. Today, these services are rather an optional addition to the well-developed public transport service in German cities. From the user perspective they are a more comfortable or faster alternative to public transit and a less expensive and more sustainable alternative to conventional taxis.

In the future, autonomous vehicle technology and the elimination of costs for drivers could lead to reduced operating costs compared to driver-controlled vehicles. Several studies estimate costs of 0.30 to 0.38 EUR per passenger-kilometer (Bösch et al., 2018; Trommer et al., 2016) and in consequence also reduced fares for such on-demand mobility services. In recent years, various pilot projects have been implemented in Germany in which automated vehicles are used.[1] In some applications, these vehicles operate on public roads and are available to users free of charge. Operation is usually limited to a fixed corridor length of less than 2 kilometers, and speed levels are around 10 to 20 km/h (kilometers per hour). In the coming months, a first implementation of an App-based DRT service with autonomous vehicles is expected in Kelheim, Germany.[2] It is expected that in the coming years, more and more App-based DRT services will make use of automated vehicle technologies. It can be assumed that higher speed levels can be realized, thus significantly increasing the attractiveness of these services.

Not every mobility service is equally suitable for every area type. Different local conditions require different mobility solutions. City and regional administrations need guidance on how to design today's and future DRT services. This study aims at providing solutions by carrying out simulation experiments for different pricing scenarios and DRT services in urban and rural areas.

In several existing studies, DRT services are simulated for a fixed travel demand based on today's level of car or taxi trips in a city (Maciejewski and Bischoff, 2015; Bischoff and Maciejewski, 2016; Bischoff et al., 2018; Nagel et al., 2018; Bischoff, 2019) or alternatively based on today's level of public transit trips (Leich and Bischoff, 2019; Bischoff et al., 2019).

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[1] Further information can be found here: `https://www.bmvi.de/DE/Themen/Digitales/AVF-Forschungsprogramm/`

[2] Research project "KelRide", see `https://www.bmvi.de/SharedDocs/DE/Pressemitteilungen/2021/30-scheuer-foerderung-ki-mobilitaetsprojekte.html`

These studies do not account for transport users' mode choice decisions and focus on the mechanics of the dynamic vehicle routing problem, e.g. waiting times resulting from the DRT vehicle fleet size (Maciejewski and Bischoff, 2015) or rebalancing algorithm (Bischoff and Maciejewski, 2020; Schlenther et al., 2020). In several other simulation studies, mode choice reactions are accounted for and the individual decision making process whether to use the DRT mode or not depends on person-specific preferences, daily activity-trip-patterns, alternative modes of transportation and the service quality of the DRT mode (Zhao and Kockelman, 2018; Kaddoura et al., 2020a; Liu et al., 2019; Vosooghi et al., 2019; Hörl et al., 2019; Kaddoura et al., 2020b; Zwick et al., 2020). In a recent study, Zwick et al. (2020) use a simulation approach to investigate autonomous DRT services in different areas in and around Munich with varying population sizes and trip densities. Zwick et al. (2020) observe a logarithmic increase in system efficiency with the number of trip requests and a reduction in vehicle-kilometers in the case of more than 1000 requests per $km^2$ (square kilometer). In a similar study, Kaddoura and Schlenther (2020) systematically look into different population densities and observe a non-linear relationship between DRT trip density and service parameters such as required fleet size and vehicle-kilometers.

In most of the existing simulation studies, the behavioral parameters for the DRT mode are either set based on plausible assumptions, e.g. equal to those for car passengers (Zwick et al., 2020), public transit passengers (Hörl et al., 2019), or based on stated preferences from mode choice experiments (Liu et al., 2019). Some studies make use of data from existing taxi or DRT services. In most of these studies, the information about trip patterns are directly simulated without accounting for mode choice behavior (see e.g., Maciejewski et al., 2016; Zwick and Axhausen, 2020). This study proposes a new approach: Real-world DRT user data is used to set up and calibrate an existing traffic model which explicitly accounts for transport users' mode choice reactions.

The overall contribution of this paper is to explore today's and future DRT services by combining real-world DRT user data with state-of-the-art methods of agent-based simulation. The existing DRT service BerlKönig in Berlin, Germany is transferred to a multi-modal simulation model for the Greater Berlin area, from where calibrated user behavior is transferred to other regions and time horizons.

# 2 Methodology

## 2.1 Agent-based transport simulation framework: MATSim

The simulation experiments carried out in this study use the agent-based and dynamic transport simulation framework MATSim[3] (Horni et al., 2016). In MATSim, transport demand is simulated as individual agents. An agent's intended behavior for a specific day is described by a so-called travel plan which consists of an activity-trip-chain, including the modes of transportation, departure times and the route. An agent's entire choice set is described by a number of travel plans. Each agent tries to individually maximize his expected utility and adapts to the transport supply following an evolutionary iterative approach which consists of the following three steps:

1. All agents individually execute their daily travel plans and the mobility behavior is simulated. Vehicles interact on the road network applying a queue model which

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[3] Multi-Agent Transport Simulation, see `www.matsim.org`

accounts for dynamic congestion and spill-back effects. Also, ride-sharing or public transit passengers compete for the same transport resources and interact with each other.

2. Each agent evaluates her experienced behavior (plan) taking into consideration both the utility from being at an activity and the travel-related part, including the discomfort of traveling and monetary cost.

3. A fraction of agents is enabled to adjust their behavior (replanning), e.g. change their route, departure time or mode of transportation. All other agents choose among their existing plans following a multinomial logit model.

## 2.2 DRT simulation

The simulation of on-demand mobility services is based on an existing module for dynamic vehicle routing problems (Maciejewski, 2016; Maciejewski et al., 2017) and the DRT module (Bischoff et al., 2017) for the simulation of ride-hailing. (1) DRT users first walk to the next road segment or virtual DRT stop inside the service area. (2) Then, a DRT ride is requested. (3) The ride request is then assigned to the next available DRT vehicle minimizing the total vehicle operation time. If the DRT system operates at capacity limit and ride requests cannot be served within the predefined service quality criteria, the request is assigned to the vehicle causing the least additional operation time. At the same time, in particular for pooling, the dispatch and insertion algorithm considers predefined service quality parameters for the passengers that are already scheduled to use the same vehicle. (4) The DRT user waits for the DRT vehicle to arrive and then enters the vehicle. (5) Finally, the DRT user arrives at the destination road segment or virtual DRT stop, gets off the vehicle and walks to the destination activity.

## 2.3 Dynamic DRT fleet size adjustment

To control the waiting times for DRT vehicles, the DRT vehicle fleet size is dynamically adjusted. For the adjustment of the fleet size, a proportional controller is used which randomly adds or removes vehicles. As control variable, the 90th waiting time percentile is used and in most simulation experiments set to 10 minutes. The approach uses an outer loop to adjust the DRT fleet size and an inner loop to simulate transport users' reactions to the DRT service. A more detailed description of the applied DRT vehicle fleet adjustment approach is provided in Kaddoura et al. (2020c).

## 2.4 DRT simulation speed-up

To speed-up simulation experiments, the DRT assignment described in Sec. 2.2 is simplified in some iterations and DRT users are teleported using a dynamic beeline distance factor and a beeline speed obtained from DRT travel statistics. In regular iteration intervals, the DRT mode is simulated in detail to update DRT travel statistics (average waiting time, average in-vehicle time, average travel distance) and re-adjust the DRT teleportation parameters. As an extension of the existing DRT speed-up module described in Kaddoura et al. (2020b), a moving average approach was implemented and used in this study. The moving average approach takes into consideration DRT travel statistics from several previous iterations instead of just using values from the previous iteration. This yields a significant improvement in stability throughout the simulation process.

### 2.5 Intermodal public transit routes with DRT access and egress

In order to set up the new DRT service not only as an alternative mode but also complementary to existing public transit, the simulation was enhanced by intermodal routing. A new "routing mode" is introduced which is assigned to a special intermodal public transit router which selects the best performing access mode and the best performing egress mode from a list of permissible access and egress modes which comprises walk and DRT.[4] The expected generalized cost is calculated for both access and egress to close public transit stops. Access and egress modes are selected independently which allows for mode chains for intermodal trips such as "walk → public transit → walk → DRT → walk". The original routing mode "public transit" is kept as a monomodal alternative with only walk for access and egress. The intermodal public transit functionality is based on the original SwissRail-Raptor intermodal public transit router by Rieser et al. (2018) and enhancements such as modelling intermodal public transit as a separate mode and more elaborate search radii for the public transit stop search will be described in more detail in an upcoming paper.

## 3 Case studies and simulation experiments

### 3.1 Case studies: Berlin, Gladbeck, Vulkaneifel

In this study, simulation experiments are carried out for three different regions in Germany: the Greater Berlin area depicted in Fig. 1, the city of Gladbeck including the surrounding region shown in Fig. 2, and the sparsely populated rural area of the administrative district of Vulkaneifel (Volcanic Eifel), see Fig. 3. For each case study, the activity-based transport model is provided as an excerpt from the nation-wide MATSim model of Germany by Senozon Deutschland GmbH (`www.senozon.com`). The road network is generated based on OpenStreetMap (`www.osm.org`) data and contains all roads in the area of interest and its surrounding area. The MATSim public transit schedule is converted from GTFS data and contains all relevant public transit lines in the area of interest.

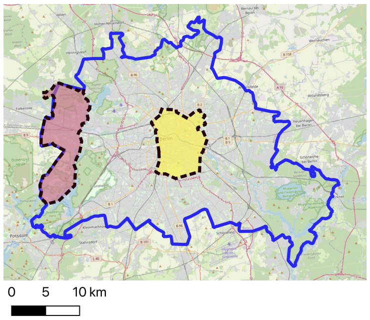

Figure 1: Berlin area: blue line; BerlKönig service area: yellow zone; Spandau: red zone

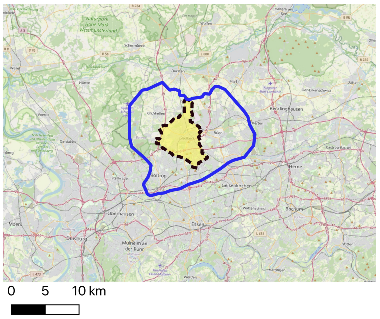

Figure 2: Greater Gladbeck region: blue line; Gladbeck: yellow zone

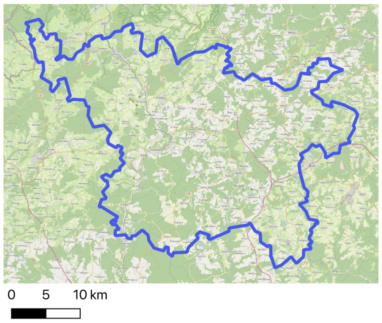

Figure 3: Vulkaneifel region: blue line

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[4] The term "routing mode" within MATSim refers to the way a trip is routed.

The synthetic population is based on regular traffic surveys and anonymized mobile phone data for the year 2018. In this study, the population includes all persons with an age of 14 or older that travel from, to or through the area of interest. An extended version of the Vulkaneifel case study which includes all school children is described in Sec. 5.2. In the base case, transport users are enabled to use the car, public transit, bicycle, ride and/or walk mode. The walk, bicycle and ride modes are simulated without network assignment, neglecting interactions between users and instead assuming fixed mode-specific speed parameters. Travel times of public transit users result from simulated access/egress times to/from the transit stop, waiting times, and in-vehicle times. In this simulation setup, public transit vehicles do not interact with DRT vehicles, private cars or bicycles. In order to reduce computation times, a 25% population sample is used and road capacities are accordingly reduced to 25% of the real-world capacity. Since travel patterns of the agents extend to all parts of Germany and to further reduce computation times, the least relevant agents, i.e. agents that travel very far and thus spend most time outside the area of interest, are removed together with the infrastructure they use. In consequence, about 10 % of the agents are removed, yet the infrastructure (network and transit schedule) still covers an area much larger than the actual area of interest. For an in-depth information of the applied demand generation methodology, in particular the Mobility Pattern Recognition, see Neumann and Balmer (2020).

## 3.2 DRT mode and simulation setup

The DRT mode is added to the existing modes of transportation and may be used for trips or trip parts starting and ending within the service area. Note that passengers can also walk into the service area in order to use the DRT. The DRT service allows for pooling (ride-sharing), operates as a door-to-door service with one virtual DRT stop per link and the vehicle capacity is set to 4 passengers. In various simulation experiments, the DRT service area and DRT fare levels are set differently (see Sec. 3.3). In the initial iteration, the vehicles are distributed using a weighted random draw based on the population density within the service area. Then, at the beginning of each iteration, the vehicles are put back on their initial road segment to avoid concentrations in some areas and an undersupply of DRT vehicles in other areas. The pick-up and drop-off takes 1 minute. DRT vehicles interact with other DRT vehicles as well as private cars. The DRT mode can be used as a regular trip mode or as an access and/or egress mode for the schedule-based public transit mode (see Sec. 2.5).

The transport users are allowed to change their routes, departure times and modes of transportation. For each sub-tour (= trip chains starting and ending at the same activity location), the transport mode may be changed to a single chain-based mode, i.e. car or bicycle, or to a combination of one or more non-chain-based modes, i.e. public transit, DRT, ride, and walk. An agent's choice set is limited to 3 daily travel plans. The total number of iterations is set to 500. During the first 400 iterations (choice set generation), in each iteration the share of agents who are selected for replanning (see Sec. 2.1), i.e. who change their mode, route and/or departure time, is set to 10% per choice dimension. In the final 100 iterations, all agents select from their existing daily travel plans of their individual choice sets based on a multinomial logit model.

Behavioral parameters for the DRT mode and the marginal utility of money are taken from the Berlin case study which has been calibrated and validated against real-world

DRT trip data (see experiment BlnCity-DRT-1 in Sec. 3.3).

### 3.3 Simulation experiments

Simulation experiments are carried out for the different case studies described in Sec. 3.1 with different assumptions regarding the DRT service area and the time horizon (today's scenario vs. future scenario). Simulation experiments are carried out for the DRT service areas described in Tab. 1 and shown in Fig. 1, 2, and 3.

Table 1: Key characteristics for each service area

| DRT service area | Simulated residents | Area size in $km^2$ | Trips* in area (by origin, all modes) | Trips* per resident (by origin, all modes) |
|---|---|---|---|---|
| Eastern inner-city of Berlin | 565,340 | 61 | 2,652,516 | 4.69 |
| Entire city of Berlin | 2,842,980 | 892 | 9,044,756 | 3.18 |
| Spandau, borough of Berlin | 156,488 | 76 | 358,084 | 2.29 |
| Greater Gladbeck area | 286,412 | 210 | 750,972 | 2,62 |
| Dsitrict of Vulkaneifel | 49,772 | 911 | 65,348 | 1.31 |

* The trip number refers to an average working day.

For each DRT service area, simulation experiments are carried out for the following scenarios:

- Simulation experiments for the **today's scenario** are based on the real-world ride-hailing implementation in Berlin in the year 2019 (before Corona). That is, both the fare and calibrated user preferences are directly transferred from Berlin to other regions. The fare amounts to 1.50 EUR per kilometer with a minimum charge of 4.00 EUR per ride.
- Simulation experiments for the **future scenario** are based on the assumption that ride-hailing is perceived by users in a similar way to (schedule-based) public transport and also the fare is the same as for today's public transit. Technically, this is done by setting behavioral and cost parameters for the simulated DRT mode equal to those for today's public transit.

In both scenarios, the DRT mode is assumed to be regulated: The DRT operator provides a fixed service quality and adjusts the fleet size such that waiting times are below 10 minutes in 90% of all DRT rides.

An overview of all conducted simulation experiments is given in Tab. 2.

## 4 Results

### 4.1 Using real-world ride-hailing user data for the calibration of the base case

The goal of the model calibration was to correctly represent the users of on-demand services for an average working day. The existing real-world on-demand services in Berlin consist of primarily 3 types:

(a) the DRT service *BerlKönig* in the Eastern inner-city area of Berlin provided by BVG (`www.bvg.de`) and Via (`www.viavan.com`),

Table 2: Simulation experiments

| Simulation experiment | Case study | DRT service area | Scenario |
|---|---|---|---|
| Bln-BC* | Berlin | - | Today |
| BlnCity-DRT-1** | Berlin | Eastern inner-city of Berlin | Today |
| BlnCity-DRT-2 | Berlin | Eastern inner-city of Berlin | Future |
| Bln-DRT-1 | Berlin | Entire city of Berlin | Today |
| Bln-DRT-2 | Berlin | Entire city of Berlin | Future |
| Sp-DRT-1 | Berlin | Borough Spandau in Berlin | Today |
| Sp-DRT-2 | Berlin | Borough Spandau in Berlin | Future |
| Gl-BC* | Gladbeck | - | Today |
| Gl-DRT-1 | Gladbeck | Greater Gladbeck area | Today |
| Gl-DRT-2 | Gladbeck | Greater Gladbeck area | Future |
| Vu-BC* | Vulkaneifel | - | Today |
| Vu-DRT-1 | Vulkaneifel | Vulkaneifel district | Today |
| Vu-DRT-2 | Vulkaneifel | Vulkaneifel district | Future |

* Base case without DRT

** Calibrated base case with DRT (pre-Corona)

(b) other DRT services, e.g. *CleverShuttle*, and

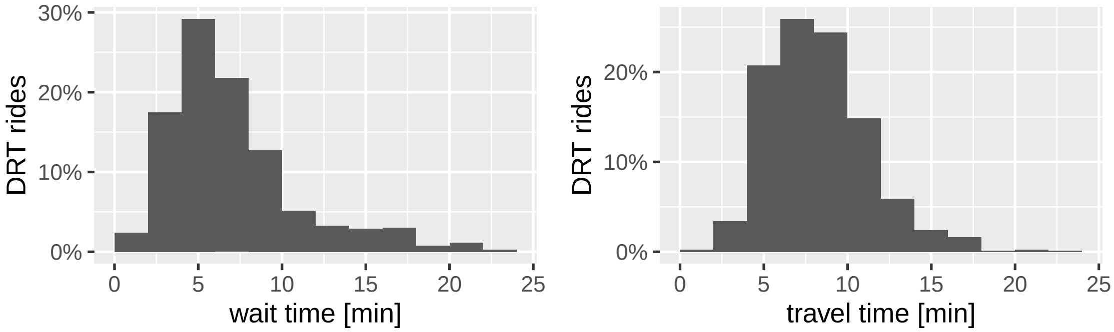
(c) regular taxis.

For (a), detailed user data for a pre-Corona average working day based on 10 representative days (Monday-Thursday) in August and September 2019 was provided by BVG. This included in particular the distance distribution for DRT rides and the origin-destination relations by zone and time of day. The user data which is used for calibration only covers the weeks where travel demand has reached a relatively constant level. Furthermore, weeks with special offers like price reductions are ignored. For (b), hardly any data is available; other operators provide services in the entire city, however, with smaller fleet sizes that provoke ride rejections throughout the day. For (c), general information about the number of rides is available from survey data and spatial distributions are available from other studies (Bischoff et al., 2015).

The starting point for the calibration was the already calibrated model for the metropolitan region of Berlin (see Sec. 3.1) which was then extended by adding the DRT mode. The simulated service area, service quality and fares match the real-world implementation of the BerlKönig service. The underlying model offered the modes motorized individual transport (car), schedule-based public transit, ride (car passengers), bicycle, and walk. Besides the newly introduced DRT, there is no other on-demand service present. Due to the removal of long-distance trips to other areas of Germany, there is fewer demand to and from airports and long-distance train stations. As reported in (Bischoff et al., 2015), this is a typical domain of regular taxi services. As such, within the model, it is expected to observe less DRT demand to and from long-distance public transport services compared to reality.

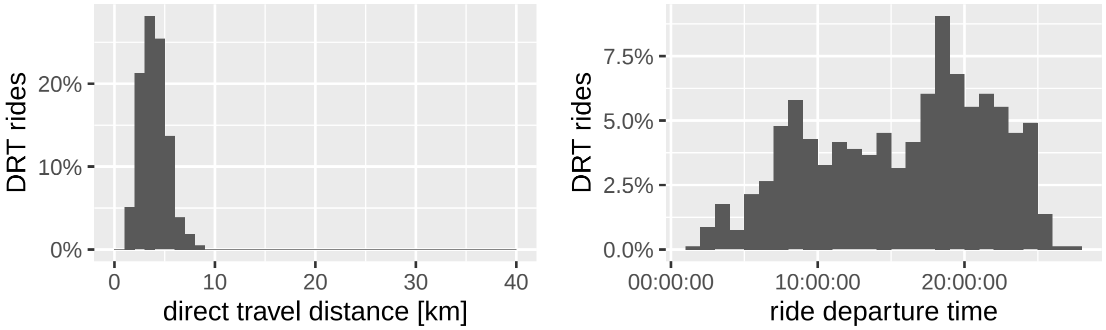
The base case model with DRT is calibrated for an average working day with the focus on matching the temporal and spatial demand patterns as observed for the real *BerlKönig* case (a). The calibration objective for the absolute ride-hailing trip level is defined based on the given information about (a) plus an estimate for (b) and (c). As main calibration parameters, the alternative specific constant for the DRT mode and the marginal utility of money are used.

Technically, a trip in MATSim is composed of multiple trip parts called ”legs”, e.g. a DRT trip is composed of a walk leg for access, the actual DRT leg and a walk leg for egress. To keep the nomenclature simple, in the following the more common term ”DRT ride” instead of DRT leg is used. Intermodal public transit trips for which the DRT mode is used as access and/or egress mode may have one or two DRT rides. In most cases, the DRT mode is only used as either access or egress mode. Thus, the number of DRT rides corresponds roughly to the sum of ”pure” DRT trips, i.e. without public transit, and intermodal public transit trips with DRT for access and/or egress, i.e. trips that include one or two DRT rides. From a DRT operator perspective, the number of trips involving DRT is probably less relevant than the actual number of DRT rides. The latter equals to the number of boardings and alightings. The resulting DRT ride distance, waiting time, travel time, and departure time distribution are shown in Fig. 4. The total ride-hailing demand level amounts to 3180 rides per day. 784 (25%) of these rides are used in an intermodal context, i.e. in combination with the schedule-based public transit mode. This ride level is considered as plausible: For (a), the observed daily ride number amounts to approximately 2000 rides per day for an average pre-Corona day in February 2019 (Abgeordnetenhaus Berlin, 2019). For (b) and (c), again omitting access/egress rides for long-distance public transport service, the daily ride number is assumed to be approximately 1000 rides.



(a) Waiting times

(b) Travel times



(c) Direct route DRT ride distances

(d) Drt ride departure times

Figure 4: User data for the calibrated base case with ride-hailing (Exp. BlnCity-DRT-1).

A comparison of the simulation experiments Bln-BC and BlnCity-DRT-1 reveals that most DRT users have switched from public transit to the DRT mode which in the model represents both conventional taxis, see (c) above, and the actual existing DRT modes, see (a) and (b) above.

The number of DRT rides per origin-destination relation is shown in Fig. 5. The DRT mode is used most frequently within and between the boroughs of Neukölln in the southern half

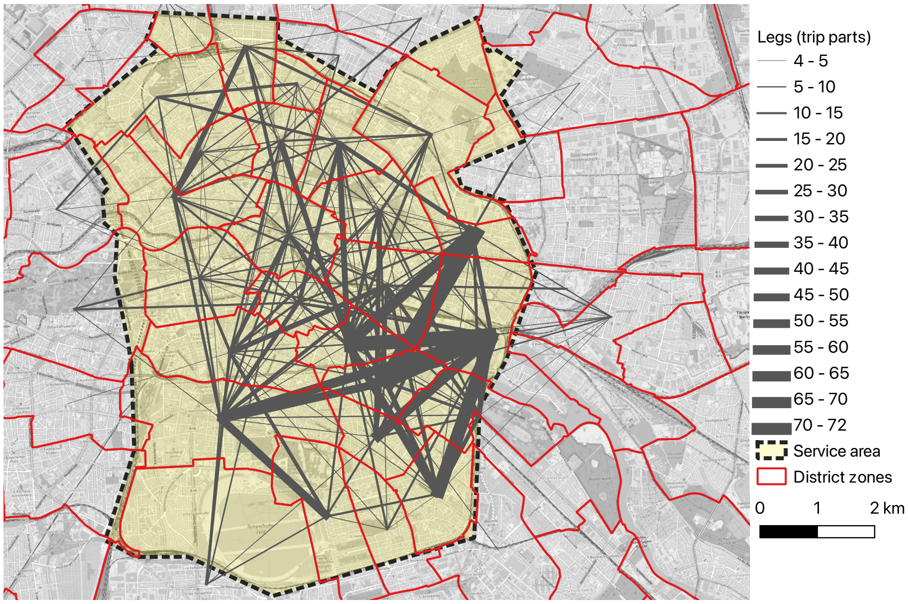


Figure 5: Origin-destination patterns of daily DRT rides (average working day; Simulation Exp. BlnCity-DRT-1); Background map: ©OpenStreetMap Contributors (`www.osm.org`)

of the service area and Friedrichshain-Kreuzberg. Both boroughs are known for having many clubs and other night life locations. Large DRT traffic flows can also be seen between Friedrichshain-Kreuzberg and the somewhat less vivid Prenzlauer Berg located in the North of the service area. In contrast, for the central borough of Mitte, traffic flows are rather small. This is mainly induced by the well above average transit quality in the area featuring a dense network of high-frequency train services and one of Berlins's largest transit hubs at Alexanderplatz. Mitte also features more office space and shopping locations and fewer residential areas and fewer night life destinations. The southern edge of the service area covering parts of the boroughs of Tempelhof and Neukölln is again dominated by residential use which explains rather low DRT traffic volumes.

Fig. 6 depicts the mode share by time of day for trips using only DRT and trips using a combination of DRT and public transit. For both types of DRT, demand rises significantly

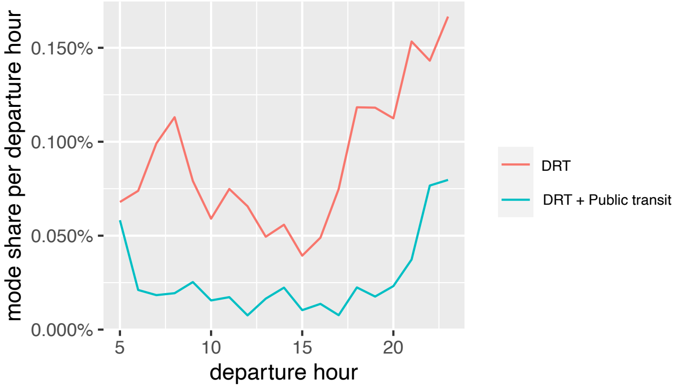


Figure 6: Mode share per departure hour of DRT and intermodal DRT and public transit combinations for all trips starting in the service area (Simulation Exp. BlnCity-DRT-1).

in the evening when regular transit starts to reduce its service frequency. In addition, there is a small peak during the morning rush-hour for trips that rely solely on DRT. The origin-destination patterns of DRT rides shown in Fig. 5 also confirm the high demand between the leisure-focused boroughs which occur in particular during the afternoon and evening.

Waiting time for BlnCity-DRT-1 is guaranteed to stay below 10 minutes for at least 90% of all DRT rides. This requires a total of 17 vehicles to serve all simulated DRT users in the 25% population sample. Upscaling the required fleet to the full 100% sample needs to factor in the non-linear relationship between population sample and fleet size. According to Kaddoura and Schlenther (2020) a factor of 2.4 is required which yields a total of 41 vehicles.[5] For comparison, the total fleet size of the real-world implementation of the BerlKönig is larger and amounts to approximately 150 vehicles (BVG, 2021). However, the fleet size of *BerlKönig* had been tailored to the substantially higher demand on Friday and Saturday evenings. That is, the fleet size of 41 vehicles seems plausible for an average weekday which is represented by the model.

## 4.2 Model transfer to other service areas and regions

In a first step, the parameters from the calibrated base case, BlnCity-DRT-1, are transferred to other service areas within the city of Berlin. For the Spandau case as depicted in Fig. 1, the service yields 1,176 DRT rides per day. Setting the service area to the entire city area of Berlin yields 38,472 DRT rides per day, including 13,684 rides (36%) in intermodal trips during which DRT is used as access/egress mode for public transit.

In a second step, the simulation setup is transferred to the urban region of Gladbeck and the rural region of the Vulkaneifel. For Gladbeck, the resulting number of DRT rides amounts to 6,660 rides per day, including 2,144 rides (32%) in intermodal trips in combination with public transit. For the Vulkaneifel, the demand level amounts to 10,128 DRT rides per day, including 1,252 rides (12%) in intermodal trips in combination with public transit. In Tab. 3, the demand levels are set in relation to other figures, such as the number of residents and the size of the service area provided in Tab. 1.

Table 3: Simulation results: Today's scenario (upscaled to the 100% population)

| Experiment | DRT rides | DRT vehicles | $\frac{DRT\,rides}{Total\,trip\,number}$ | $\frac{DRT\,rides}{residents}$ | $\frac{DRT\,rides}{km^2}$ | $\frac{DRT\,rides}{DRT\,vehicles}$ |
|---|---|---|---|---|---|---|
| BlnCity-DRT-1 | 3,180 | 41 | 0.0012 | 0.0056 | 52.13 | 77.56 |
| Bln-DRT-1 | 38,472 | 936 | 0.0043 | 0.0135 | 43.13 | 41.10 |
| Sp-DRT-1 | 1,176 | 34 | 0.0033 | 0.0075 | 15.47 | 34.59 |
| Gl-DRT-1 | 6,660 | 96 | 0.0089 | 0.0233 | 31.71 | 69.38 |
| Vu-DRT-1 | 10,128 | 290 | 0.1550 | 0.2035 | 11.12 | 34.92 |

The largest relative DRT ride share of 0.1550 is observed in the Vulkaneifel simulation experiment (Vu-DRT-1). In the other simulation experiments, the relative ride share is below 0.01. The smallest relative ride share of 0.0012 is observed for the Berlin inner-city DRT service area (BlnCity-DRT-1). Also the number of DRT rides per residents is highest in the Vulkaneifel case (Vu-DRT-1) and the lowest in the Berlin inner-city DRT experiment (BlnCity-DRT-1). While the previous parameters indicate the user potentials, the following parameters indicate the operability and show an opposite effect. For the number of DRT rides per km$^2$, a maximum of 52 rides/km$^2$ is observed in the Berlin inner-city

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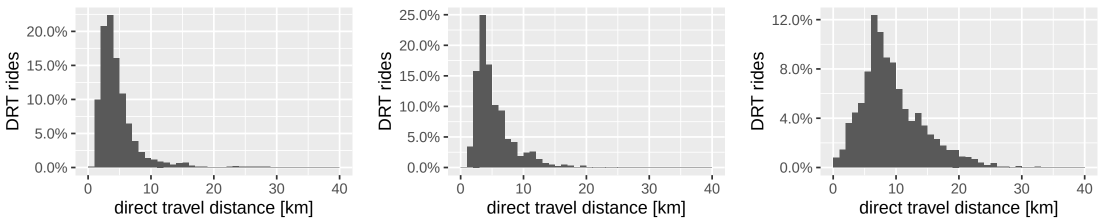
[5] The same upscaling factor is used for all other simulation experiments, including the experiments for Gladbeck and Vulkaneifel.

DRT experiment (BlnCity-DRT-1) and a minimum of 11 rides/km$^2$ in the Vulkaneifel experiment (Vu-DRT-1). Also, the number of served DRT rides per vehicle is at a maximum in the Berlin-city experiment (BlnCity-DRT-1) and lowest in the Vulkaneifel (Vu-DRT-1) and Spandau (Sp-DRT-1) experiment.

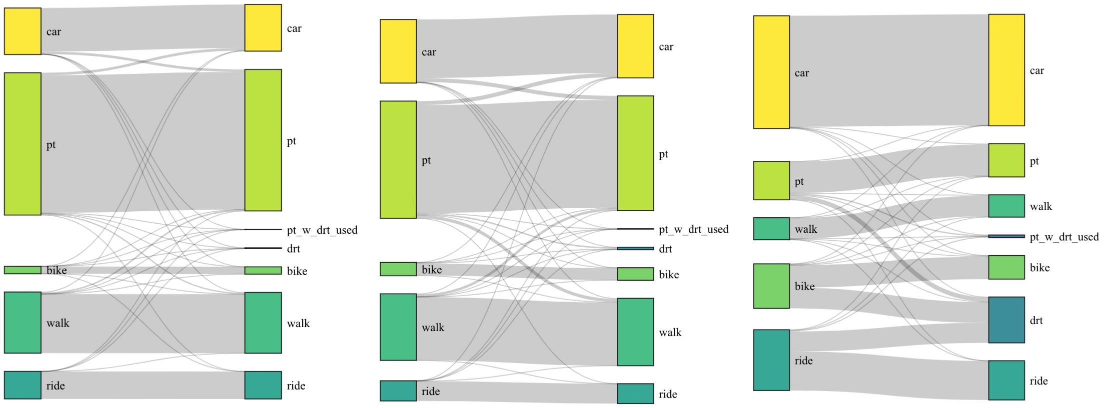


(a) Berlin: Bln-DRT-1 (b) Gladbeck: Gl-DRT-1 (c) Vulkaneifel: Vu-DRT-1

Figure 7: Direct travel distance (without detours for pooling) histograms

Fig. 7 shows the distance distribution of all DRT rides (direct distance without detours). The maximum distance travelled is obviously limited by the size of the service area. In the Berlin experiment (Bln-DRT-1) and Gladbeck experiment (Gl-DRT-1), most DRT rides are rather short with a distance of about 5 kilometers. In the Vulkaneifel experiment (Vu-DRT-1), the average DRT ride is about twice as long as in Berlin or Gladbeck.

In the today's scenario the mode shift effects are rather small. As shown in Fig. 8, the number of trips where the mode remains the same in the base case (left-hand side) and the DRT case (right-hand side) is the most dominant effect. Yet, there are some minor mode shift effects between the existing modes as well as towards the DRT mode. For the Vulkaneifel, a strong mode shift is observed from bicycle, ride and – to a lesser extent – from public transit to DRT.



(a) Bln-BC → Bln-DRT-1 (Berlin) (b) Gl-BC → Gl-DRT-1 (Gladbeck) (c) Vu-BC → Vu-DRT-1 (Vulkaneifel)

Figure 8: Mode shift effects from base case without DRT (Left) to simulation experiment with DRT (Right); trips with origin and destination within the service area; with "pt" for schedule-based public transit, "drt" for single-mode DRT trips, and "drt_w_pt_used" for trips where DRT was used as access and/or egress for public transit.

### 4.2.1 Spatial analysis for Berlin

Fig. 9 depicts the daily DRT passenger volumes per road segment for the simulation experiment in which DRT is implemented in the entire Berlin area. Fig. 10 depicts the corresponding spatial distribution of daily DRT rides per origin-destination relation.

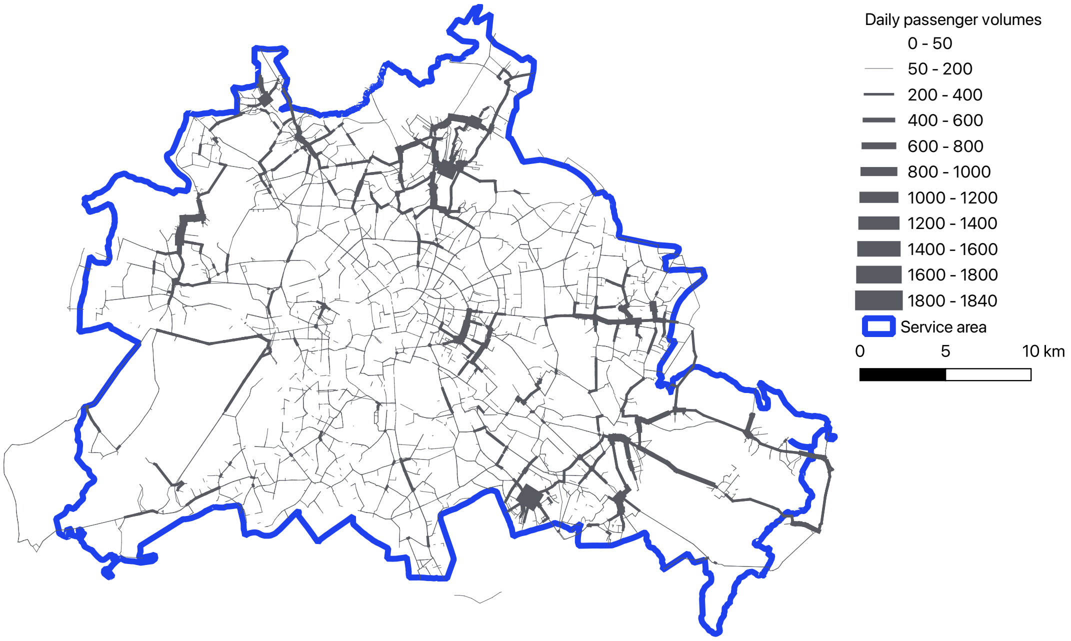


Figure 9: Daily DRT passenger volumes (Simulation Exp. Bln-DRT-1)

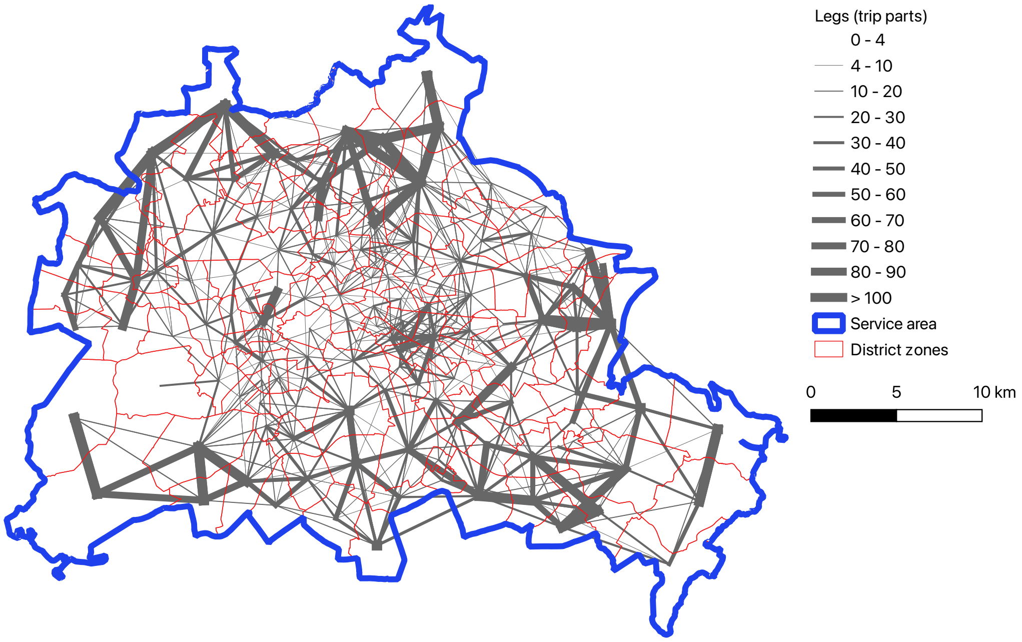


Figure 10: Origin-destination patterns of daily DRT rides (Simulation Exp. Bln-DRT-1)

These visualizations show that the DRT service is mainly used in the outer parts of the city where schedule-based public transit service provision is not as good compared to e.g. the central borough of Mitte. In Fig. 9, the road segment with the highest DRT passenger volume is located far outside the city center close to the terminus of a subway line in Rudow in the southeastern periphery of Berlin. Like Rudow, most other areas with high DRT passenger volumes per road segment are located close to commuter train stations in the outskirts of the city, e.g. Adlershof, Köpenick, Rahnsdorf, Mahlsdorf, Blankenburg, Karow, Waidmannslust, and Frohnau. However, besides those areas where DRT is apparently used as a feeder service to the subway, there is another notable high passenger volume corridor between Tegelort and Spandau in the Northwest of Berlin which does not serve any train station, but rather connects two parts of the city divided by a river. Due to the river there is no direct road and no bus service connecting those districts. Instead, DRT vehicles are using the car ferry to cross the river which was included in the model as a road with a very low speed. Furthermore, especially in the Southeast high DRT passenger volumes are observed on roads with parallel but infrequent bus or tram services. In the city center, the highest passenger volumes occur in parts of Friedrichshain-Kreuzberg known for their nightlife which confirms the findings from the Berlin-city experiment (BlnCity-DRT-1, see Fig. 5 in Sec. 4.1). Overall, as shown in Fig. 10, tangential DRT traffic flows are stronger than radial traffic flows. The strongest origin-destination-pairs are rather short and are located in the periphery. This suggests DRT is mostly used complementary to public transit where public transit service provision is rather poor.

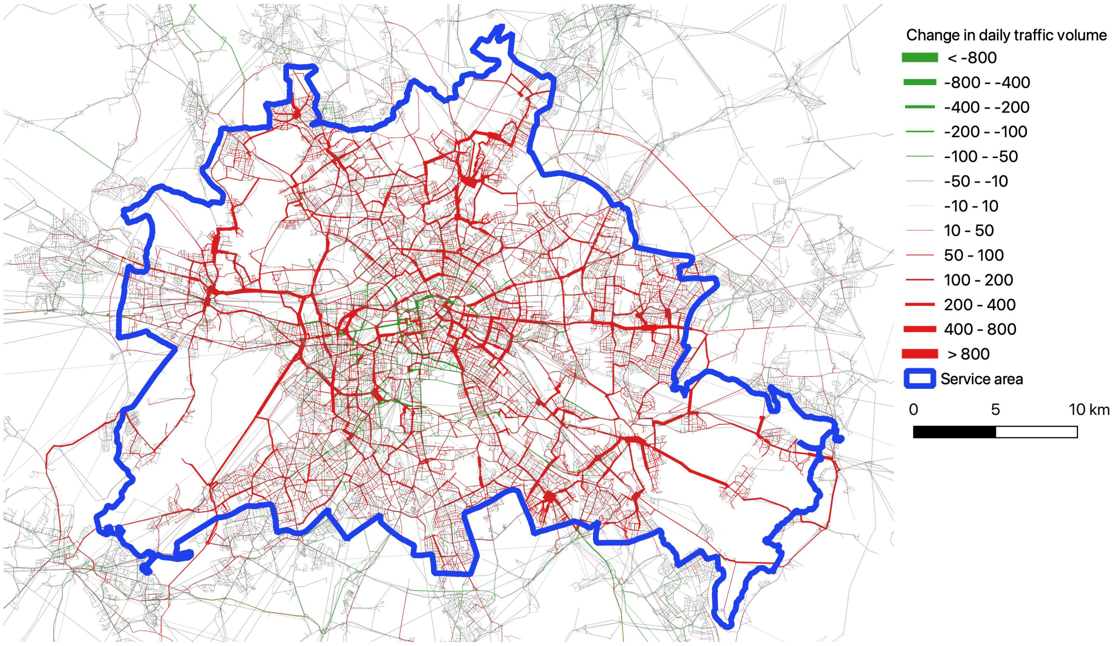


Figure 11: Change in traffic volume (Simulation Exp. Bln-DRT-1 vs. Bln-BC)

Fig. 11 depicts the change in daily traffic volume per road segment over all vehicle types includung private cars and DRT vehicles in comparison with the base case. Overall, an increase in traffic is observed for most road segments, in particular in the DRT hot-spot areas described above. However, the absolute increase distributed over the day is rather of minor importance relative to the total volumes.

### 4.2.2 Spatial analysis for Gladbeck

Fig. 12 shows the daily DRT passenger volumes for Gladbeck. The origin-destination pattern in Fig. 13 illustrates the main function of DRT as a feeder to the most important commuter rail station of Gladbeck (Gladbeck West) in the center of the DRT service area. A further function of the DRT mode is serving complementary trips to the radial bus network that favors the city center of Gladbeck but does not deliver tangential connections in low-demand remote areas.

Figure 12: DRT passenger volumes (Simulation Exp. Gl-DRT-1)

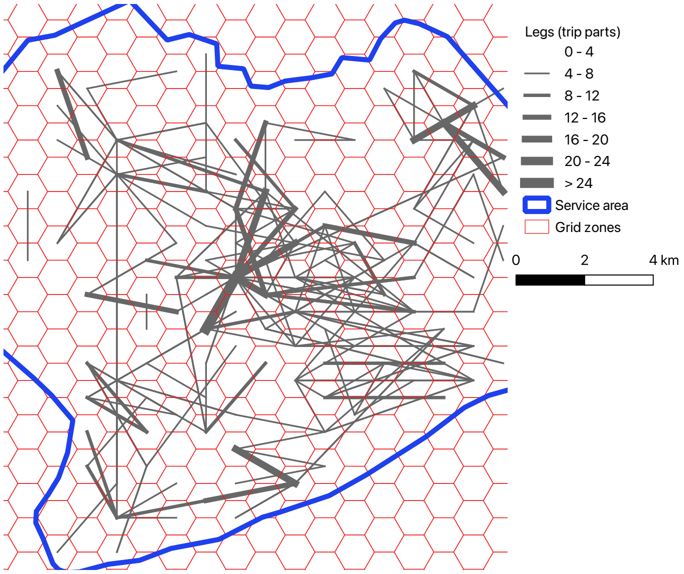


Figure 13: Origin-destination patterns of daily DRT rides (Simulation Exp. Gl-DRT-1)

### 4.2.3 Spatial analysis for Vulkaneifel

Fig. 14 and Fig. 15 show the DRT passenger volumes per road segment and origin-destination relation for the district of Vulkaneifel. Most DRT rides directly connect

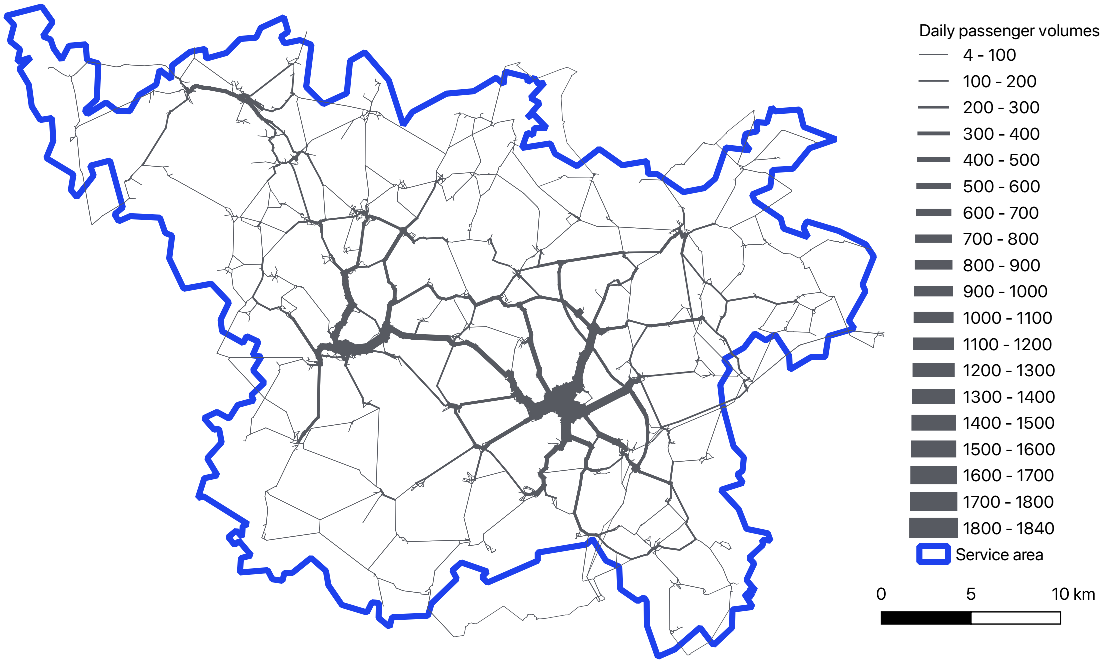


Figure 14: DRT passenger volumes (Simulation Exp. Vu-DRT-1)

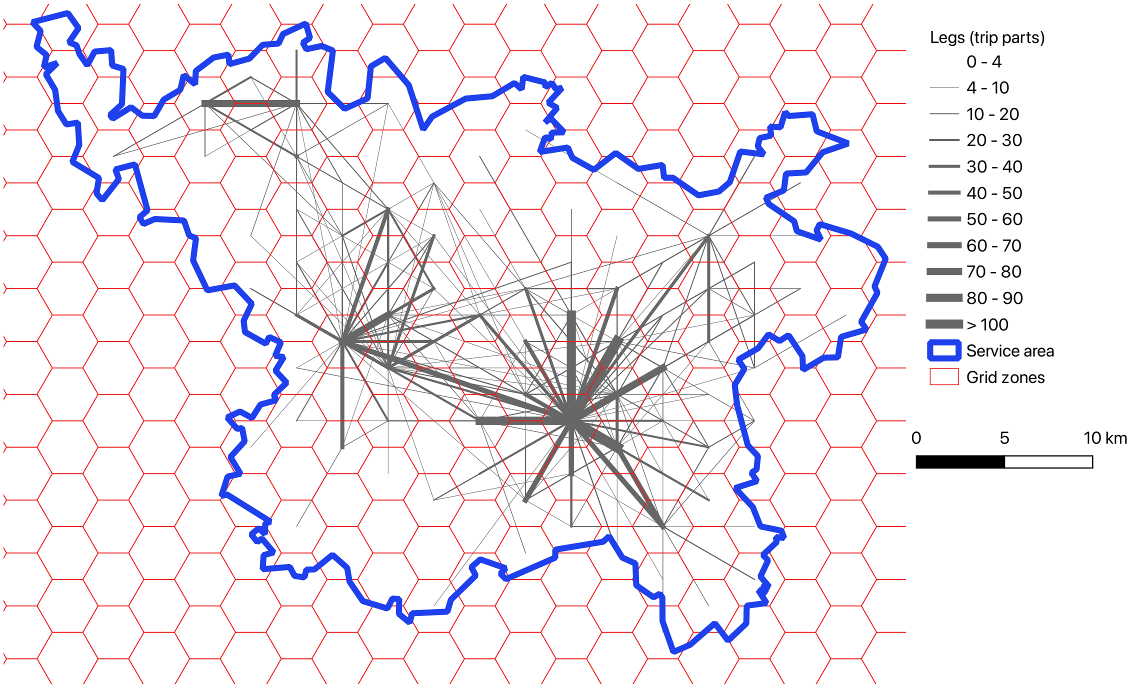


Figure 15: Origin-destination patterns of daily DRT rides (Simulation Exp. Vu-DRT-1)

one of the regional centers, i.e. the towns of Gerolstein, Daun, and Hillesheim to their surrounding villages. There is also a direct DRT connection between the two major centers of Gerolstein and Daun which attracts demand from the existing regular albeit less frequent bus connection. Since bus service quality is even lower for other connections there are only few trips that use DRT in combination with public transit. Almost all intermodal trips use DRT as a feeder to the train station in Gerolstein and the bus hubs in Gerolstein, Daun, and Ulmen for access and egress to bus lines leaving the DRT service area. This provides a better access to economic centers outside the Vulkaneifel region, especially to Cologne in the North using the train from Gerolstein.

## 4.3 Model transfer to other time horizons

In this section, the model setup is transferred into the future. Simulation experiments for the **future scenario** are based on the assumption that ride-hailing is perceived by users in a similar way to (schedule-based) public transport and also the fare is the same as for today's public transit. Again, the DRT operator provides a fixed service quality and adjusts the fleet size such that waiting times are below 10 minutes in 90% of all DRT rides.

Tab. 4 provides the key figures for the simulation results of the future scenario. Integrating the DRT service into the public transit pricing system yields a strong increase in DRT rides. The largest modal share – of 0.5688 – is observed again in the Vulkaneifel. In the Berlin experiment, 3.77 million DRT rides, including 0.88 million rides (23%) in intermodal trips, are served by a fleet of 171,655 vehicles. In the future scenario of Gladbeck, the number of DRT rides amounts to 403,308, including 154,704 rides (38%) in intermodal trips. In the Vulkaneifel experiment for the future scenario, there are 37,168 DRT rides, including 3,056 rides (8%) in intermodal trips, mainly to the train station in Gerolstein.

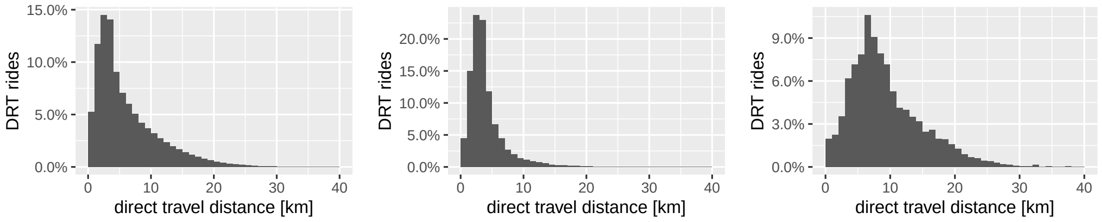
In the Berlin and Vulkaneifel experiments for the future scenario, the share of intermodal trips is significantly reduced in comparison to the today's scenario. That is, most intermodal trips within the service area are now replaced by direct DRT trips, mainly due to the fact that the DRT mode is priced the same as schedule-based public transit but offers the same trip without transfers. In contrast, in the Gladbeck case, the intermodal trip share has slightly increased since the DRT service area is located inside the Ruhr area and the service area border runs right through the urban region. That is, there are more trips starting or ending outside the service area where the DRT mode can not be used for the entire trip, and in consequence acts as a feeder to regular transit to neighbouring cities.

Fig. 16 depicts the distance distribution for all DRT rides in the future simulation experiments for Berlin, Gladbeck, and the Vulkaneifel. There are more long rides in comparison to the today's scenarios shown in Fig. 7, but also more very short trips below 2 kilometers. In Gladbeck, the average DRT ride distance decreases from 5.2 to 4.0 kilometers in the

Table 4: Simulation results: Future scenario (Upscaled to 100% population)

| Experiment | DRT rides | DRT vehicles | $\frac{DRT\,rides}{Total\,trip\,number}$ | $\frac{DRT\,rides}{residents}$ | $\frac{DRT\,rides}{km^2}$ | $\frac{DRT\,rides}{DRT vehicles}$ |
|---|---|---|---|---|---|---|
| BlnCity-DRT-2 | 753,912 | 18,732 | 0.2842 | 1.33 | 12,359.21 | 40.25 |
| Bln-DRT-2 | 3,771,100 | 171,655 | 0.4169 | 1.33 | 4,227.69 | 21.97 |
| Sp-DRT-2 | 100,504 | 2,808 | 0.2807 | 0.64 | 1,322.42 | 35.79 |
| Gl-DRT-2 | 403,308 | 3,384 | 0.5370 | 1.41 | 1,920.51 | 119.18 |
| Vu-DRT-2 | 37,168 | 914 | 0.5688 | 0.75 | 40.80 | 40.65 |

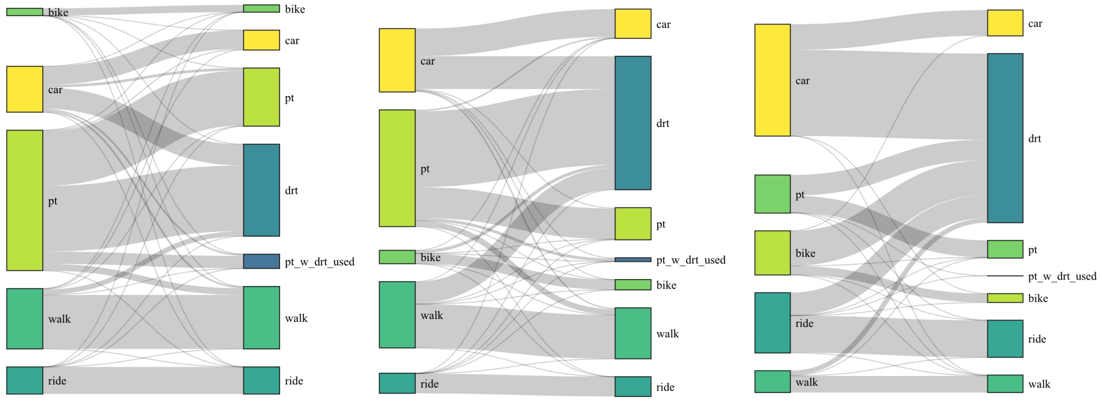
future scenario. In the Vulkaneifel case, there are some gains in the very short and long distance range, but there is no significant change in the average DRT ride distance. In contrast, the future Berlin scenario massively gains in long DRT rides and the average DRT ride distance increases from 4.7 to 6.2 kilometers. This reflects the direct competition to the train services available throughout the city. With the lower fares, the DRT mode attracts passengers from longer regular transit trips. In contrast, in Gladbeck, most transit riders want to leave the service area and thus depend on long-distance train connections, i.e. they are forced to use public transit and can not improve by switching to the DRT mode. In the Vulkaneifel district, there is no real competing public transit and DRT rather attracts passengers from other modes, i.e. from bicycle and even from walk for short distances and mainly from the ride mode for longer distances.



(a) Berlin: Bln-DRT-2 (b) Gladbeck: Gl-DRT-2 (c) Vulkaneifel: Vu-DRT-2

Figure 16: Direct travel distance (without detours for pooling) histogram

Fig. 17 depicts the mode shift effects for the DRT simulation experiments in comparison to the base cases. In the urban regions of Berlin and Gladbeck, the strongest mode shift effect is observed from from public transit to DRT. Yet, a significant share of users switch from car to DRT. In contrast, in the rural region of the Vulkaneifel, approximately half of all DRT users switch from the car mode; the remaining users switch from public transit, bicycle, and walking.



(a) Bln-BC → Bln-DRT-2 (Berlin) (b) Gl-BC → Gl-DRT-2 (Gladbeck) (c) Vu-BC → Vu-DRT-2 (Vulkaneifel)

Figure 17: Mode shift effects from base case without DRT (Left) to simulation experiment with DRT (Right); trips with origin and destination within the service area; with ”pt” for schedule-based public transit, ”drt” for single-mode DRT trips, and ”drt_w_pt_used” for trips where DRT was used as access and/or egress for public transit.

Fig. 18 depicts the DRT demand per origin-destination relation in the future Berlin scenario (Bln-DRT-2). A comparison with the today's scenario shown in Fig. 10 reveals that spatial patterns have changed from rather tangential connections on the outskirts to more radial connections leading to the central city area. For Gladbeck (Gl-DRT-2) and Vulkaneifel (Vu-DRT-2), the spatial origin-destination patterns have not significantly changed compared to Fig. 13 and Fig. 15, except for the higher absolute demand level.

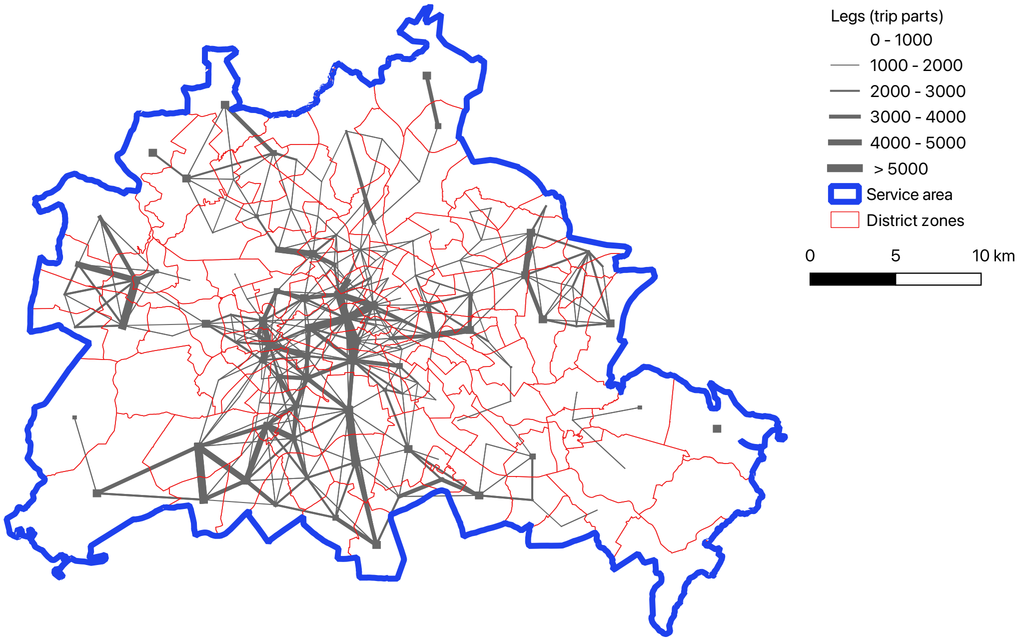


Figure 18: Origin-destination patterns of daily DRT rides (Simulation Exp. Bln-DRT-2)

The strong mode shift effect towards DRT yields a significant increase in traffic volumes, shown in Fig. 19 for Berlin (Bln-DRT-2), Fig. 20 for Gladbeck (Gl-DRT-2), and Fig. 21 for Vulkaneifel (Vu-DRT-2). In Berlin, the strongest increase in daily traffic volumes is observed on the inner-city trunk roads and motorways leading to or around the city center (see Fig. 19). There is no single hub of demand but the DRT demand pattern follows the interrelated structure of the boroughs of Berlin, with slightly more demand at the remote hubs of Spandau and Tegel.

In contrast, the strongest increase in traffic volume for Gladbeck is observed around the four individual hubs of the area – namely, the city center of Gladbeck in the central part of the service, Bottrop in the Southwestern part of the service area, and Buer in the Eastern part of the service area (see Fig. 20). Traffic volumes on roads connecting these four centers are rather low.

In the Vulkaneifel experiment, the smaller population density and rural area translates into a rather small absolute increase in traffic volume of up to approximately 1000 vehicles per day (see Fig. 21). Traffic volumes increase in particular again around centers of the region, i.e. the towns Daun, Gerolstein, and Hillesheim but not between these centers.

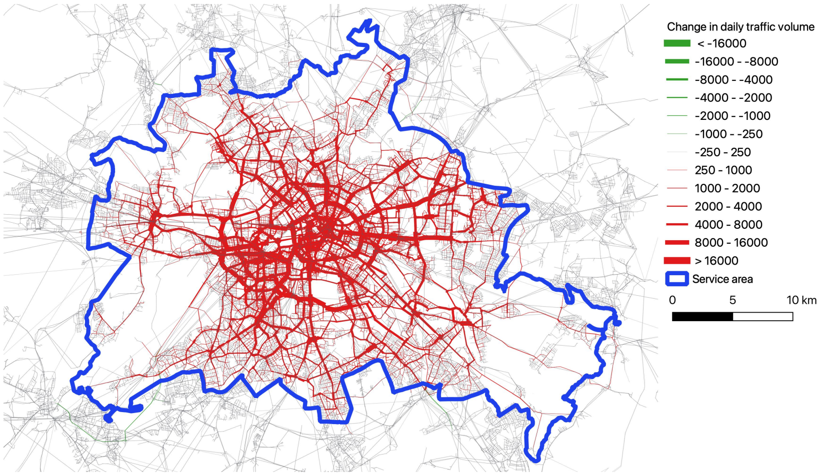


Figure 19: Change in traffic volume (Simulation Exp. Bln-DRT-2 vs. Bln-BC)

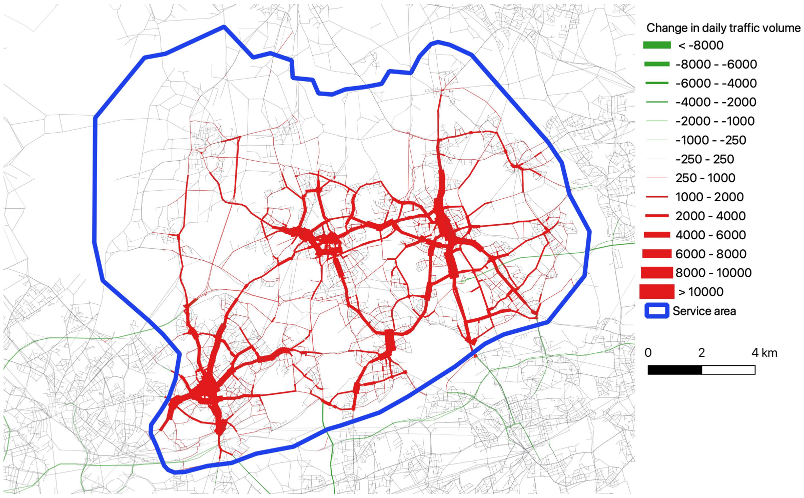


Figure 20: Change in traffic volume (Simulation Exp. Gl-DRT-2 vs. Gl-BC)

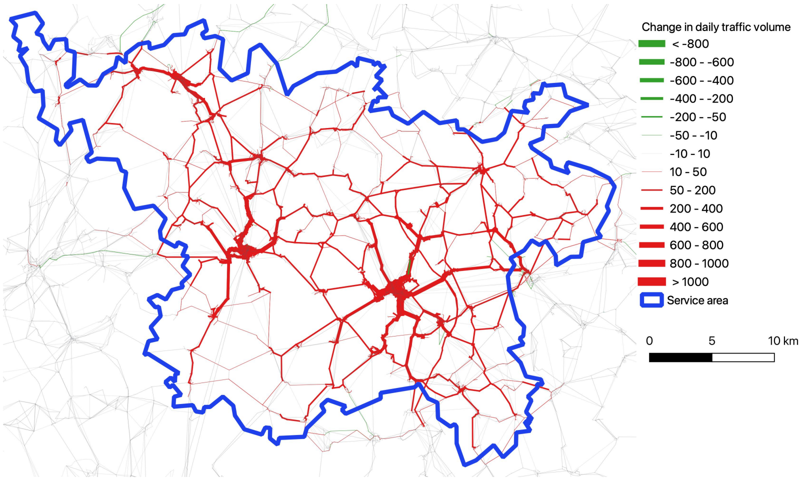


Figure 21: Change in traffic volume (Simulation Exp. Vu-DRT-2 vs. Vu-BC)

## 4.4 Estimation of the operator's profit

Table 5: Today's DRT scenarios: Estimation of the daily operator's profit (the numbers are upscaled to the 100% population)

| Simulation experiment | BlnCity-DRT-1 | Bln-DRT-1 | Sp-DRT-1 | Gl-DRT-1 | Vu-DRT-1 |
|---|---|---|---|---|---|
| Revenues [EUR] | 19,116 | 180,666 | 8,139 | 53,032 | 143,317 |
| Number of DRT vehicles | 41 | 936 | 34 | 96 | 290 |
| Vehicle fix costs* [EUR] | 733 | 16,736 | 608 | 1,716 | 5,185 |
| Operation time [hours] | 915 | 16,556 | 645 | 2,156 | 4,660 |
| Driver costs** [EUR] | 16,136 | 292,041 | 11,385 | 38,040 | 82,204 |
| Total vehicle-kilometers | 16,976 | 221,908 | 6,843 | 45,779 | 99,877 |
| Vehicle operating costs*** [EUR] | 1,698 | 22,191 | 684 | 4,578 | 9,988 |
| Total costs [EUR] | 18,567 | 330,968 | 12,677 | 44,334 | 97,377 |
| Profit [EUR] | 549 | −50,302 | −4,538 | 8,698 | 45,940 |

* Vehicle fix cost per day: 17.88 EUR/vehicle
** Driver cost rate: 17.64 EUR/hour
*** Vehicle operating cost rate: 0.10 EUR/km

Table 6: Future DRT scenarios: Estimation of the daily operator's profit (the numbers are upscaled to the 100% population)

| Simulation experiment | BlnCity-DRT-2 | Bln-DRT-2 | Sp-DRT-2 | Gl-DRT-2 | Vu-DRT-2 |
|---|---|---|---|---|---|
| Revenues [EUR] | 639,984 | 6,791,897 | 102,201 | 467,485 | 102,339 |
| Number of DRT vehicles | 18,732 | 171,655 | 2,808 | 3,384 | 914 |
| Vehicle fix costs* [EUR] | 334,928 | 3,069,195 | 50,207 | 60,506 | 16,349 |
| Operation time [hours] | 232,812 | 1,981,523 | 42,603 | 61,349 | 14,037 |
| Driver costs** [EUR] | 0 | 0 | 0 | 0 | 0 |
| Total vehicle-kilometers | 1,700,944 | 14,438,801 | 298,907 | 1,479,674 | 316,793 |
| Vehicle operating costs*** [EUR] | 170,094 | 1,443,880 | 29,891 | 147,967 | 31,679 |
| Total costs [EUR] | 505,023 | 4,513,075 | 80,098 | 208,473 | 48,029 |
| Profit [EUR] | 134,961 | 2,278,822 | 22,103 | 259,012 | 54,310 |

* Vehicle fix cost per day: 17.88 EUR/vehicle
** Driver cost rate: 0 EUR/hour
*** Vehicle operating cost rate: 0.10 EUR/kilometer

In this section, the revenues and a simple cost model are used to estimate the operator's profit for the today's scenario (see Tab. 5) and the future scenario (Tab. 6). The cost model accounts for the operating hours, the vehicle-kilometers, and the fleet size. Daily vehicle fix costs are assumed to be 17.88 EUR per vehicle (Planco et al., 2015, see p. 284, Tab. 8-32).[6] In the future scenario, the DRT mode is operated with automated vehicles and driver costs are assumed to be zero. In the today's scenario, the DRT mode is assumed to be driver-controlled and driver costs are assumed to be 17.64 EUR per hour (Planco et al., 2015, see p. 284, Tab. 8-37). The total operation time is computed as the sum of all vehicles' operation times which are defined as the first vehicle movement until the last one throughout the day. Variable vehicle operating costs are assumed to be 0.10 EUR/kilometer (0.067 EUR/kilometer for distance-related depreciation and tire wear plus 0.033 EUR/kilometer for energy consumption, again following to Planco et al., 2015). In the today's scenario, the revenues are computed as the maximum of 4.00 EUR and 1.50 EUR/kilometer based on the direct ride distance (without detours). In the future scenario, the revenues result from a distance-based fare of 0.29 EUR/kilometer based on the direct ride distance (without detours) which approximately corresponds to the

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[6] See p. 284, Tab. 8-32, "Vorhaltungskosten ohne Fahrpersonalkosten" (fixed costs without personnel costs) for a VW Golf 1.4 Trendline per year divided by 365, with "Allgemeine Kosten" (overhead costs) of 5.291 EUR/year for the vehicle fleet management.

fare level for conventional public transit. The upscaling of DRT related parameters from the 25% population sample to the full 100% population is done based on the upscaling parameters provided in Kaddoura and Schlenther (2020). That is, the fleet size is scaled up with a factor of 2.4, the operation time is scaled up with a factor of 2.5 and the vehicle-kilometers are scaled up with a factor of 3.6.

In the today's DRT scenarios, a profitable service is observed in the Berlin inner-city (BlnCity-DRT-1), Gladbeck (Gl-DRT-1), and Vulkaneifel (Vu-DRT-1) cases. For the Berlin city wide service (Bln-DRT-1) and the Spandau case (Sp-DRT-1), total cost exceed the revenues and the DRT provider makes losses. In the future DRT scenario, the elimination of driver costs yields a profitable service in all cases. If the assumption regarding the revenues is altered and assumed to amount to 0.20 EUR/kilometer, for Berlin (Bln-DRT-2), Gladbeck (Gl-DRT-2), and Vulkaneifel (Vu-DRT-2) the service remains profitable, however, in the Berlin inner-city (BlnCity-DRT-2) and Spandau (Sp-DRT-2) cases the DRT provider makes losses. The calculation in Tab. 5 and Tab. 6 only looks at the DRT operator and does not account for the operational costs and revenues of the conventional schedule-based public transit. As there is a strong mode shift effect from schedule-based public transit to DRT, also some of the revenues are shifted from the schedule-based public transit mode to DRT. To this effect, the schedule-based public transit provider would respond by adjusting the supply in order to reduce operation costs, e.g. by eliminating bus lines with low demand levels.

# 5 Discussion

## 5.1 Heiligensee

In May 2020, the DRT service of *BerlKönig* was extended in a modified form to Heiligensee, the Northwestern part of the borough of Reinickendorf in Berlin. Under the name *BerlKönig BC*, this service connects Heiligensee to the subway station of Alt-Tegel. The service area of the *BerlKönig BC* is not connected to the service area of the actual inner-city *BerlKönig*. For *BerlKönig BC* the pricing was significantly reduced to only 0.50 EUR per ride compared to 1.50 EUR/kilometer and the minimum charge of 4.00 EUR per ride for the *BerlKönig* in the inner-city Berlin area. However, in the *BerlKönig BC* case, a regular public transit trip is necessary in addition to this 0.50 EUR supplement. The same service extension was implemented in the model and additional simulation experiments were carried out. The simulation results show a high DRT demand level of 2,760 rides per day. Most of these rides, a total of 2,120, are used in combination with schedule-based public transit. However, real-world user data showed a very different picture. The number of served trips was roughly at the level of 10 rides per day in August 2020 (Hasselmann, 2020) and about only 7 rides per day in October 2020 (Die Dorfzeitung, 2020). The service was stopped at the end of the year 2020 (Die Dorfzeitung, 2020). The large discrepancy between model and reality could be explained by the Corona pandemic and the overall reduced mobility in the year 2020 related to lockdowns and the change in behavior (social distancing, home office). Also, user preferences may have changed during the pandemic, resulting in users who are less willing to share a ride with people from other households.

## 5.2 Simulation of school traffic in the Vulkaneifel region

Discussions with local stakeholders in the Vulkaneifel region have revealed that future's DRT is expected to be able to also serve school traffic demand. Today, school traffic demand is mainly served by schedule-based public transit or parents who drive their children. Children who live close to the school either walk or take their bicycle. Depending on their age, some older pupils also use their own moped or car to get to school. Some of the existing bus services in the Vulkaneifel only operate on-demand and users need to register their rides via a call center. A strong limitation of the today's on-demand services is that buses have to be ordered several hours or even days ahead, i.e. these services can not be requested spontaneously. The simulation experiments for the Vulkaneifel described in the previous sections use the case study in which the population does not include children below the age of 14 years (see Sec. 3.1). To still be able to investigate the impact of school traffic demand on the resulting DRT service, two additional simulation experiments are carried out for the future's scenario: Vu-DRT-2a and Vu-DRT-2b.

**Experiment Vu-DRT-2a** is similar to experiment Vu-DRT-2, but with the DRT pre-booking option. The pre-booking is implemented in a simplified way: Agents are assumed to request a ride before departing from an activity. Thus, waiting times do not negatively affect the users' benefits. The target waiting time is altered to 30 minutes for again at least 90% of the ride requests. Consequently, the approx. 37 thousand DRT rides can now be served with a fleet size of only 461 vehicles instead of the 914 vehicles required in experiment Vu-DRT-2.

**Experiment Vu-DRT-2b** adds the additional school-related DRT demand to the DRT demand from experiment Vu-DRT-2a. For the missing population, new agents are created based on census data and activity patterns are drawn from mobility survey data of a similar region and assigned to these agents. Missing activity locations especially for primary schools and kindergarten are taken from OpenStreetMap and cross-checked with the actual school locations. Non-educational activities use the same facilities that are already part of the model. For the entire Vulkaneifel region, the resulting number of additional DRT relevant trips in the morning amounts to approx. 4000 trips. DRT relevance is defined as (i) trips to school that start and end inside the Vulkaneifel region, (ii) also all other trips in the afternoon that start and end in the Vulkaneifel region, and (iii) the beeline trip distance between home and education activity (school) is more than 2 kilometers. All DRT relevant trips are now fixed to the DRT as sole transport mode. Together with the resulting DRT demand from experiment Vu-DRT-2a, the newly added DRT demand of the pupils is simulated for one iteration. The DRT fleet size is adjusted such that (i) no pupil has to leave earlier compared to taking the regular bus, (ii) approx. 10% of the pupils leave the house later compared to taking the regular bus, (iii) no pupils are allowed to arrive late for their first lesson, i.e. 7.30 a.m. for schools in Daun and 8.00 a.m. for all other schools. The resulting number of the additional 4000 DRT rides is rather small compared to the approx. 37 thousands rides in experiment Vu-DRT-2a.Yet, in experiment Vu-DRT-2b, the DRT fleet required to also serve the additional demand almost doubles compared to experiment Vu-DRT-2a – a direct result of the temporally concentrated demand when arrivals at schools peak between 7 and 8 in the morning. During off-peak time periods, all DRT users benefit from the then larger fleet size which results in overall lower waiting times and almost no pooling-related detours.

# 6 Conclusion and outlook

In this study, a new approach was proposed which uses an existing DRT service as a starting point for the investigation of today's and future on-demand services. In a first step, the existing DRT service *BerlKönig* in the Eastern inner-city center area of Berlin is implemented in the model taking into consideration the real-world service characteristics (e.g., service area, service quality, fares). Real-world DRT user data is used to calibrate the transport model which accounts for transport users' mode choice reactions. In a second step, the model setup is altered, e.g. the DRT service area is extended to the entire city area of Berlin. Furthermore, the DRT service is transferred to other regions in Germany (Gladbeck, Vulkaneifel). In a third step, the calibrated model setup is transferred to a future scenario where the DRT mode is operated by autonomous vehicles and the DRT mode is integrated into the regular (schedule-based) public transit system. Technically, this is done by setting behavioral and cost parameters for the simulated DRT mode equal to those for today's public transit.

The proposed methodology was successfully applied to three case studies in Germany and allows for a spatially and temporally detailed investigation of today's and future DRT concepts. The simulated *BerlKönig* service confirms observations made in the real-world, e.g. passenger volumes by origin-destination relation and an increase in relative trip frequency in the afternoon and evening times.

Overall, the study highlights the importance to simulate the entire transport system, including demand which does not directly interact with the DRT mode. DRT is not only influenced by non-DRT users by competing for limited road capacities but it is also important to detect mode shifts and other intended or unintended side effects. That is, the present study goes far beyond most existing studies (see Sec. 1) which only model DRT demand by tracking users of an existing DRT system or by using floating car data of regular taxis. These studies limit the model to academic use cases which are useful for benchmarking different dispatch strategies but not sufficient for the investigation of the system-wide effects in the entire transport system.

One of the key findings is that potentials for the DRT mode are identified for two different perspectives:

- From the operator's point of view, areas with high population densities (Berlin inner-city center, Gladbeck) are found to be most promising since travel demand can be served more efficiently compared to the low-demand areas. That is, there are more rides per DRT vehicle and fewer vehicle-kilometers per served passenger; however, relative DRT trip shares are rather low.
- The opposite is observed for the users' point of view: In areas (and times) with rather poor schedule-based public transit provision (Vulkaneifel, Spandau, entire Berlin area including outskirts), the DRT mode is a very attractive alternative to the existing modes of transportation. In these areas, relative DRT trip shares are rather high, however, the DRT service is less efficient (larger relative fleet size, more vehicle-kilometers per DRT ride) which results in higher operational costs.

In the today's scenario, the increase is traffic volume is rather small and is not expected to yield a significant increase in traffic congestion. The future scenario is found to differ greatly from the today's scenario. Reduced monetary costs and higher affinities for new mobility concepts yield a drastic increase in DRT trip shares and vehicle-kilometers. In the future scenario, total traffic volumes are found to dramatically increase in the urban case studies. Depending on the capacity impact of autonomous vehicles, this can lead to a strong increase in congestion. In contrast, for the rural case study of the Vulkaneifel district, the increase in traffic volume is rather low and an increase in traffic congestion is only expected locally at single hot-spots, e.g. schools in the morning period.

In the today's scenario, the assumptions regarding operator's costs are found to yield a profitable service in the Berlin inner-city case (BlnCity-DRT-1), Gladbeck case (Gl-DRT-1) and Vulkaneifel case (Vu-DRT-1). In the other cases for the today's scenario, the costs exceed the revenues and the DRT operator makes losses. In contrast, in the future scenario, a profitable service is found for all DRT service areas.

A further observation is that, spatial DRT usage patterns are very different depending on the specific case study and service area. The simulation outcome for the rural area (Vulkaneifel) differ greatly from the results for urban areas (Berlin, Berlin inner-city, Gladbeck). The spatial patterns also change between the today's and future scenario, e.g. from rather tangential connections to radial connections in the Berlin case study.

In both the today's and future scenario, there is a mode shift effect from regular (schedule-based) public transit to the DRT mode. In the today's scenario, this is the predominant mode shift effect. However, in the future scenario, a significant number of users also change from the private car mode to the DRT mode. From a sustainability perspective, there are also undesired mode shift effects, e.g. from bicycle and walk to DRT.

The most important takeaways for the technical setup of future DRT simulation studies are the following:

- The base case needs to contain **all relevant modes of transportation** from which users may switch to innovative mobility concepts, in particular conventional ride-hailing modes (taxis) and the informal ride sharing mode, i.e. car passengers, often also referred to as "ride".
- Travel demand should cover the **entire population and all trip purposes** that are relevant for DRT services, in particular long-distance travelers on their way to airports or railway stations and school traffic demand.
- **DRT related parameters** for simulated dispatching, pooling and rebalancing should be set based on the (expected) real-world service and may be adjusted/calibrated depending on the specific service area (e.g. different parameters for rural vs. urban areas).
- The option of **pre-booking** a DRT ride before departing from an activity location improves the DRT operator's flexibility which allows to reduce operational costs without reducing user benefits. This feature should be considered by the DRT simulation framework.
- Because of the non-linear relationship between trip density and ride-sharing service parameters, it is recommended to carefully upscale simulation results for population samples and rather use **large population samples**, optimally the full population.

Additional points for future studies include:

- As monetary costs, e.g. the DRT fares, play an important role, an **income-dependent willingness to pay** should be considered for future implementations of such models, e.g. by means of a person-specific income-dependent marginal utility of money. Optimally, this parameter together with further behavioral parameters are validated against real-world demand sensitivities. Also, the general attitude towards new mobility concepts, the ownership of a smartphone, and the willingness to try out new modes instead of using the own car should be reflected by heterogeneous behavioral parameters, e.g. based on socio-demographic attributes.
- Most of today's DRT services are used especially on Friday and Saturday evenings. It should therefore be considered to set up a transport model for **weekend days** in addition to the average working day.

To further improve DRT simulation studies, spatially and temporally disaggregated survey data is required. Especially for low-demand areas and times of day, the DRT as a system reacts to individual requests. Operational key figures depend on very accurate temporal and spacial demand patterns. The commonly used zonal-based demand is too coarse for DRT and in particular intermodal transport decisions. The same holds true for activity start and end times. Typically, mobility surveys report activity times with a resolution of 15 minutes or more. This needs to be disaggregated in order to not e.g. artificially increase the pooling rate.

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# References

Abgeordnetenhaus Berlin. Schriftliche Anfrage des Abgeordneten Tino Schopf (SPD) vom 26. Februar 2019 (Eingang beim Abgeordnetenhaus am 04. März 2019) zum Thema Sinnhaftigkeit des Einsatzgebietes des BerlKönig und der Kooperation mit Daimler und Antwort vom 18. März 2019 (Eingang beim Abgeordnetenhaus am 22. März 2019). Drucksache 18/18077, 2019. URL `https://pardok.parlament-berlin.de/starweb/adis/citat/VT/18/SchrAnfr/s18-18077.pdf`.

Bischoff, J. *Mobility as a Service and the transition to driverless systems*. PhD thesis, TU Berlin, Berlin, 2019.

Bischoff, J. and M. Maciejewski. Simulation of City-wide Replacement of Private Cars with Autonomous Taxis in Berlin. *Procedia Computer Science*, 83:237–244, 2016. ISSN 1877-0509. doi: 10.1016/j.procs.2016.04.121.

Bischoff, J. and M. Maciejewski. Proactive empty vehicle rebalancing for Demand Responsive Transport services. *Procedia Computer Science*, 170:739–744, 2020. doi: 10.1016/j.procs.2020.03.162.

Bischoff, J., M. Maciejewski, and A. Sohr. Analysis of Berlin's taxi services by exploring GPS traces. In *Models and Technologies for Intelligent Transportation Systems (MT-ITS), 2015 International Conference on*, pages 209–215, June 2015. doi: 10.1109/mtits.2015.7223258. URL `http://dx.doi.org/10.1109/mtits.2015.7223258`.

Bischoff, J., M. Maciejewski, and K. Nagel. City-wide shared taxis: A simulation study in Berlin. In *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, Oct. 2017. doi: 10.1109/itsc.2017.8317926.

Bischoff, J., I. Kaddoura, M. Maciejewski, and K. Nagel. Simulation-based optimization of service areas for pooled ride-hailing operators. *Procedia Computer Science*, 130:816–823, 2018. doi: 10.1016/j.procs.2018.04.069.

Bischoff, J., K. Führer, and M. Maciejewski. Impact assessment of autonomous DRT systems. *Transportation Research Procedia*, 41:440–446, 2019. ISSN 2352-1465. doi: https://doi.org/10.1016/j.trpro.2019.09.074. URL `https://www.sciencedirect.com/science/article/pii/S2352146519304910`.

Bösch, P. M., F. Becker, H. Becker, and K. W. Axhausen. Cost-based analysis of autonomous mobility services. *Transport Policy*, 64:76–91, May 2018. doi: 10.1016/j.tranpol.2017.09.005.

BVG. BerlKönig FAQ, 2021. URL `http://www.berlkoenig.de/faq`. Accessed 13.04.2021.

Die Dorfzeitung. BerlKönig BC verabschiedet sich aus Reinickendorf. *Die Dorfzeitung*, Dec. 2020. URL `https://die-dorfzeitung.de/berlkoenig-bc-verabschiedet-sich/`. published 23. Dezember 2020.

Hasselmann, J. Senat will kein Billigtaxi finanzieren. *Der Tagesspiegel*, Aug. 2020. URL `https://www.tagesspiegel.de/berlin/aerger-um-ein-konzept-der-bvg-senat-will-kein-billigtaxi-finanzieren/26113204.html`. published 20.08.2020.

Hörl, S., M. Balac, and K. Axhausen. Dynamic demand estimation for an AMoD system in Paris. In *2019 IEEE Intelligent Vehicles Symposium (IV)*, pages 260–266, July 2019. doi: 10.1109/IVS.2019.8814051. URL `https://www.researchgate.net/publication/334637984_Dynamic_demand_estimation_for_an_AMoD_system_in_Paris`.

Horni, A., K. Nagel, and K. W. Axhausen, editors. *The Multi-Agent Transport Simulation MATSim*. Ubiquity, London, 2016. doi: 10.5334/baw.

Kaddoura, I. and T. Schlenther. The impact of trip density on the fleet size and pooling rate of ride-hailing services: A simulation study. VSP Working Paper 20-36, TU Berlin, Transport Systems Planning and Transport Telematics, Dec. 2020.

Kaddoura, I., J. Bischoff, and K. Nagel. Towards welfare optimal operation of innovative mobility concepts: External cost pricing in a world of shared autonomous vehicles. *Transportation Research Part A: Policy and Practice*, 136:48–63, 2020a. doi: https://doi.org/10.1016/j.tra.2020.03.032.

Kaddoura, I., G. Leich, and K. Nagel. The impact of pricing and service area design on the modal shift towards demand responsive transit. *Procedia Computer Science*, 170:807–812, 2020b. doi: 10.1016/j.procs.2020.03.152.

Kaddoura, I., G. Leich, A. Neumann, and K. Nagel. A Simulation-based heuristic for the improvement on-demand mobility services. VSP working paper, TU Berlin, Transport Systems Planning and Transport Telematics, 2020c.

Knie, A., L. Ruhrort, J. Gödde, and T. Pfaff. Ride-Pooling-Dienste und ihre Bedeutung für den Verkehr. Nachfragemuster und Nutzungsmotive am Beispiel von "CleverShuttle" - eine Untersuchung auf Grundlage von Buchungsdaten und Kundenbefragungen in vier deutschen Städten. Technical report, Wissenschaftszentrum Berlin für Sozialforschung (WZB), 2020. WZB Discussion Paper, No. SP III 2020-601, Berlin.

Leich, G. and J. Bischoff. Should autonomous shared taxis replace buses? A simulation study. *Transportation Research Procedia*, 41(18-05):450–460, 2019. ISSN 2352-1465. doi: https://doi.org/10.1016/j.trpro.2019.09.076. URL `https://www.sciencedirect.com/science/article/pii/S2352146519304934`. URL `http://www.vsp.tu-berlin.de/publications`.

Liu, Y., P. Bansal, R. Daziano, and S. Samaranayake. A framework to integrate mode choice in the design of mobility-on-demand systems. *Transportation Research Part C: Emerging Technologies*, (105):648–665, 2019.

Maciejewski, M. Dynamic Transport Services. In Horni et al. (2016), chapter 23. doi: 10.5334/baw.

Maciejewski, M. and J. Bischoff. Large-scale Microscopic Simulation of Taxi Services. *Procedia Computer Science*, 52:358–364, 2015. ISSN 1877-0509. doi: 10.1016/j.procs.2015.05.107. URL `http://www.sciencedirect.com/science/article/pii/S1877050915009072`.

Maciejewski, M., J. M. Salanova, J. Bischoff, and M. Estrada. Large-scale microscopic simulation of taxi services. Berlin and Barcelona case studies. *Journal of Ambient Intelligence and Humanized Computing*, pages 1–9, 2016. ISSN 1868-5145. doi: 10.1007/s12652-016-0366-3. URL `http://dx.doi.org/10.1007/s12652-016-0366-3`.

Maciejewski, M., J. Bischoff, S. Hörl, and K. Nagel. Towards a Testbed for Dynamic Vehicle Routing Algorithms. In Bajo, J., Z. Vale, K. Hallenborg, A. P. Rocha, P. Mathieu, P. Pawlewski, E. Del Val, P. Novais, F. Lopes, N. D. Duque Méndez, V. Julián, and J. Holmgren, editors, *Highlights of Practical Applications of Cyber-Physical Multi-Agent Systems: International Workshops of PAAMS 2017, Porto, Portugal, June 21-23, 2017, Proceedings*, pages 69–79. Springer International Publishing, 2017. ISBN 978-3-319-60285-1. doi: 10.1007/978-3-319-60285-1.

Nagel, K., J. Bischoff, G. Leich, and M. Maciejewski. Simulationsbasierte Analyse der Wirkungen von Flotten autonomer Fahrzeuge auf städtischen Verkehr. *Zeitschrift für Verkehrswissenschaft*, (1-3):197–224, 2018.

Neumann, A. and M. Balmer. Mobility Pattern Recognition (MPR) und Anonymisierung von Mobilfunkdaten. White paper, Senozon Deutschland GmbH and Senozon AG, 2020. URL `https://senozon.com/wp-content/uploads/Whitepaper_MPR_Senozon_DE-3.pdf`. V1.0.

Planco, ITP, and TUBS. Grundsätzliche Überprüfung und Weiterentwicklung der Nutzen-Kosten-Analyse im Bewertungsverfahren der Bundesverkehrswegeplanung. Endbericht FE Projekt Nr. 960974/2011, Planco GmbH, Intraplan Consult GmbH, TU Berlin Service GmbH, 2015. Im Auftrag des BMVI. Auch VSP WP 14-12, see `http://www.vsp.tu-berlin.de/publications`.

Rieser, M., D. Métrailler, and J. Lieberherr. Adding Realism and Efficiency to Public Transportation in MATSim. In *18th Swiss Transport Research Conference*, Monte Verità / Ascona, May 16-18, 2018, May 2018.

Schaller, B. The new automobility: Lyft, Uber and the future of American cities. 2018.

Schlenther, T., G. Leich, M. Maciejewski, and K. Nagel. Addressing Spatial Service Provision Equity for Pooled Ride-Hailing Services through Rebalancing. VSP Working Paper 20-35, TU Berlin, Transport Systems Planning and Transport Telematics, Dec. 2020.

Trommer, S., V. Kolarova, F. E., L. Kröger, B. Kickhöfer, T. Kuhnimhof, B. Lenz, and P. Phleps. Autonomous Driving: The Impact of Vehicle Automation on Mobility Behaviour. Institute for Mobility Research (ifmo), 2016.

Vosooghi, R., J. Puchinger, M. Jankovic, and A. Vouillon. Shared autonomous vehicle simulation and service design. *Transportation Research Part C: Emerging Technologies*, 107:15–33, 2019. doi: 10.1016/j.trc.2019.08.006.

Zhao, Y. and K. Kockelman. Anticipating the regional impacts of connected and automated vehicle travel in Austin, Texas. *Journal of Urban Planning and Development*, 144(4), 2018. doi: 10.1061/(ASCE)UP.1943-5444.0000463.

Zwick, F. and K. W. Axhausen. Analysis of ridepooling strategies with MATSim. Technical report, ETH Zurich, 2020. Conference Paper; STRC 20th Swiss Transport Research Conference.

Zwick, F., E. Fraedrich, N. Kostorz, and M. Kagerbauer. Ridepooling als ÖPNV-Ergänzung: Der Moia-Nachtservice während der Corona-Pandemie. *Internationales Verkehrswesen*, 72(3):84–88, 2020.

Zwick, F., N. Kuehnel, R. Moeckel, and K. W. Axhausen. Ride-pooling efficiency in large, medium-sized and small towns. Simulation assessment in the Munich metropolitan region. 2020.