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Impact assessment of autonomous demand responsive transport as a link between urban and rural areas

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ABSTRACT

Disruptive developments in automated driving systems, new powertrain concepts and digital mobility are shaping changes in the way people move in rural and urban areas. In combination with these technical potentials, novel mobility concepts as for instance demand responsive transportation (DRT) can improve the everyday mobility of people in terms of both cost-efficiency and sustainability. Moreover, challenges related to demographic transitions and urbanisation can be addressed and negative developments mitigated. One potential application of DRT might be the connection of rural areas with the urban core.

The following paper aims to evaluate the viability and feasibility of DRT systems in the interplay of rural and urban areas. The city of Bremerhaven and the immediate surrounding are selected as area of investigation and the agent-based modelling framework MATSim is used to simulate the inhabitant mobility behaviour. On this basis, the global operational costs are calculated for different scenarios, e.g. fully automated vehicles and various powertrain types. The results imply that automated DRT systems are applicable to reduce the economic and environmental costs of transportation when applied in the interplay of rural and urban areas.

1. Introduction

Technological advancements in the field of fully automated vehicles bear the potential to accelerate the emergence of demand responsive and shared automated vehicle (SAV) services. Demand responsive transportation (DRT) evolved from both the special needs of certain subpopulations such as elderly or disabled people and the necessity to cut costs in low demand areas while providing a sufficient coverage with transportation services (Mulley et al., 2012). Usually, DRT operations are either flexible in schedules, routes or both and might target or be limited to a certain user group (Sharmeen & Meurs, 2019). Especially in Europe where flexible transportation for certain groups often co-exist with mainstream public transport more complement or rather uniform and *accessible for all* DRT services could foster cost reductions and more efficient operations (Mulley et al., 2012). Moreover, future technological progress and increased availability of automated vehicles (AVs) might change existing cost structures and are thus capable to extend the scope of application.

A combination of DRT systems' flexibility and the cost-cutting potential of AVs yields opportunities to disrupt the transportation sector especially in terms of accessibility and availability (Meyer et al., 2017; Mulley et al., 2012). Urban cores and metropolitan areas might become the territories of not only public but also commercial actors. Even today prominent examples such as *UberPool* or *MOIA* (Gilibert et al., 2019) illustrate that a concentrated demand in small and densely populated areas potentially leads to profit margins and might be capable to shift certain transportation services from a subsidised business to profitable operations. Such developments may further reduce the necessity for car ownership in urban areas and thus foster a situation where a considerable share of especially urban motorised individual traffic (MIT) is

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replaced by demand responsive SAVs. Higher flexibility, faster transportation schemes and connected services may blur the line between conventional and innovative transportation modes. Particularly the interplay between urban cores with the surrounding rural areas might serve as a suitable field of application of such new services. As an example, Gilibert et al. (2019) found a significant demand for direct and flexible public transportation in suburban areas of the German city of Hanover with comparably long distances and a lack of public transportation. Semi-urban areas are often insufficiently connected to the city centres and their centralised job opportunities. However, accessibility for those areas is still superior to purely rural regions (Horner & Mefford, 2007; Reichelt & Haas, 2015; Scheiner, 2016; Schleith et al., 2019; Weber, Sultana, & Maret, 2006). The introduction of SAVs in those semi-urban locations may show better results than purely rural areas due to higher passenger/trip demand.

These current and future developments offer both challenges and opportunities for policymakers and transport operators. From a policy perspective those transformations require regular assessments and analyses of existing structures and, where appropriate, a balancing of interests in the face of change. In regions where public transport is not economically viable it is usually either not provided at all or operates under conditions far from covering costs while offering mere basic transportation services. Technological progress might not only allow for a higher quality of services in urban areas but also for an increase in the quantity of services provided outside the urban core. If commuters can be convinced of the new offer, this could bring economic as well as ecological advantages. Reducing the dependence on MIT is associated with mitigating external effects of e.g. congestion, noise, fragmentation or land sealing. From a customer's perspective, the public means of transport provided must be perceived as sufficiently reachable, accessible and reliable to be considered as adequate or in the case of car ownership, as an alternative to MIT. Furthermore, excessive fares are naturally a deterrent.

Simulation studies can be carried out to obtain an initial estimate of the costs and efficiency of a new transport system. Studies like Liu et al. (2017) or Shen, Zhang, and Zhao (2018) cautiously suggest that SAV operations could complement or even substitute conventional modes of transport in order to face the upcoming economic and ecological challenges. The Association of German Transport Companies recently identified practicable scenarios for DRT systems (VDV, 2019). There, the need for scientific assessment on the economic efficiency and feasibility of such systems and a lack of reliable experience and data bases beyond pilot projects is highlighted. Indeed, existing simulation studies on DRT systems primarily focus on the application of AV services in either distinctively urban or rural regions. Especially in an urban-rural context, the scope of research is set to topics such as system optimisation or customer acceptance, while cost estimations based on simulation studies are rare. The aim of the following study is therefore to bridge this gap, with a particular focus on the interplay of the urban core and its periphery. Operations of demand responsive SAVs are simulated in a synthetic setting and the resulting economic and environmental costs calculated for several scenarios.

The analysis proceeds as follows. Section 2 provides an overview of the state of research and related work. Subsequently in Section 3, the selection of Bremerhaven as the research area is reasoned and its political, infrastructural and demographic characteristics as well as the inhabitant mobility behaviour are introduced. In Section 4, the methodological framework and setup of the simulations are introduced. In Section 5, the simulation results are presented and evaluated. Section 6 sums up and discusses the main findings of the study.

2. Related work

DRT schemes exist in various forms depending on the underlying operational approach. These can be classified into three categories: *Fixed on-demand schemes* (service on demand but according to a fixed schedule), *point deviation schemes* (flexible operation along a corridor with set departure and arrival times) and *flexible area based schemes* (corresponding to no fixed routes nor schedules) (Böhler et al., 2009). Moreover, further distinction in public transportation and individual transport services like taxis is common. Usually, the public option comes along with ride pooling, whereas the private solutions do not (Davison et al., 2012). Furthermore, the operational scheme can be divided into door-to-door and stop-based services.

DRT systems are present in different forms all over the world and have a relatively long tradition as means of transport, with many cities in the Global South relying on them as one of the main pillars of their transportation system (Salazar Ferro, 2015). For developed countries, DRT is traditionally proposed as a solution for several specific problems. Firstly, it is deployed for providing paratransit or baseline mobility for certain groups of people without access to another mode of transport. Such population groups are for example elderly persons in Canada (Lehuen & Suen, 1978) or in the USA (Nelson et al., 2010). Secondly, implementations of DRT-like systems are a common measure to improve or maintain mobility in rural areas with low demand at relative low operational costs and date back to the 1960s (Ministry of Transport Great Britain, 1965). Recent developments in the underpinning technology, a broader access to internet services and a reduction in costs let DRT concepts experience an increased attention in the mobility sector. During the last decade, the importance of these systems increased significantly and their field of (also commercial) application extended to urban areas (Davison et al., 2012). Thirdly, with respect to the other applications, automated DRT schemes are often thought to solve the 'last mile' problem of conventional public transportation systems by providing flexible, fast and inexpensive service. Scheltes and de Almeida Correia (2017) use agent-based simulations to assess the potential of automated DRT vehicles to improve the overall trip quality of public transport passengers. Their findings imply that larger fleets, higher in-vehicle capacities and more sophisticated booking, pooling and routing systems outperform small-scale approaches and are thus more promising to be accepted and utilised by travellers. However, the scope of the study is limited to operational aspects whereas economic aspects are not considered.

Individual mobility patterns vary for different groups, e.g. by age, income, education or family status (Kersting et al., 2020). Accordingly, travel demand, mode choices and thus the resulting demand for public transportation in general or DRT in specific are not uniformly distributed within the population (Gilibert et al., 2019; Haglund et al., 2019). Elderly people in particular are often assumed to benefit from flexible schedules and the opportunity to mitigate walking distance to and from a bus stop (Meurer et al., 2014; Wang, 2007). Activities that are related to a more frequent DRT utilisation are working and educational activities, especially for younger user groups and solo-travellers (Jain et al., 2017).

An analysis from 2016 of rural DRT found 17 active systems in Germany (König & Grippenkoven, 2017). In 2014, 66 providers of DRT schemes were active in Great Britain, with 23 operating in urban and 43 in rural regions (Davison et al., 2014). In rural areas, challenges for a successful DRT scheme are linked to low demand combined with relatively high operational costs (Mulley & Nelson, 2009). An increasing number of new transport related companies provide urban DRT schemes such as *UberPool*, *Lyft Line*, Via or *Abel*, partly offering customers to share a ride (Alonso-González et al., 2018). The on-demand shared ride-hailing service *MOIA* operates in two German cities (Hamburg and Hanover) on a commercial and experimental base. So far, the service is utilised primarily for airport trips and leisure activities but also for commuting and for the reasons of flexibility, capactiy and safety (Gilibert et al., 2019). For urban areas research implies that a growing supply of such services evokes cannibalisation effects and thus may lead to a lower utilisation of conventional public transport. Commercialisation and technological developments are a potential risk to established transport modes such as buses and light rail services (Clewlow & Mishra, 2017). However, public transportation operators started to offer DRT services in metropolitan areas like in Berlin (BVG, 2017) or the Kutsuplus program in Helsinki (Haglund et al., 2019; Jokinen, Sihvola, & Mladenovic, 2019).

Technological advances foster the vision of mobility provided through SAV as an evolution or enhancement of DRT schemes by changing cost structures, services quality or availability. Such approaches could result in novel business models capable of inducing significant changes in the way mobility services are demanded and provided (Litman, 2017; Trommer et al., 2016). Also, reductions of overall emissions compared to traditional vehicle fleets are expected (Fagnant & Kockelman, 2014).

Advanced transportation simulations allow to test and compare theoretical changes to a region's transport system in terms of feasibility, viability and external effects. Previous research has established a variety of frameworks. For instance, Čertický, Jakob, and Píbil (2016) adapted the transport simulation framework *AgentPolis* in order to provide an easy-to-access but rather inflexible simulation test ground for autonomic DRT-systems that was then applied for the city of Prague. The framework allows to calculate operational costs and greenhouse gas emissions for various scenarios.

Inturri et al. (2019) used agent based modelling via the platform NetLogo to explore the efficiency of shared DRT schemes inspired by an Italian city's traffic system. Consistent to Scheltes and de Almeida Correia (2017), their findings suggest a trade-off between operational costs and customer satisfaction that is mainly channelled by the fleet size and vehicle capacity. Moreover, assigning certain vehicles to specific routes improves the performance of the system. Relating to similar studies, the suggested potential of DRT schemes to increase service quality is not yet analysed in the light of expected operational or environmental costs.

Giuffrida et al. (2020) utilised the framework presented in Inturri et al. (2019) and reproduced in a simulation an existing fleet of shared DRT vehicles in city districts of Dubai. Their findings emphasise the sensitivity of DRT systems acceptance with regard to their service quality and reliability. Given a demand satisfaction rate of at least 85%, they find a shared minibus taxis system to be of lower economic cost than a ride sharing system with small vehicles.

Calculations in a scenario in Singapore indicate that replacing all modes of personal transportation by SAVs could reduce the existing passenger vehicle fleet by two thirds (Spieser et al., 2014). Simulations based on the Multi Agent Transport Simulation (MATSim) show SAVs beeing capable to substitute the entire private car fleet. For Zurich and the surrounding area, the implementation of a SAV system could decrease the number of vehicles compared to the private fleet by up to 90% at acceptable service parameters (Boesch, Francesco, & Axhausen, 2016). Similar results are found for a case study in Berlin, where SAV services could replace private vehicles leading to a fleet reduction of 90% (Bischoff & Maciejewski, 2016). Research on a central area in Austin reveals that already a low share of regional trips conducted by SAVs can create a replacement ratio of one SAV to 9.3 conventional vehicles while causing increases in vehicle kilometre traveled (VKT) by 8% (Fagnant, Kockelman, & Bansal, 2016). By carrying out the task of traditional taxis in Berlin, SAV usage reduces the amount of VKT (Bischoff, Maciejewski, & Nagel, 2017). In terms of public transportation, investigations in the city of Cottbus show that automated vehicles can offer faster and cheaper service than traditional public transport (Bischoff, Führer, & Maciejewski, 2018). Nevertheless, the field of application is case sensitive. Replacement of buses by automated shared taxis in Berlin as a feeder system for mass rapid transit resulted in a mixed outcome in terms of travel times and costs (Leich & Bischoff, 2019). In the context of DRT as public transport replacement in areas with low population density research shows that supplying high service standards remains economically problematic due to low demand (Viergutz & Schmidt, 2019). However, Quadrifoglio, Dessouky, and Ordóñez (2008) argue on the basis of DRT simulation results that variations in setup such as larger time windows for pick-up or zoning strategies are applicable when coping with economic constraints but must be reconciled with customer satisfaction and system complexity.

As stated in VDV (2019), such DRT schemes are emerging in Germany and business models are developed for operations in urban centres of several larger cities. Although there is evidence for the potential of DRT to increase the service quality of public transport in rural areas in Germany and beyond (Sörensen et al., 2020; Vitale Brovarone & Cotella, 2020), the feasibility of DRT schemes as a connecting service for a urban core and the surrounding area is less analysed which raises a demand for research. Thus, the scope of this analysis is set to the urban centre of a medium-sized European city, which is surrounded by a rural area. For Bremerhaven, the transition from the urban to the rural area is immediate so that the results are less blurred by effects related to suburbs or other urban cores.

3. Area of investigation

The area of Bremerhaven is selected as subject of investigation due to multiple factors. It allows examining the ability of high scale DRT to connect low populated areas with more densely populated centres. In addition, Bremerhaven does not have the size of a metropolitan area and therefore lacks public transportation systems with large capacity. As a result, a DRT is, in theory, able to provide service for the whole area without being restricted by already existing public transportation systems. From a passengers perspective, this setup allows for door-to-door service that excludes the necessity of changing vehicles during the trip. The DRT system can either serve the entire population of the area or be limited to either the rural or the urban population.

3.1. Geographic analysis of Bremerhaven

The area of investigation is depicted in Fig. 1 and comprises regions of two federal states in Germany. The city of Bremerhaven (an exclave of the federal state of Bremen) is located in the centre of the area. In the west, Bremerhaven is bounded by the North Sea. In the other directions, it is surrounded by the district of Cuxhaven, which belongs to the federal state of Lower Saxony. In the north of Bremerhaven lies the former municipality Langen which is now part of the town Geestland. The municipality of Schiffdorf is located to the east and the municipality of Loxstedt southwards of Bremerhaven.

Bremerhaven is organised on three levels of administration: At the highest level, the city is divided into two boroughs (German: *Stadtbezirke*), South and North Bremerhaven. As depicted in Fig. 1, the next lower administrative level divides the borough North into four and the borough South into five districts (German: *Stadtteile*). At the lowest level, the total of nine districts are divided into 24 neighbourhoods (German: *Ortsteile*) (Statistik Bremen, 2020).

Bremerhaven has 117,473 inhabitants (Bürger- und Ordnungsamt Abteilung Statistik und Wahlen Bremerhaven, 2018) and covers an area of 93.82 km^2 (Statistisches Landesamt Bremen, 2014). In Schiffdorf, Loxstedt and Langen reside 51,691 inhabitants in an overall area of 376.39 km^2. Langen is the most populated municipality with a population of 11,577, followed by Loxstedt with 5,639 and Schiffdorf with 3,556. Thus, the whole area of investigation has a size of about 470 km^2 and a population of around 169,000. Bremerhaven's population density (1252.11 inhabitants per km^2) is more than nine times higher than the population density of the surrounding area (137.33 inhabitants per km^2).

The north-south axis of the area is about 33 km long, while the east-west distance stretches 20 km at the widest part. Therefore, the investigated region has the shape of an elongated rectangle with a north-south extension.

From the perspective of spatial planning, Bremerhaven is classified as a regional centre by the German Federal Office for Building and Regional Planning (BBSR, 2017). It implies that the town provides basic and higher-level public services and represents the centre of economic

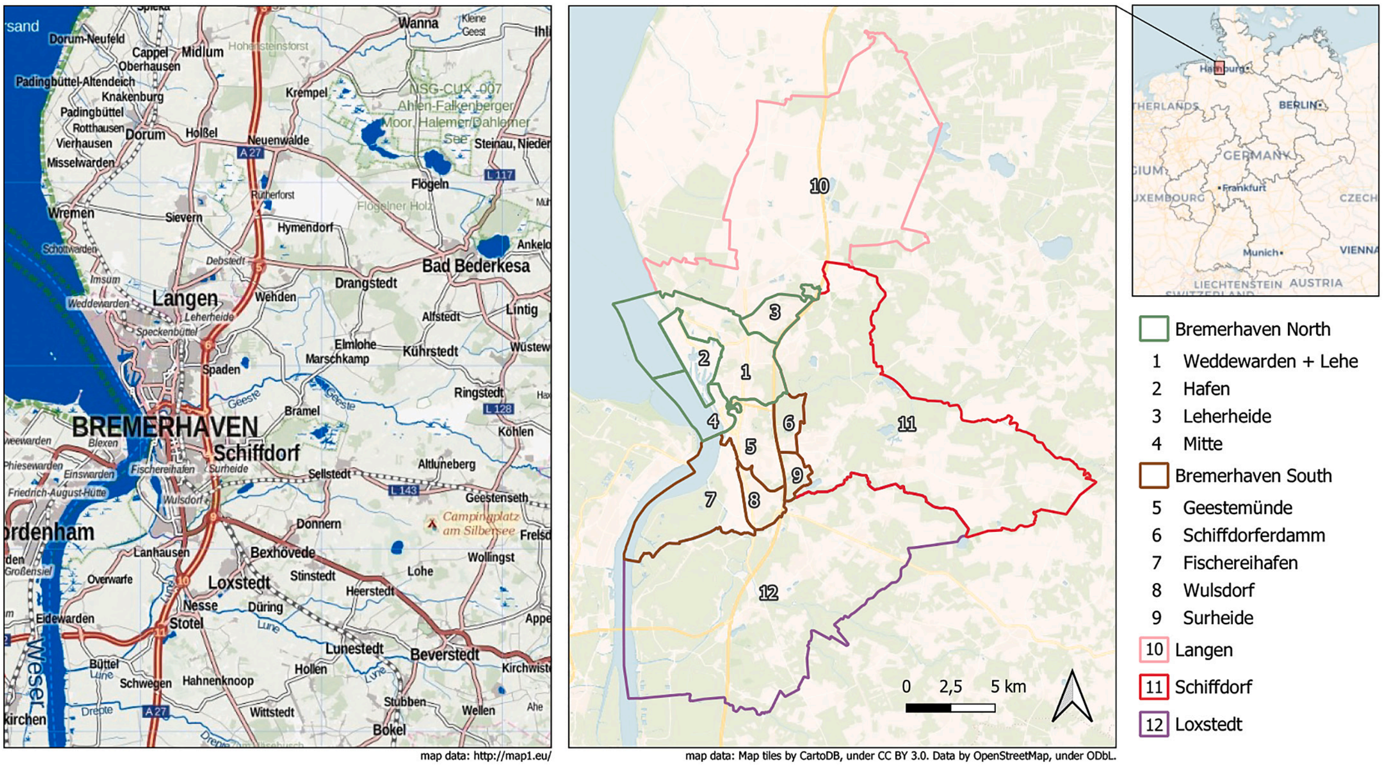

Fig. 1. The city of Bremerhaven and the surrounding municipalities. The left map depicts the land use and infrastructure of Bremerhaven and the surrounding municipalities Langen, Schiffdorf and Loxstedt. The second map depicts the administrative levels of Bremerhaven and the surrounding municipalities. The same classification is also applied for the simulation. The map on the right shows the geographical location of Bremerhaven in Germany.

activities in the region. As a result, originating traffic from the surrounding area primarily targets Bremerhaven. According to a survey conducted by Helmert, Henninger, and Ruhrberg (2015) in 2014, an estimated amount of 220,900 trips occur every day between the city core and the surrounding municipalities.

The existing road infrastructure also highlights the importance of Bremerhaven as a regional centre and underlines the longitudinal dispersion of the investigated area. As depicted in Fig. 1, the federal motorway *Bundesautobahn 27* connects the area from the south to north and crosses the municipalities Loxstedt, Langen, Schiffdorf as well as the city of Bremerhaven. The motorway can be accessed via 8 junctions throughout the area. The main road *Bundesstrasse 6* is located in the west of the motorway, running parallel to it from the north to the south. It connects the city centre with the municipality Loxstedt. The other three federal roads in the region provide a more latitudinal connection. The main roads *Bundesstraße 71* and *Bundesstraße 437* both connect to the motorway *Bundesautobahn 27* in Loxstedt while providing an east-west link. The federal road *Bundesstraße 212* is situated in the centre of Bremerhaven and is also the shortest. It reaches from the central district Bremerhaven Mitte to the federal motorway *Bundesautobahn 27*.

3.2. Mobility behaviour in the urban core and the rural periphery

In general, mobility behaviour in urbanised areas differs from mobility patterns in more rural regions. This also applies to Bremerhaven and its surrounding periphery. The results in Helmert et al. (2015) indicate that the MIV is the most popular form of transport. With 51.7% in urban and 71.9% in rural areas the proportion of daily car journeys is significantly higher for the latter. In contrast, the share of trips with public transport in urban areas with 15% is more than twice as high as in rural areas with 7.3%. In addition, the importance of walking trips with 14.5% is significantly higher in Bremerhaven compared to 5.4% in the surrounding rural areas. The importance of cycling is comparable for both regions, although with 18.8% being slightly more prevalent in the city in contrast to 15.4% in the surrounding municipalities.

With 3.3 in Bremerhaven and 3.1 in the rural context, the daily number of trips per capita do not differ significantly between the city core and the neighbouring municipalities (Helmert et al., 2015). With a share of mobile persons of 90.4% on the whole population 9.6% of Bremerhaven inhabitants conduct no trips during the day. For the surrounding area, no reliable values are available. Thus, the average share of mobile population in Lower Saxony with 89.3% is applied to the rural areas (Lenz et al., 2010). This results in 3.66 trips per day for Bremerhaven and 3.47 for Langen, Schiffdorf and Loxstedt.

4. Methodology

In order to investigate the abilities of DRT schemes to connect rural areas with the urban core, the activity-based multi agent simulation framework MATSim is used (Axhausen, Nagel, & Horni, 2016). The following section describes the data source, the process of demand generation and the the general specifications of the simulation setup. Moreover, several quality parameters are defined in order to evaluate and compare the results of the different scenarios. VDV (2019) suggests, that DRT and conventional public transport are not likely to operate feasibly when complementing each other. Thus, only "absolute" scenarios were employed in order to evaluate the economic and environmental impacts of a radical systemic change from conventional public transport to DRT.

4.1. Generation of demand and locations

In the simulation scenarios, four different activity types are created to model daily operational tasks of agents. They consist of *home* activities, *work*, *leisure* and *shopping*. *Work* includes going to school as well as studying. *Shopping* activities also include everyday matters like medical appointments or trips to authorities.

In order to create locations where different activities take place, information from multiple sources are used. Fig. 2 exemplifies the process involved in extracting residential buildings from OpenStreetMaps (OSM) snapshot data (OpenStreetMap contributors, 2019) using quantum geographic information system software (QGIS Development Team, 2019). In the first step, landuse areas of the “residential” class are exported (Fig. 2a). Next, all buildings within the “residential” landuse polygons are isolated (Fig. 2b). Finally, all building shapes that are clearly not identified as residential areas by means of OSM classes or visual inspection are filtered out. The remaining buildings are included in the simulation as residential buildings (Fig. 2c).

It should be noted that due to the nature of the OSM data, not all residential units can be completely and accurately captured. For example, flats may be located above small retail shops, which are marked as “retail” in the OSM data and therefore will be excluded. Another problem arises when no data is stored for building polygons. In individual cases the most obvious instances can be identified by visual inspection, but it can happen that small non-residential facilities are falsely included in the simulation as “residential”.

In the subsequent step, a quantity of agents corresponding to the number of inhabitants in the individual districts is uniformly distributed over space in the residential polygons created.

Population data for Bremerhaven is taken from the Bureau of Statistics Bremerhaven (Bürger- und Ordnungsamt Abteilung Statistik und Wahlen Bremerhaven, 2018). For Schiffdorf and Loxstedt, local municipality data is used (Gemeinde Loxstedt, 2019; Gemeinde Schiffdorf, 2019) and for Langen data from the State Office for Statistics Lower Saxony is used (LSN, 2019).

Work locations are created by using OSM shapefiles and OSM points of interest (POI) (OpenStreetMap contributors, 2019). Furthermore, the workplaces determined from OSM data are verified and supplemented with data from the company database of the city of Bremen economic development agency (WFB, 2020b). Leisure locations are also generated from OSM POI and OSM shapefiles as well as from home locations. Locations for everyday matters are constructed from OSM POI, OSM shapefile data and verfied and supplemented with data from the business database of city of Bremen economic development agency (WFB, 2020a).

Sections of populations, daily activities, length of activities and mobility behaviour are drawn from demographics, labour statistics and mobility surveys (Magistrat Bremerhaven 2018; BLS, Bayerisches Landesamt für Statistik, 2019; SLB, Statistisches Landesamt Bremen, 2019; Lenz et al., 2010; Helmert et al., 2015). Corresponding to the demographics, the simulated urban population comprises 55,024 agents while the rural population consists at maximum of 30,627 agents.

For the simulation, the area of investigation is separated into eleven districts according to the second level of administration (Fig. 1), with the exception that the district Weddewarden is added to the district of Lehe. By that, eight urban and three rural areas exist. The individual activity polygons in the database were assigned to the corresponding districts in order to allow to distribute trips among agents according to the the origin-destination (OD) matrix and the purpose of the journey.

The population used in the simulation is compounded from multiple sub-populations using a *python* script. In general, a set of rural agents and a set of urban agents is generated. Urban agents carry out more activities during the day and thus conduct more trips (3.66 vs 3.47 as

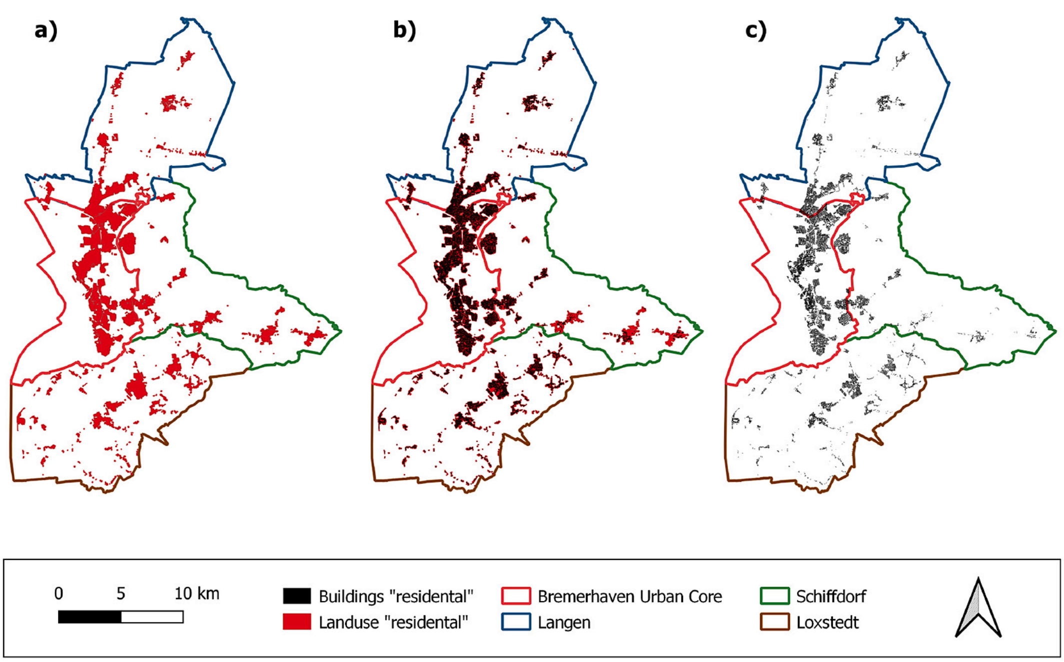

Fig. 2. Exemplary illustration of the work processes involved for determining living spaces from OSM data using QGIS. In the first step, landuse areas of “residential” class are extracted (red polygons in picture (a)). Next, all buildings within the “residential” landuse polygons are extracted (black polygons in picture (b)). Finally, all building areas that are clearly not identified as residential areas by means of OSM classes or visual inspection are filtered out. The remaining buildings were included in the simulation as residential buildings and agents were uniformly distributed to the polygons according to the number of inhabitants in the individual districts (black polygons in picture (c)) (OpenStreetMap contributors, 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presented in the previous section). Nevertheless, the number of trips per day and therefore the amount of activities for all agents varies between 1 and 5. The number of activities per agent is generated from an iterative algorithm using weightings. The first and last activity is always *home* and takes place at the home location assigned to the agent. Each agent performs at least one activity per iteration or day and returns *home* after all activities are completed. No "home stayer" agents are created since MATSim does not consider or ignores them during the mobility simulation. Several test runs were performed with different weightings to approximate the mobility behaviour as closely as possible to the data from the mobility survey. Finally, weightings are set as follows: 20% of the agents have one activity a day, 30% have two, 20% have three, 15% have four and 15% have five activities a day.

Once the home addresses and the number of daily activities have been established, the types of activities are determined. Again, an iterative algorithm with weightings is utilised. In addition, conditions are introduced that influence the choice of activities and the weighting to avoid implausible or illogical activity or travel chains. These come into effect depending on the number of activities already performed, the time of day and the type of previous activity. The conditions will prevent, for example, the first activity of the day being *home*, that two identical activities of the *work*, *school* or *home* type are subsequently executed and/or that no *work*, *school* or *home* activities are performed after 4 pm. Furthermore, the length of the activities depends on the number of activities carried out during the day in order to avoid activites ending at night or the next day.

Prior to the previously described step, the agents are divided into two subgroups. One group consists of agents who are more likely to carry out *work* or *school* as their first activity of the day. This requires the agents to leave their homes between 6 and 8 am. Similar to a working or school day, the typical duration of these activities lasts between six and eight hours. Based on the results of the survey, the relative share of this subpopulation is higher in Bremerhaven (61%) compared to the surrounding areas (56%) (Helmert et al., 2015). The other group of agents (39% and 44% respectively) starts their activities between 9 and 12 am. Activities from all four categories are randomly assigned to them but *work* activities are less likely and typically last between three and four hours.

In the final step, the locations of the activities are assigned individually. For this purpose, the quantitative traffic relations between districts are taken from the survey and transferred to a mobility matrix (Helmert et al., 2015). The number of activity locations is then sampled to the absolute number of activities in the agents' plans and linked according to the mobility matrix. Thereby the main diagonal element of the mobility matrix is used for intra-district traffic and the antidiagonal elements for extra-district traffic.

4.2. Simulation scenarios

All simulations are run with MATSim version 13.0-2020w40-SNAPSHOT (Axhausen et al., 2016) and include DRVP (Maciejewski et al., 2016) and DRT modules (Bischoff et al., 2018). The approach aims to simulate a typical weekday in the region. The simulated region follows the boundaries as shown in Fig. 1 and its main characteristics described above.

The road network is created from OSM snapshot and simplified to nodes and edges (OpenStreetMap contributors, 2019). The maximum speed for individual traffic sections stored in the OSM data are also transferred and recorded in the attributes of the individual edges. Considering that there is no traffic jam on the route, the vehicles then travel at the maximum permitted speed. For motorway sections in Germany, where no speed limits have been officially set, a target speed of 130 km/h is allowed in the simulation. Since private cars and DRT vehicles are operated in the same traffic mode, the speed of these is limited by the network and is therefore similar.

In order to assess the potential of DRT as a connecting mobility service of rural areas with an urban core, two sets of scenarios are employed. The simulations of the first sets are limited to the population of the rural areas of Langen, Loxstedt and Schiffdorf in order to provide a comparative scenario opposed to the population of the whole sample. Consequently, the second scenario refers to the population of a combination of both the rural area and the urban core of the city of Bremerhaven.

For each set, a baseline scenario is provided, in which MIT carried out by individually owned cars is the only transport mode. It is assumed that each agent owns a vehicle and uses it for the trips to his activities during the day. Subsequently, all MIT vehicles are removed from the simulation and the complete mobility demand is serviced by a DRT door-to-door scheme based on minivans with a vehicle capacity of 6 passengers. The capacity of 6 seats resembles vehicles in the class of an ordinary van. This vehicle class does not require a specific licence for passenger transport in Germany. The decision for this setup is taken in order to compare a reasonably simple and cost-efficient alternative modal system with the MIT. In both sets of scenarios and all simulations, every agent can conduct trips within the whole area of investigation (Fig. 1).

For the baseline scenarios, only trips that were specified as self-drive car or car passenger trips in the survey are taken into account (Helmert et al., 2015). The population for the rural set of simulations comprises 30,627 agents. In addition, the MIT passenger quota of 20% was taken into account as determined in the survey. Since the overall macroeconomic mileage is investigated and MIT passenger do not add additional mileage into the system, the population size and thus also the number of vehicles is reduced by this percentage. This results in a total of 24,524 vehicles. Consequently, for the combined set 85,651 agents where created, resulting in 68,561 vehicles. Since the pick-up and drop-off times for these additional passengers are not taken into account, the simulated travel times are marginally underestimated.

Each scenario runs 100 iterations or virtual days, where each virtual day has 86,400 s or 24 h (0 am - 12 pm). At the end of each virtual day, all executed agent plans are evaluated with a score that reflects the utility. For example, a trip longer than planned or coming too late to an activity leads to a smaller utility. Before the start of the next iteration a random 10% of the agents are selected to be allowed to modify their plans. 5% of the agents try out a new route to get to their activities. The other 5% of agents shift the time of their activities forward or backward by a maximum of 30 min. Subsequently, the modified plans are carried out in the next iteration and evaluated again. After 80 iterations the modification of plans is prohibited and agents only execute the plans that have the highest utility score. This leads to a model equilibrium in the 100th iteration and the model can be evaluated. Nevertheless it can be observed that after 20 iterations a quasi-equilibrium is reached and the model metrics do not change significantly in the following iterations. For robustness reasons, the scenarios were run with 100 iterations. An iteration in MIT scenarios ran between 100 and 300 s and in DRT scenarios between 1500 and 6000 s.

In order to obtain realistic values of operational and ecological costs, the baseline scenarios must reflect the actual driving performance of the investigated region. For this reason, two key figures were set as targets for the calibration: The average number of daily car trips per agent and the daily average distance per trip. In the final baseline scenario, each agent makes 3.61 trips by car per day in the entire study region, with an average distance of 8.2 km. Compared to the results of the survey, which show that the population travels an average of 3.57 trips per day and 7.9

km per trip, the actual driving performance is marginally overestimated (Helmert et al., 2015).

In DRT scenarios, the assignment of requests to a DRT vehicle is done using a centralised, on-the-fly process with insertion heuristic (Bischoff et al., 2017). Agents emit DRT requests immediately after the end of the previous activity. Prebooking is not allowed. If an agent requests a ride, the trip is dispatched to the DRT vehicle where the realisation of the request will cause the smallest detour with regard to the already planned route under the condition that three service criteria are not exceeded or violated: vehicle occupancy, maximum waiting time $\mathbf{t}^{wait}$ and maximum total travel time threshold $\mathbf{t}_r$. If no reasonable allocation is possible, the request will immediately be rejected.

The occupancy of all buses is monitored for the whole simulation run. Upon receipt of a new request, the system first checks which buses will have free seats available on the desired route. Buses that will exceed the maximum passenger capacity between stops are not considered for the allocation of the request. The second condition $\mathbf{t}^{wait}$ defines the expected maximum waiting time of a customer to be picked up by a DRT vehicle at the desired pick-up location. In case that this is likely to be exceeded, the request will be rejected immediately. The third condition $\mathbf{t}_r$ limits the total travel time of already boarded (and thus scheduled) agents in the vehicle. This parameter is defined by Eq. (1),

$$\mathbf{t}_r = \alpha \mathbf{t}^r_{direct} + \beta \tag{1}$$

where.

- $\mathbf{t}_r$ represents the total travel time threshold for request r sharing the same vehicle,
- $\mathbf{t}^r_{direct}$ depicts the total travel time of request r assuming a direct single car network trip without detours or stops,
- α models the parameter for the detour factor in terms of travel time from the direct route and
- β models the parameter for additional cumulated time loss due to boarding and alighting of fellow passengers during the total travel time.

An exceeding of the total travel time $\mathbf{t}_r$ of any passenger sharing the same vehicle would lead to an immediate rejection of the new request. For the DRT scenarios, the service criteria parameters are set as follows:

- As mentioned before, the capacity of DRT vehicles is set to 6 in order to resemble vehicles in the class of an ordinary van.
- $\mathbf{t}^{wait}$ is set to 1200 s (20 min), since previous research implies a limited tolerance of passengers to wait for the vehicle (Avermann & Schlüter, 2020; Bischoff et al., 2018).
- α is set to 1.5 because previous studies shows that this allows for efficient results if vehicle capacity is above two (Bischoff et al., 2017).
- β is set to 1200 s (20 min) and thus reflects the default setting for the DRT setup (Bischoff et al., 2017; Bischoff et al., 2018).

Beyond that, the insertion heuristic requires further parameters for the assignment process. In order to estimate the distances between the individual DRT vehicles and the desired pick-up locations of the customers on arrival of a new request, beeline distances with a detour factor and an average beeline travel speed are used. For DRT scenarios, this values are set to 1.3 and 8.33 *m/s* respectively and thus reflect the default settings for DRT setup (Bischoff et al., 2017; Bischoff et al., 2018) Moreover, a fixed duration of 60 s is assumed for stops for passengers to board or alight. This parameter is required to determine the time windows for the arrival at the next stops.

Once a travel request is successfully assigned to a DRT vehicle, it is guaranteed to be serviced, even if the above-mentioned criteria are violated later. A rejection is not possible afterwards. In case of delays during the journey for example due to an overcrowded road network or traffic jams this would only affect newly incoming requests and not those already accepted. Thus, it is possible that the estimated travel time is extended due to unforeseen circumstances.

4.3. Quality parameters and economic aspects

With regard to passengers, overall travel times as well as waiting and in-vehicle times present relevant criteria. Furthermore, reliability of the offered service plays an important role in the success of a DRT service. If passengers can not be certain that their transport request will be served in time or at all, the utilisation of the DRT system can be expected to be low due to a lack of reliability. As a result, it is assumed that a minimum of 95% of all requested journeys must be served within a reasonable waiting time in order to meet the quality parameter (Bischoff et al., 2018).

Another relevant factor for the evaluation of the overall efficiency of the system and the interpretation of the rejection rate is the strategy used when all trips are completed and no new requests are present. In that case the DRT vehicle remains inactive until the receipt of a new request or the duty shift ends (at 12 pm or end of iteration). Provisional driving around or strategic relocation of vehicles is possible during that state but not applied for reasons of simplicity.

5. Results

This section presents the results from the first and second set of simulations. The scenarios are evaluated on the basis of the indicators and criteria introduced above.

5.1. Rural area

Table 1 depicts the simulation results for the first scenario, that contains only the rural population (30,626). According to the service criteria defined in the previous section, at least 1800 vehicles with a capacity of 6 passengers in the DRT scheme are necessary to provide a service rate of above 95%. To illustrate the effects of minor changes in the fleet size, additional scenarios with 1600 and 2000 vehicles are computed. Corresponding values for the MIT scenario are depicted as the *baseline* scheme.

The third column contains the values for the average waiting time. All values are below 13 minutes and decrease with an increasing number of DRT vehicles. Columns four and five show the average in-vehicle travel and the average total travel time, that consists of walking to the pick-up point, waiting and in-vehicle time. In the case of the actual time spent in a DRT vehicle, a marginal increase can be observed whereas in case of the total travel time a reverse trend is apparent. This could be explained by the fact that with increasing number of DRT vehicles more customers are served who would have been rejected in other scenarios. Therefore, possibly more detours with passengers who have already boarded the vehicle have to be made which increases the average time spent in the vehicle. This and the generally long time spent in the vehicle is supported by the relatively high occupancy rate illustrated in Fig. 5. As already stated, the service rate depicts the share of trips that are not rejected. With 1800 vehicles, 96.4% of the requested trips are served.

In the baseline scenario each inhabitant of the area owns a car and no public transportation takes place. Thus, neither the average waiting time nor a service rate nor the share of empty runs can be computed. 883,730 vehicle kilometres traveled (VKT) are caused by 30,627 inhabitants, resulting in approximately 29 VKT per capita. However, the travel times for the baseline scenario are slightly underestimated, since passenger pick-up and drop-off duration is not included in the simulation. The share of empty runs is close to 8% in all scenarios and does descrease marginally with the number of vehicles in operation increasing.

Table 2 shows the relative deviation of the indicators from Table 1 with the 1800 vehicle DRT scheme as base. With reagrd to the service criteria (columns three to six), a higher number of DRT-vehicles overall

Table 1
Rural population sample scenarios. Baseline: MIT is simulated for agents in the areas of Langen, Schiffdorf and Loxstedt. DRT: replacement of private cars with door to door scheme.

Scheme	Vehicles	Average waiting time (min)	Average in-vehicle travel time (min)	Average travel time (min)	Service rate	Vehicle kilometres traveled	Empty runs
DRT	1600	12:14	19:51	32:06	0.947	592,164	0,0848
DRT	1800	11:59	19:58	31:57	0.964	609,495	0,0815
DRT	2000	11:49	20:02	31:51	0.978	622,965	0.0794
Baseline	24,524	–	10:52	10:52	–	883,730	–

Table 2
Relative change of values compared to the DRT scenario with 1800 vehicles.

Scheme	Vehicles	Average waiting time (min)	Average in-vehicle travel time (min)	Average travel time (min)	Service rate (%)	Vehicle kilometres traveled (%)	Empty runs (%)
DRT	1600 (−11.1%)	+2.1%	−0.6%	+0.5%	−1.8%	−2.8%	+4.0%
DRT	1800 (±0)	±0	±0	±0	±0	±0	±0
DRT	2000 (+11.1%)	−1.4%	+0.3%	−0.3%	+1.5%	+2.2%	−2.6%
Baseline	24,524 (+1362%)	–	−45.6%	−66.0%	–	+45.0%	–

Table 3
Rural and urban population sample scenarios. Baseline: MIT is simulated for agents in the areas of Langen, Schiffdorf and Loxstedt as well as in Bremerhaven. DRT: replacement of private cars with door to door scheme.

Scheme	Vehicles	Average waiting time (min)	Average in-vehicle travel time (min)	Average travel time (min)	Service rate (%)	Vehicle kilometres traveled	Empty runs (%)
DRT	4000	11:44	18:37	30:21	0.935	1,209,271	0.0533
DRT	4500	11:35	18:35	30:09	0.955	1,251,797	0.0518
DRT	5000	11:26	18:35	30:02	0.973	1,285,876	0.0500
Baseline	68,561	–	9:35	9:35	–	2,054,208	–

leads to improved outcomes. This is in line with the expectations since a larger fleet naturally decreases waiting time and thus number of rejected requests. In comparison to the baseline scenario the DRT schemes yield significantly higher travel time values. The average travel time of the agents increases by around 66% when switching from a car based scenario to pure DRT.

A higher number of vehicles within the DRT fleet results in higher total VKT. This observation is primarily due to an increased service rate and a more individual routing and thus less pooling (compare Figs. 5 and 6 in appendix). It should be noted that in the rural scenario the population is reduced by the city residents resulting in a lower probability of a crowded network and alteration of traffic dynamics. This point will be considered in the discussion at the end.

5.2. Rural and urban area

The results for the simulations of the complete population sample are depicted in Table 3. For a population of 85,651 inhabitants, 4500 minivans are the smallest sufficient number of vehicles in order to fulfil the quality parameters. To evaluate the effects of a larger or smaller fleet, additional scenarios with 4000 and 5000 vehicles are computed.

The patterns behind the computed values are similar to the first set of scenarios. The average waiting time is below 12 min for all scenarios and decreasing with higher number of vehicles in use. According to expectations, the travel time values are lower than in the rural scenarios. As previously observed, the number of DRT vehicles has no significant influence on the average in-vehicle travel time.

The efficiency parameters reveal, that under the given constraints an increase of the population from 30,627 to 85,651 approximately doubles the VKT in the DRT scenarios. This disproportion could be due to a higher pooling rate, or increased bundling of multiple passenger journeys into one route (Sörensen et al., 2020), in the comparably densely populated city of Bremerhaven. This assumption is further supported by Figs. 5 and 6 in appendix, where a higher proportion of trips with 2 or more passengers can be observed in the second set of DRT scenarios. In the baseline scenario, the 85,651 inhabitants caused more than 2 million vehicles kilometres per day, resulting in approximately 24 vehicle kilometres traveled per capita in comparison to around 29 VKT per capita

Table 4
Relative change of values compared to the DRT scenario with 4500 vehicles.

Scheme	Vehicles	Average waiting time (min)	Average in-vehicle travel time (min)	Average travel time (min)	Service rate	Vehicle kilometres traveled	Empty runs
DRT	4000 (−11.1%)	+1.3%	+0.2%	+0.7%	−2.1%	−3.4%	+2.9%
DRT	4500 (±0)	±0	±0	±0	±0	±0	±0
DRT	5000 (+11.1%)	−1.3%	±0%	−0.4%	+1.9%	+2.7%	−3.5%
Baseline	68,561 (+1422%)	–	−48.4%	−68.2%	–	+64.1%	–

Table 5
Operational and environmental costs for both scenarios and with different vehicle types per day. The cost rates for operational costs are taken from Bösch et al. (2018). The cost rates for environmental costs are taken from Matthey and Bünger (2019). The operational costs vary for urban and rural areas. For this reason, mixed costs weighted by population size were calculated for the second scenario. For environmental costs, no distinction is made between urban and rural areas in Matthey and Bünger (2019).

		Scenario 1					Scenario 2			
		Baseline	*DRT 1600*	*DRT 1800*	*DRT 2000*		*Baseline*	*DRT 4000*	*DRT 4500*	*DRT 5000*
Vehicle kilometres traveled (VKT)		883,730	592,164	609,495	622,965		2,054,208	1,209,271	1,251,797	1,285,876
Vehicle type	Operational costs rural setting (€-Cent/VKT)					Operational costs mixed setting (€-Cent/VKT)				
MIT (Conventional)	64.21	567,443.03 €				64.21	1,319,006.96 €			
MIT (Electric)	58.63	518,130.89 €				58.63	1,204,382.15 €			
DRT (Conv. SAV)[a]	58.00		343,455.12 €	353,507.10 €	361,319.70 €	65.34[e]		790,137.67 €	817,924.16 €	840,191.38 €
DRT (E. SAV)[b]	55.00		325,690.20 €	335,222.25 €	342,630.75 €	62.55[e]		756,399.01 €	782,999.02 €	804,315.44 €
DRT (Conv. nSAV)[c]	235.00		1,391,585.40 €	1,432,313.25 €	1,463,967.75 €	289.84[e]		3,504,951.07 €	3,628,208.42 €	3,726,983.00 €
DRT (E. nSAV)[d]	231.00		1,367,898.84 €	1,407,933.45 €	1,439,049.15 €	285.52[e]		3,452,710.56 €	3,574,130.79 €	3,671,433.16 €
Vehicle type	*Environmental costs (€-Cent/VKT)*									
MIT (Gasoline)	6.42	56,735.46 €					131,880.15 €			
MIT (Diesel)	7.53	66,544.86 €					154,681.86 €			
MIT (Electric)	6.10	53,907.53 €					125,306.69 €			
DRT (Gasoline)	6.56		38,845.95 €	39,982.87 €	40,866.50 €			79,328.18 €	82,117.88 €	84,353.47 €
DRT (Diesel)	7.73		45,774.27 €	47,113.96 €	48,155.19 €			93,476.65 €	96,763.91 €	99,398.21 €
DRT (Electric)	8.02		47,491.55 €	48,881.49 €	49,961.79 €			96,983.53 €	100,394.12 €	103,127.26 €

[a] *Conv. SAV = Autonomous vehicles with conventional combustion engines*
[b] *E. SAV = Autonomous vehicles with electric engines*
[c] *Conv. nSAV = Non-automated vehicles with conventional combustion engines*
[d] *E. nSAV = Non-automated vehicles with electric engines*
[e] Sample calculation of operational costs for scenario 2 with autonomous DRT vehicles powered by electric motor: rural area: 0.55 CHF, urban area: 0.74 CHF ⇒ (0.55 CHF * 30,626 + 0.74 CHF * 55,024) / 85,650 = 0.6721 CHF⇒ 0.6721 CHF * 0.9306 €/CHF = 0.6255 €

in rural areas. A viable explanation are shorter trip distances within the city core. At the same time the share of empty runs decreases from approximately 8 to 5%, which again can be explained by a higher and more concentrated demand.

When comparing the relative changes in Table 4 with the rural set of simulations, the differences of the DRT service to the baseline scenario are significantly higher. Within the DRT simulations the influence of a variation in the number of vehicles exerts a comparably strong and positive influence on the efficiency parameters service rate and vehicle kilometres traveled, whereas the number of empty runs decreases.

6. Cost calculation

Next to the presented service and performance criteria, the expected costs and environmental effects are necessary to assess the impact of a DRT-system implementation. Table 5 depicts the estimated operational and environmental costs resulting from the baseline and the DRT simulations for both scenarios. The cost rates for operational costs are taken from Bösch et al. (2018). Since these are given in Swiss francs, they are converted into Euro at the exchange rate of 1 CHF = 0.9306 € (08.10.2020). The cost rates for environmental costs are taken from Matthey and Bünger (2019). At first sight, switching from MIT to a DRT service can reduce the VKT in both scenarios by about one third. In the simulated scenarios, 24,524 and 68,561 cars are replaced by 1800 and 4500 minivans respectively. Thus, the simulated changes result in a vehicle fleet reduction of 86 and 85% respectively, which is in line with Bischoff and Maciejewski et al. (2016).

6.1. Operational costs

The operational costs are taken from the cost tables in Bösch et al. (2018) and are calculated for all simulations introduced above with different types of vehicles, drive types and automation levels. In accordance with the characteristics of the simulated vehicles, midsize vehicle comparable to a VW Golf or similar are assumed for the MIT in the baseline scenarios. For the DRT case, minivans similar to a VW Multivan are assumed. The operational costs are calculated for fuel based and electric drive types as well as for fully automated and non-automated vehicles. Moreover, the cost table is further categorised by type of operation. For MIT, costs are taken from the operational category *"private ownership"*. For DRT, costs are taken from the operational category *"PT with pooling"*. For scenario 1 (rural population), the provided costs for rural areas are applied. For scenario 2 (rural and urban population), mixed costs weighted by population size are calculated as shown in the sample calculation at the bottom of Table 5.

As depicted in Table 5, the operational costs per VKT are about 4 times lower for fully automated than for driver-steered vehicles. While the aggregated global costs for operating an DRT system with automated vehicles in the rural areas are below 400,000 € per weekday, at least approximately 1.3 million € would have to be spend for a non-automated system. This difference is primarily due to to wages and other costs related to human drivers. Moreover, fully automated vehicles usually have a lower fuel consumption and maintenance costs due to a more considerate driving behaviour (Bösch et al., 2018).

In contrast, the switch from conventional combustion engines to electric engines results in both the MIT and the DRT scenario to a comparable small cost reduction of approximately 20,000 and 30,000 € per day respectively. However, the estimated operating costs of 1600 fully automated vehicles with combustion engine approximately equal the costs of 2000 fully automated electric vehicles and thus illustrate the potential of cost-neutral but positive effects on the service parameters such as the share of rejected requests.

In any case, the aggregated global operational cost of the DRT scenarios with automated vehicles are significantly smaller than the corresponding MIT costs.

6.2. Environmental costs

For the environmental costs, 2016 is used as the base year for calculations (Table 5). The cost rates taken from Matthey and Bünger (2019) are calculated in a holistic approach. They incorporate emissions from the operation of vehicles (such as combustion of the fuels, abrasion and dust turbulence), emissions from other life cycle phases (e.g. construction, maintenance and disposal of vehicles) as well as from the provision of fuels. Moreover, the negative effects on humans, nature and the landscape due to noise, fragmentation or land sealing are taken into account.

The effects are calculated for vehicles driven by gasoline, diesel and electric power in reference to Matthey and Bünger (2019). For diesel vehicles higher costs than for gasoline vehicles are assumed due to air pollutant emissions and higher costs for both production and infrastructure provision. Although the local effects of electric cars are less striking, the global costs for energy deployment, vehicle production and infrastructure provision leaves the environmental costs comparable to gasoline vehicles in the MIT case. For DRT, the environmental costs of a purely electric fleet are higher than for diesel or gasoline driven vehicles. Unlike operational costs, environmental costs in Matthey and Bünger (2019) are not differentiated between urban and rural areas and are therefore the same for both scenarios.

When comparing the environmental costs of the DRT and the MIT systems, a significantly less negative impact of the DRT systems is noticeable without any exception. Although the environmental costs of DRT-vehicles are higher in terms of € per VKT, this disadvantage is outweighed by the significantly lower VKT in DRT-scenarios. The optimal scenario from an environmental perspective is a DRT-system with a gasoline-driven minivan fleet. However, every DRT approach causes less environmental costs than any MIT scenario.When comparing the environmental costs of the DRT and the MIT systems (Table 5), a significantly less negative impact of the DRT systems is noticeable without any exception. Although the environmental costs of DRT-vehicles are higher in terms of € per VKT, this disadvantage is outweighed by the significantly lower VKT in DRT-scenarios. The optimal scenario from an environmental perspective is a DRT-system with a gasoline-driven minivan fleet. However, every DRT approach causes less environmental costs than any MIT scenario.

7. Discussion and conclusion

Disruptive developments in automated driving systems, new powertrain concepts and digital mobility are shaping the potential for changes in the way people move in rural and urban areas. In combination with new technological abilities, novel mobility concepts as for instance DRT can likely improve the everyday mobility of people in terms of both cost-efficiency and sustainability. Moreover, challenges related to demographic transitions and urbanisation can be addressed and negative developments mitigated. One potential application of DRT might be the connection of rural areas with an urban core. In order to provide a foundation for evaluation, service parameters and operational as well as environmental costs are calculated on the basis of simulations. The first set of scenarios models both a pure MIT and a DRT approach, that exclusively serves the rural population and thus connects the periphery with the urban core of Bremerhaven. The second set of scenarios is simulated for the entire population sample to evaluate the feasibility of expanding the DRT service to city residents.

7.1. Implications for managerial practice

The results imply several recommendations for policy- and decision makers regarding public transport. Most notably, both operational and environmental costs significantly decrease when transforming a MIT-based scenario into one with an fully automated DRT fleet. This is generally attributable to a significant decrease of VKT caused by pooling of similar trips. Moreover, the number of vehicles can be reduced by more than 90%. By that, several negative side effects such as congestion, noise, fragmentation or land sealing can be mitigated and allow new perspectives for urban planning and regional management. The findings are generally in line with previous research (e.g. Bischoff et al. (2018), Maciejewski et al. (2016), and Boesch et al. (2016)). From an economic perspective, the replacement of a human driver by an autonomous driving system leads to a significant cost reduction by cutting operational costs and increasing efficiency. Without the use of fully automated driving systems, DRT cannot compete with MIT baseline scenarios from a pure economic perspective and under the underlying assumptions of the simulation setup.

Since the chosen approach evaluates only very different and extreme scenarios, the current real world transportation patchwork in the research area is not explicitly evaluated. As suggested by Mulley et al. (2012), a duplication of mainstream public transport and DRT for certain user groups as well as competition to e.g. taxi companies may lead to increased costs and institutional obstacles. Thus, a pure DRT scenario as conducted in this study is likely to outperform such a mix of competing and partly redundant services in terms of overall economic measures as well as overall customer satisfaction. Although the MIT scenario excels in terms of convenience and rapidity, the *accessible for all* DRT framework is rather capable of integrating the substantial needs of certain user groups while serving the entire population.

Currently, specific concerns might arise from the ongoing COVID-19 pandemic. There is first evidence, that public transportation could essentially contribute to the spread of the disease within a region due to comparably high contact intensities and the sojourn of a large number of people that probably wouldn't meet in other locations (Schröder, 2020; Bossert et al., 2020; Tirachini & Cats, 2020). It can be assumed, that this infection risk holds for minibuses. Nevertheless, connected, smart and centralised mobility services could easily be adapted to fast changing circumstances and potentially used to mitigate infection dynamics with respect to their flexible and digital setup. Possible adaptions would be the establishment of contact tracing mechanisms or the reduction of joint passengers per vehicle, especially for risk-group travellers. In automated vehicles, drivers could neither act as infection spreaders nor are they exposed to infectious passengers. Potentially infected could be transported to hospitals or test centres in isolation by certain vehicles. Connected, flexible and automated systems are likely to prove more efficient in simultaneously providing transportation services and considering specific policy measures than scheduled mass transit systems. In the specific case of the current pandemic, MIT might turn out to be more efficient in isolating travellers from each other than PT. Nevertheless, a share of the population is excluded e.g. from car ownership and is forced to make a choice between immobility and an increased risk of infection in mass transit systems in the current situation. Policymakers should consider such trade-offs in future transportation strategies, since high-income employees are more often privileged in terms of working from home options or car availability.

Secondly, the current situation represents an unprecedented economic challenge for public transport operators (Tirachini & Cats, 2020). Finding an appropriate time to resume normal operations is a political responsibility and requires further scientific work on the risk of infection in a dynamic situation and ways to prevent infection.

7.2. Contribution to scholarly knowledge

Our results show that with the setup presented and the assumptions made, a theoretical reduction of over 80% of the vehicle fleet within the test environment and the corresponding reduction of the driving volume can be achieved by maintaining a certain service quality. Moreover, the results imply that automated and shared DRT systems significantly reduce vehicle kilometres traveled and can therefore be assumed to leave a significantly smaller environmental footprint while improving the overall service quality.

Since the available data do not provide sufficient depth in certain details, the simulated scenarios come along with several limitations.

Firstly, it has to be considered, that all calculated costs are based on current values and are likely to change with technological progress and economic, political or social changes. Especially for the comparable new electric vehicles further research might mitigate environmental and operational costs. Moreover, the willingness to accept or pay for innovative modes of transports and sustainable mobility might change with an increased awareness for environmental problems (Nyga, Minnich, & Schlüter, 2020).

Secondly, public transportation is not incorporated in the simulated baseline framework. Since the share of public transportation in the modal split is comparably small, the results are not expected to be extensively biased. However, future research should take conventional public transportation into account e.g. to test for cannibalisation effects or possible multimodal interactions with DRT. Furthermore, it should also be emphasised that in the rural scenario the population is reduced by the city residents resulting in a lower probability of a crowded network and alteration of traffic dynamics. Further simulations should therefore be carried out to investigate this limitation.

Thirdly, the replacement of the entire MIT of a region is a radical and so far theoretical approach. In practice, the willingness to accept new technologies like DRT systems or fully automated vehicles will determine the share of MIT that can be realistically replaced. By including findings on human behaviour in such simulations, further research could simulate the estimated depth and speed of such transitions.

As a final point, it should be noted that the population used in the simulation scenarios slightly overestimates the real data, as already mentioned in Section 4. For this reason, the population generation algorithm should be improved and extended for new scenarios.

The aim of this contribution is to investigate the potential of DRT systems with automated vehicles as a connecting service between an urban core and its rural periphery. The simulation results suggest that a pure DRT service provision in the Bremerhaven region could establish an efficient interlink between areas of different population density. Moreover, such a large-scale system implies several advantages in service quality and environmental terms. Our cost calculations suggest future technological progress in terms of fully automated vehicles and propulsion types to be crucial for overcoming economic obstacles and improve customer acceptance. Such approaches yield a high potential to mitigate economic costs, which should be discussed from regional economic perspectives and assessed by further research. These processes should be accompanied by the creation of a legal framework for the use of autonomous driving systems, the simplification of approval processes and the integration of public DRT services.

Appendix A

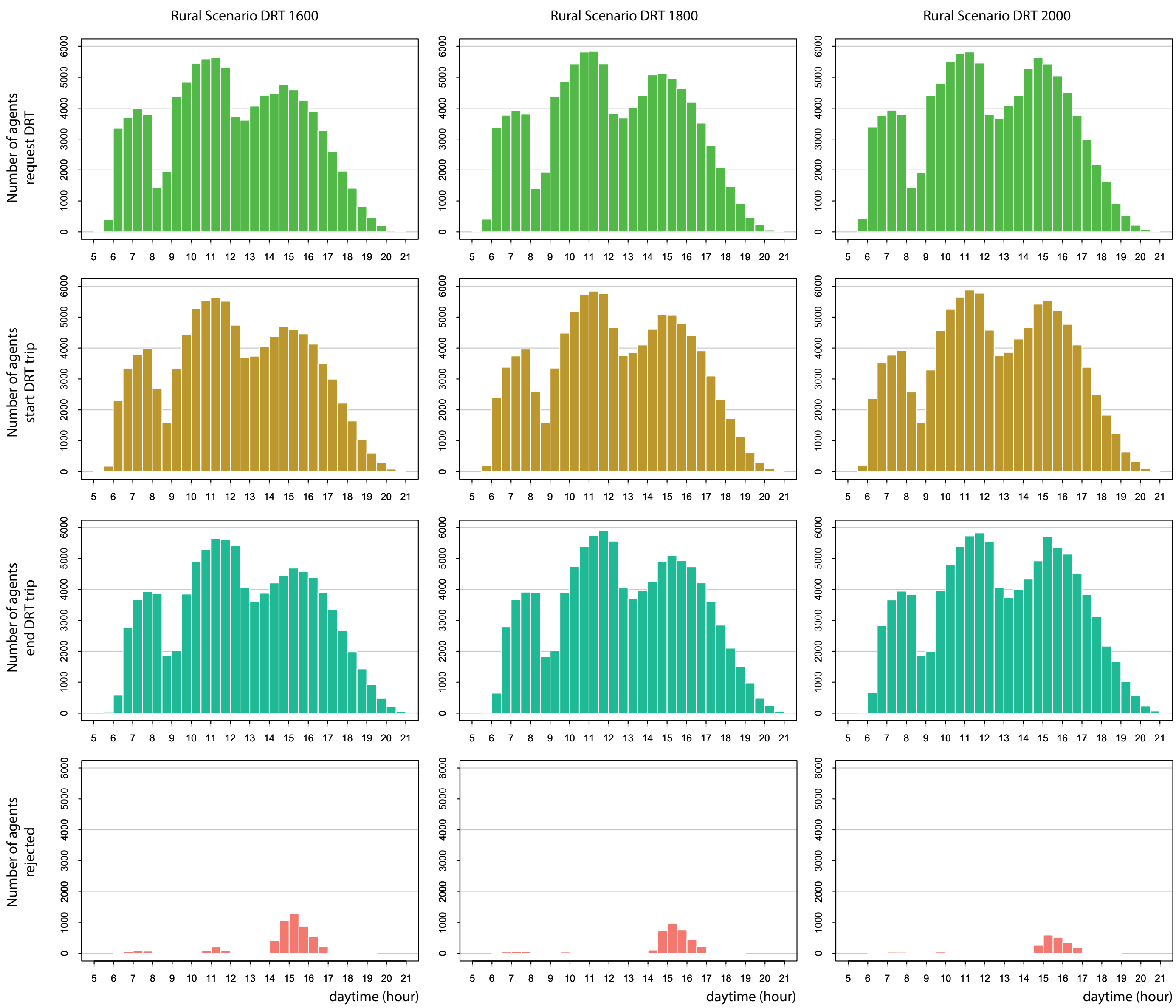

Fig. 3. Absolute number of agents in the respective travel stages of a DRT trip aggregated in 30 min periods. The columns from left to right show the three DRT scenarios of rural areas with 1600, 1800 and 2000 vehicles. The individual travel stages are colour-coded: The first row in green shows the absolute number of agents of the respective scenarios that have sent a travel request to the DRT system. The second row in yellow shows the absolute number of agents of the respective scenarios that have started a DRT journey. The third row in blue shows the absolute number of agents of the respective scenarios that have completed a DRT journey. The last row in red represents the absolute number of agents in the respective scenarios whose travel requests were rejected by the DRT system due to exceeded expected maximum waiting time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

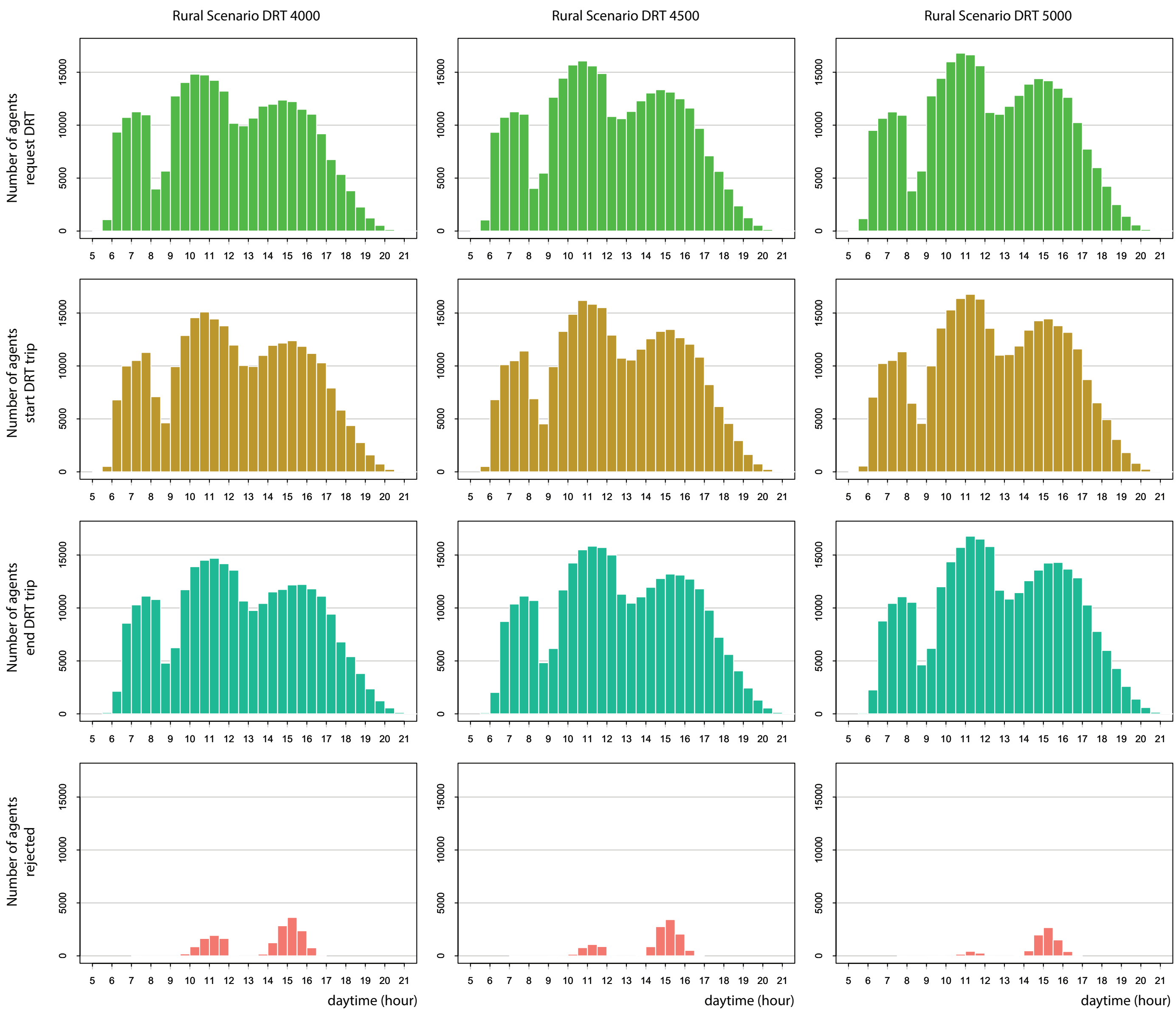

Fig. 4. Absolute number of agents in the respective travel stages of a DRT trip aggregated in 30 min periods. The columns from left to right show the three DRT scenarios of combined urban and rural areas with 4000, 4500 and 5000 vehicles. The individual travel stages are colour-coded: The first row in green shows the absolute number of agents of the respective scenarios that have sent a travel request to the DRT system. The second row in yellow shows the absolute number of agents of the respective scenarios that have started a DRT journey. The third row in blue shows the absolute number of agents of the respective scenarios that have completed a DRT journey. The last row in red represents the absolute number of agents in the respective scenarios whose travel requests were rejected by the DRT system due to exceeded expected maximum waiting time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

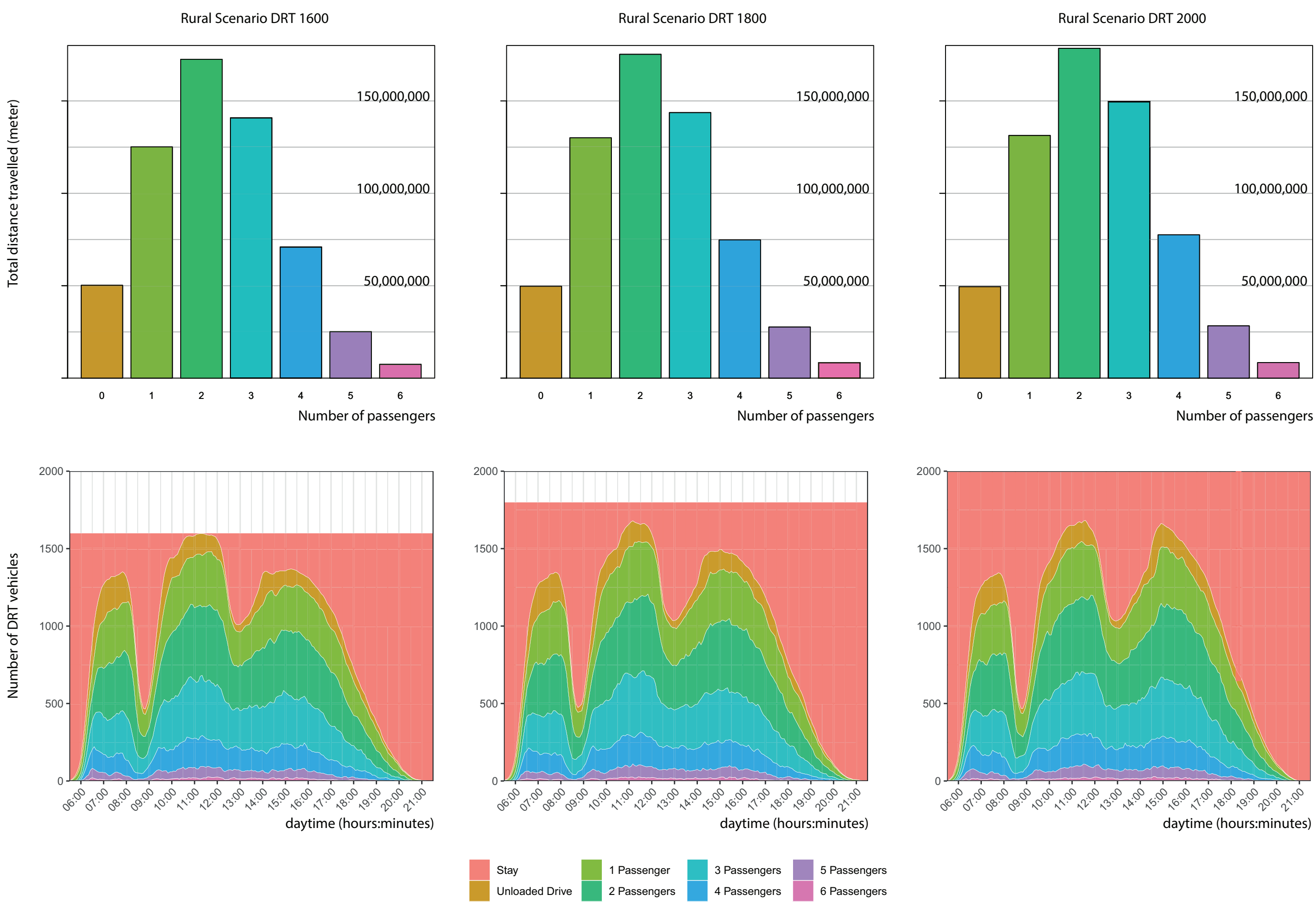

Fig. 5. The occupancy rates of DRT vehicles in relation to the total kilometres driven and the time of day. The columns from left to right show the three DRT scenarios of rural areas with 1600, 1800 and 2000 vehicles. The different occupancy states are colour-coded. The first row of diagrams shows the total mileage in metres as a function of the occupancy rate. The second row of diagrams uses a staggered graph to show the proportion of the individual occupancy rates within the vehicle fleet at the respective time of day.

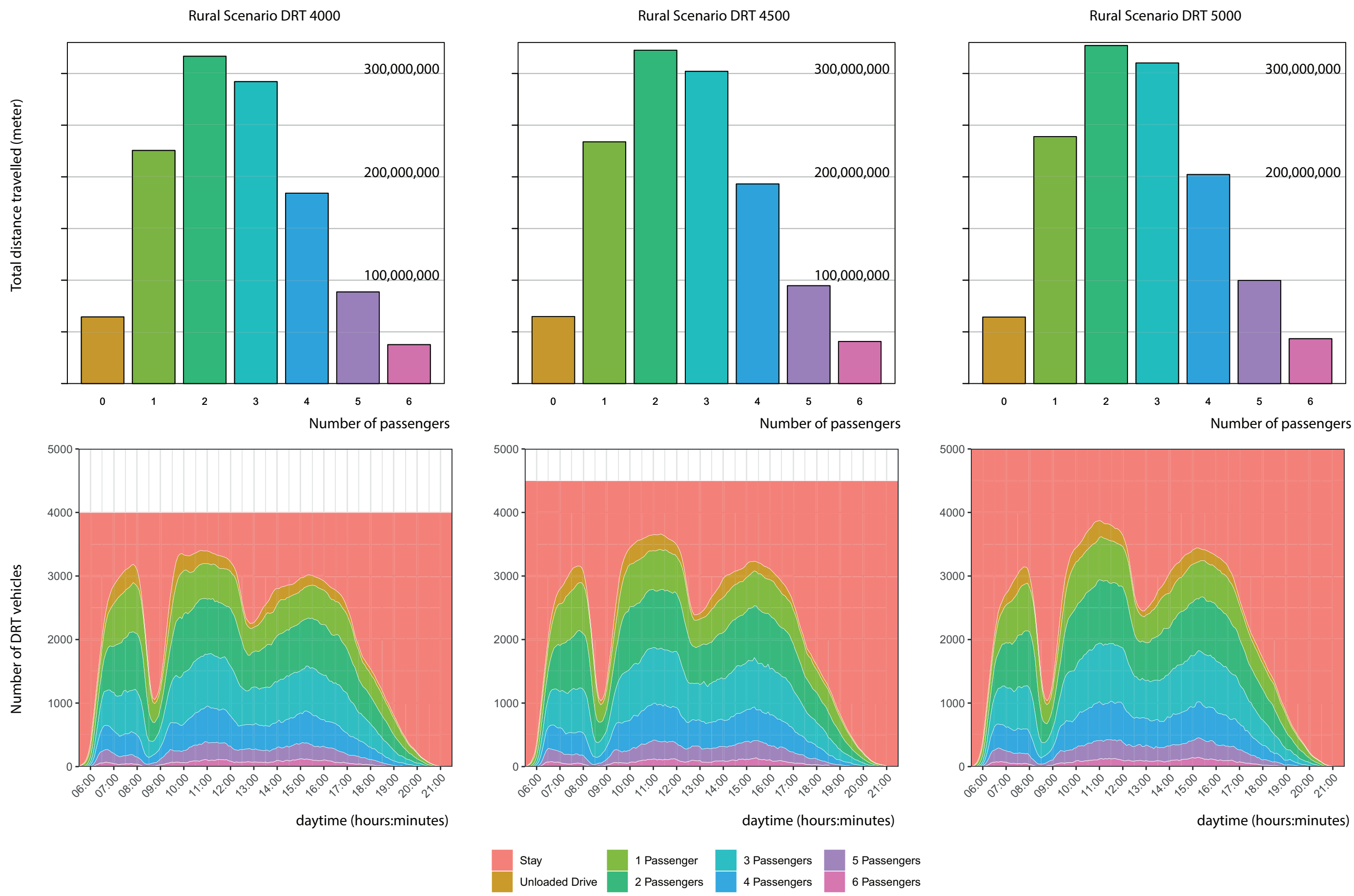

Fig. 6. The occupancy rates of DRT vehicles in relation to the total kilometres driven and the time of day. The columns from left to right show the three DRT scenarios of combined urban and rural areas with 4000, 4500 and 5000 vehicles. The different occupancy states are colour-coded. The first row of diagrams shows the total mileage in metres as a function of the occupancy rate. The second row of diagrams uses a staggered graph to show the proportion of the individual occupancy rates within the vehicle fleet at the respective time of day.

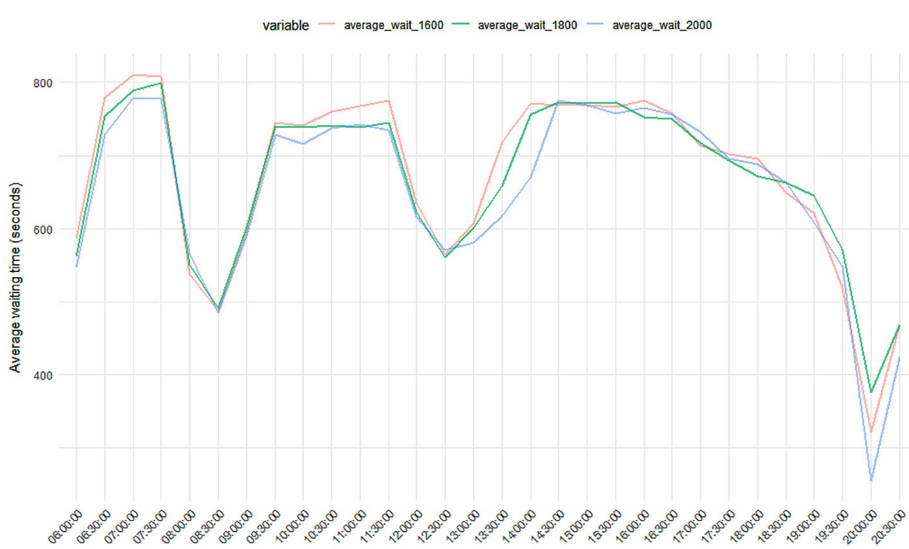

Fig. 7. Average waiting times in the course of the day for the first DRT scenario (rural only).

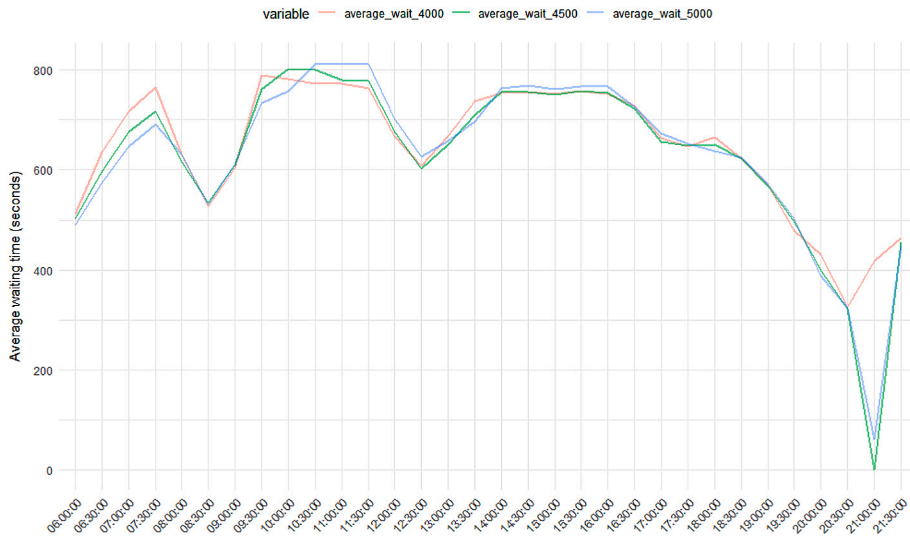

Fig. 8. Average waiting times in the course of the day for the second DRT scenario (rural + urban).

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