The feasibility and benefits of introducing an autonomous minibus on-demand system in rural public transport:

A simulation-based analysis

Master Thesis

By: Thilo Jessaï Arakelian-von Freeden
Reg. No.: 339019
Supervisors: Tino Buschmann, M.Sc.
Lisa Thiel, Dipl.-Ing.
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Submission date: ________________

Technische Universität Berlin,
Institut für Land- und Seeverkehr,
Verkehrswesenseminar
Salzufer 17-19, 10587 Berlin
www.vwsem.tu-berlin.de

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Original Task

The autonomous vehicle, that takes all driving responsibility from the passenger, is expected by professionals and the automotive industry to arrive in the next decade. New business models could emerge from its availability, such as shared autonomous vehicles, providing an on-demand mobility option. It is, however, probable that such new mobility options would be rarely found outside of densely populated areas, as those are already lacking extensive public transportation. In rural areas, alternative options to the automobile are scarce. Distances are often too long to walk or to cycle and public transport intervals and service hours are frequently unattractive. A political culture of subsidising the automobile led to choices for home and workplaces without considering existing transport options. The resulting settlement sprawl cannot be served economically by traditional public transport. To still secure livelihood for public transport captives, new ways of delivering public transport have been introduced since the late 1970s in Germany. With its potential to cut operating costs in half and the ongoing digitalisation, an autonomous vehicle fleet might have the potential to significantly increase service performance of public transport in sparsely populated areas, making it even potentially competitive to the individual motorized transport (MIT). Successes made with flexible services e.g. in Erding, Bavaria, point in that direction.

Therefore, this thesis will examine an autonomous on-demand-minibus-system for rural public transport to judge its feasibility and benefits based on a simulation. To evaluate the feasibility of such a system, different demand scenarios should be studied. Furthermore, the feasibility of such a system should be evaluated by analysing system costs (operating cost and passenger waiting time cost). The benefit assessment should be made regarding the level of service with and without the proposed system, measured by the number of served stops, the number of daily stops, and the travel time towards the next central place.

Abstract

This thesis explores if the operational design of shared autonomous vehicles with dynamic ride sharing schemes that is expected to emerge in urban application would be feasible to implement as local public transport in a typical rural German area. It seeks to provide a scenario in which rural inhabitants would profit of such a new mode of transport in the form of an autonomous minibus on-demand system. With the simulation of a system model in the study area around the town of Fehrbellin in rural north-west Brandenburg State in the Automated Transit Network simulation software *PRTsim*, a total cost optimal fleet of minibuses is identified for different demand scenarios. The results of the simulation of the morning peak hour suggest that a replacement of current local public transport services with an autonomous minibus on-demand system would require additional funding of between 0.29 and 0.37 million Euro and that waiting times upon vehicle call could exceed 90 minutes in the lower demand scenarios and 60 minutes in the high demand scenario. The added subsidy requirement would be more than the current subsidy budget for the area's local public transport and while the properties of such a system would deliver lower travel times and higher public transport availability to its passengers, the waiting times in the peak demand would be prohibitively high. Those results could not support the idea that the explored autonomous minibus on-demand system for rural public transport would be feasible under current budgetary restrictions, and that its benefits to the passengers would outweigh their discomfort due to waiting times after a vehicle call.

Zusammenfassung

Diese Arbeit untersucht, inwiefern sich das für urbane Applikationen entwickelte betriebliche Modell von geteilten autonomen Fahrzeugen mit dynamischen Fahrgemeinschaften auf den lokalen öffentlichen Personennahverkehr (ÖPNV) im ländlichen Raum übertragen lässt. Ein Szenario wird aufgezeigt, wodurch die ländliche Bevölkerung von diesem neuen Verkehrssystem in Form eines Systems autonomer Minibusse Nahverkehrs auf Abruf, profitieren kann. Mithilfe der Simulation eines operativen Modelles eines solchen Systems in dem ländlichen Untersuchungsgebiet um die Stadt Fehrbellin im nordwestlichen Brandenburg wurde die optimale Flottengröße in Bezug auf die kombinierten Kosten der Fahrgäste und des Betreibers für verschiedene Nachfrageszenarien abgeschätzt. Die Ergebnisse der Simulation der morgentlichen Nachfragespitze zeigten einen zusätzlichen Subventionsbedarf zwischen 0,29 und 0,37 Mio. € sowie Wartezeiten für die Fahrgäste von teilweise über 90 Minuten in den Szenarien niedriger Nachfrage und von maximal 60 Minuten im hohen Nachfrageszenario auf. Für den zusätzlichen Subventionsbedarf müsste die ÖPNV-Unterstützung mehr als verdoppelt werden und die Wartezeiten für den Fahrgast wären prohibitiv hoch und nicht durch Reisezeitvorteile oder erhöhte ÖPNV Verfügbarkeit auszugleichen. Die Ergebnisse konnten daher nicht die Prämisse unterstützen, dass ein Nahverkehrssystem auf Abruf aus autonomen Minibussen unter gegebenen Budgetrestriktionen machbar sei und dass die Vorteile für die Fahrgäste die Wartezeit bis zur abgerufenen Fahrt ausgleichen würden.

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List of abbreviations

B	city of Berlin
BBSR	Federal Institute for Research on Building, Urban Affairs, and Spatial Development
BMVI	Federal Ministry of Transport and Digital Infrastructure
BMVBS	Federal Ministry of Transport, Building and Urban Development
DRS	dynamic ride-sharing
eq.	equation
Fb	Fehrbellin
HVL	district of Havelland
inh.	inhabitants
LEP-BB	Landesentwicklungsplan Berlin - Brandenburg
MIT	motorized individual transport
MÜR	former district of Müritz
OHV	district of Oberhavelland
OD	origin-destination
OPR	district of Ostprignitz-Ruppin
ORP	Ostprignitz-Ruppiner Personennahverkehrsgesellschaft mbH
P	city of Potsdam
PR	district of Prignitz
PRT	Personal Rapid Transit
PT	public transport
SAE	Society of Automotive Engineers
SAV	shared autonomous vehicle
VDV	Association of German Transport Companies
VKT	vehicle kilometres travelled
VoT	value of time

List of symbols

α	overhead-and risk premium factor
C_m^a	annual maintenance cost of the vehicles
C_e^a	annual energy cost for running the vehicles
$C_{operator}^a$	annual total costs for the operator
C_{user}^a	annual total costs for the users
C_v^a	annual capital cost of the vehicles
C_{Fb}^{BA}	commuter volume towards the ($-Fb$=from) community of Fehrbellin
C_{Fb}^{BMVI}	estimated commuter volume towards ($-Fb$=from) the Fehrbellin study area in the morning peak hour
C_e	average commercial energy cost in Germany
c_s	factor of added traffic attraction by the supply centres with s $\in \{big, small\}$
C_v	vehicle purchase cost
D_{Fb}	estimated total traffic attraction of the traffic cells inside of the Fehrbellin area
D_j	estimated non-school transport traffic attraction in in traffic cell i
D_i^*	total traffic attraction per traffic cell i
$D_i^{commuters}$	commuter volume from the community of Fehrbellin to the traffic cell i from the local transportation plan
D_j^{pupils}	school transport trips with their destination in traffic cell j
ir	annual interest rate
k	disutility exponent (index r for disutility ratios)
l_{peak}	load factor correcting for the different system loads in on- and off-peak hours
m_w	value of time of the system's passengers
n	average vehicle life expectancy
O_i	estimated originating non-school transport traffic in in traffic cell i
O_i^*	estimated total originating traffic per traffic cell i

$O_i^{commuters}$	commuter volume from the community of Fehrbellin to the traffic cell i from the local transportation plan
O_{Fb}	number of trips in the morning peak hour in the Fehrbellin study area
O_i^{pupils}	originating school transport trips in traffic cell i
φ^s	share of trips entitled to school transportation taken on the system in scenario s
p_i^{attr}	weight to allocate the total traffic attraction of the Fehrbellin area to its traffic cells ($i \leq 27$)
P_i	population in the traffic cell i
P_v^{peak}	peak hour vehicle performance in vehicle-kilometre
p_i^{pop}	population share of the traffic cell i among the total population in the Fehrbellin study area.
ρ_{all}^{peak}	estimated share of trips per inhabitant in the peak hour on week days among per mean trips per inhabitant and year
$r^{commuters}$	ratio of commuters from the Fehrbellin area in the morning peak hour per commuters from the community of Fehrbellin
σ^s	modal share of the system among all trips in scenario s
sd^a	number of school days per year in Brandenburg state
T^a	number of annual trips on the system
t^{peak}	trips taken in the peak hour on the system
T_{ij}	trip estimation between cell i and j
t_{MiD}^{md}	average trips per person on a mean day in Germany
T_{ij}^{pupils}	morning peak trips of pupils entitled to school transportation
t_w	average passenger waiting time
t_{BD}^{wd}	average number of weekday trips per inhabitant of the community of Beetzendorf-Diesdorf
$t_{int\ BD}^{wd}$	average number of weekday trips per inhabitant of the community of Beetzendorf-Diesdorf with its destination inside the community
t_{MiD}^{wd}	average trips per person on a week day in Germany

u_e	estimated energy usage of the vehicles
$U_{m,l}$	travel disutility measured in MIT trip duration between traffic cell l and m
v	fleet size in number of vehicles
$v^{a}_{OPR,l}$	total annual traffic volume from the district of Ostrprignitz-Ruppin to the traffic cell $l \in \{B; P; HVL; OHV; OPR; PR; MÜR\}$
$\mathrm{v}^{a,PT}_{\mathrm{OPR},l}$	annual train and bus trip volume from the district of Ostrprignitz-Ruppin to traffic cell l
$v^{a,edu,PT}_{OPR,l}$	annual educational trip volume on PT from the district of Ostrprignitz-Ruppin to traffic cell l
$v^{peak}_{Fb,i}$	estimated commuter volume between the Fehrbellin study area and the traffic cell i
w^{peak}_{BD}	traffic share of the morning peak hour among all trips on a weekday
X	generalized cost components to the users that are fixed regarding fleet size variations
Y	fixed costs regarding fleet size adjustments

1. Introduction

On the 7th November 2017, Waymo (2017), the company that emerged from Google's self-driving car project, announced that they were starting to operate their fleet of autonomous minivans in public testing without a driver or a supervising engineer. They created the first fleet of vehicles that take all driving responsibility from the passengers on public roads.

Such fleets of vehicles with high driving automation systems are expected to create a new transport mode that merges the characteristics of taxi and free-floating car sharing services.[1] Especially in rural areas, this mobility option could be of interest as a form of public transport, as conventional public transport (PT) frequently fails to serve its passengers' demand[2] and to provide a viable alternative to the private car[3]. With the omission of a conductor, autonomous minibuses could improve feeder services to arterial PT, extend PT service hours, and individualize PT.[4]

This thesis wants to study the feasibility and benefits of an autonomous minibus system that would replace current conventional rural local PT with on-demand ride-sharing services without predefined schedules or routes. It seeks to discover if the low population density and the relatively long travel distances of a low-density German rural area[5] could support such a collective taxi-like system to run at reasonable costs while providing limited waiting times for the passengers. Therefore, a model of such a system is explored in the Automated Transit System simulator *PRTsim*. Though the simulation, an estimation of the total-cost-optimal fleet size considering the costs for the passengers and the operator[6] will be obtained, and its modelled performance in different demand scenarios explored.

First, an operational scenario for a rural autonomous minibus on-demand system is formulated based on the current state of research into driving automation technology, its mobility impact, and public rural mobility. Then, a study area is devised and local transport demand scenarios as well as the system's cost components are estimated. The following simulation of the modelled system's operation allows the optimization of the fleet size regarding the combined costs of the system to the passengers and the operator. The service figures and economic performance of the system with its optimal fleet size is then assessed for its anticipated feasibility and benefits.

[1] cf. Krueger/Rashadi/Rose 2016, p. 344
[2] cf. Steinrück/Küpper 2010, p. 17 f.
[3] cf. Kirchhoff/Tsakaretos 2007, p. 20
[4] cf. Lenz/Fraedrich 2015, pp. 189-192
[5] cf. BMVI 2013, p. 4
[6] cf. Jie et al. 2010, p. 304 f.

2. Autonomous driving technology

The recent introduction of the first fully autonomous vehicle fleet by Waymo (2017) shows that driving automation technology is approaching its market readiness. The technology is going to be disruptive for the transport sector, as it significantly changes the cost structure of mobility services, as well as the usefulness and comfort of the travel time.[7]

This chapter is going to provide an overview of the current state of autonomous driving technology development, its current and expected application, and the research regarding its traffic impact.

2.1. Driving automation systems in road vehicles

The Society of Automotive Engineers (SAE) (2016, p. 1 f.) provides in its Recommended Practice "[…] a taxonomy describing the full range of driving automation in on-road motor vehicles […]"[8]. They devised a six-level differentiation of driving automation systems according to their ability to provide the dynamic driving task on a sustained basis[9] as presented in Table 1.

Table 1: Levels of driving automation according to the SAE

	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Driver's task	Performance of the full dynamic driving task	Performance of the remaining driving task	Immediate response to unexpected incidents	Intervention upon request (fall-back)	No intervention expected	
System's task		*One-dimensional* vehicle motion control	*Two-dimensional* vehicle motion control	Performance of the dynamic driving task but *without fall-back level*	Performance of the dynamic driving task in a *limited operational design domain*	Performance of the dynamic driving task under *all conditions*
	No Driving Automation	Driver Assistance	Partial Driving Automation	Conditional Driving Automation	High Driving Automation	Full Driving Automation

Own figure based on SAE (2016, p. 17)

The SAE (2016, p. 26 f.) specifically avoids the term *autonomous vehicles* since it is imprecisely used and lacks a common definition. The term is widely adopted and commonly used synonymously with fully automated or driverless[10]. It is defined in this thesis as followed:

Fully automated or *fully autonomous* describes a road vehicle's ability to drive on public roads in mixed traffic without requiring any oversight by a driver both on the vehicle or remotely. This would apply to at least with Level 4 driving automation technology equipped vehicles.

Litman (2017, p. 11) summarizes the current state and the expected availability of driving automation systems in vehicles. SAE **Level 1** driving automation systems are available in many new

[7] cf. Hörl/Ciari/Axhausen 2016, p. 8
[8] SAE 2016, p. 1
[9] With this definition SAE (2016, p. 13) excludes systems that intervene only temporarily in the driving task (including active safety systems).
[10] cf. Litman 2017, VDV 2015, and Ford 2016

vehicles while some models have systems like lane keeping assistance or adaptive cruise control that qualify as SAE **Level 2** driving automation systems. Most vehicles which are tested for full driving automation are currently under constant surveillance by an engineer giving them a SAE **Level 3** automation status. SAE **Level 4** systems are already running on dedicated driveways, like the Ultra pod car at Heathrow Airport,[11] but are restricted to their operational design domain on designated pathways.[12] Likewise, the operation of the driverless Waymo vehicles is geo-fenced to predefined streets,[13] creating an operational design domain and defining their driving automation system as SAE Level 4 compliant.

2.1.1. Exemplary autonomous vehicle technology

Beiker (2015, p. 289-292) describes the experience made at Stanford University with the driving automation system in the electric shuttle vehicle *Navia* of the French firm Induct. The automation technology implemented in this vehicle works on the principle of simultaneous localization and mapping. This principle relies on the sensors on board the vehicle constantly checking its surroundings against a previously created three-dimensional reference map. The vehicle normally follows a virtual guide rail on a pre-calculated optimal route. Any deviations to the reference system are identified as potential obstacles that may require a change in route or trajectory. Object detection by cameras and trajectory forecasts facilitate the decision process. If no drivable route is detected, the vehicle halts and awaits input from the operation personnel thus complying with SAE Level 4 automation as it performs a fall-back into a safe state. The system is supported by laser and ultrasonic sensors for middle to long and short-range mapping, high resolution cameras for object recognition, satellite navigation, and steering and wheel angle sensors. To create the necessary reference map, repeated manual navigation of the vehicle on the operating area are required. For test purposes, the vehicle speed was limited to 20 km/h.

This technology allows SAE Level 4 grade driving automation. As the systems rely on reference maps, the vehicle would not be able to manoeuvre in areas without these maps, thus full driving automation on a SAE Level 5 would not be possible.

2.1.2. Implementation predictions

The Association of German Transport Companies (VDV) (2015, p. 6) cites several statements by heads of automobile manufacturers who predict fully autonomous vehicles to be implemented within a decade. Ford (2016) for instance announced specifically SAE Level 4 compliant vehicles in commercial mobility services in 2021. The operations would be on public roads but restricted to geo-fenced areas as their operational design domains.

Hörl/Ciari/Axhausen (2016, p. 3 f.) see, aside from the technical challenges, the following issues that need to be overcome until fully autonomous mobility becomes generally available. The **legal**

[11] Ultra 2017
[12] cf. SAE 2016, p. 25
[13] cf. Waymo 2017

and liability frameworks of road traffic activities do not yet regulate which entity would take responsibility in the case of an accident caused by a fully autonomous vehicle and thus would need to be amended. As many jobs in transport and logistics might be replaced by automated driving systems and secondary industries, like maintenance and accident response services, might see a decrease in demand due to lower accident rates, a **societal resistance** against such structural change in the labour market could arise. Lastly, it is to be expected that non-rational preferences for the conventional private car (e.g. as a status symbol) could act as **behavioural barriers** towards the adoption of autonomous mobility solutions.

Litman (2017, p. 13) expects autonomous vehicles (level 4 or higher) to be available with large price premiums in the 2020s. The implementation as a standard in most new vehicles is however not expected by the mid of the century. Wasud's (2017, p. 168 f.) overview of projected premiums for full vehicle automation expect additional costs of up to 21,200 £ (around 23,700 €) in 2020. However, he values the most probable premium for full autonomy in 2025 at the equivalent of 9,800 $ (around 8,300 €). At those prices, the technology is likely to be first used in high mileage vehicle scenarios like the above-mentioned mobility services by Ford. Accordingly, Wasud (2017, p. 171) shows that, as early as 2020, vehicle automation might be highly lucrative in lorries and taxis. Contrary to that, fully automated vehicles are expected not be economically sensible as private cars for most households based on his total cost of ownership analysis.

As a result, the emergence of shared autonomous vehicles (SAVs) as a new mode of transport is expected, combining characteristics of free-floating car sharing and taxi services with high driving automation systems.[14]

2.2. Shared autonomous vehicles

The concept of shared autonomous vehicles (SAVs) can be seen from two perspectives. Researchers like Lenz/Fraedrich (2015, p. 187) and Krueger/Rashadi/Rose (2016, p. 344) see SAVs as a form of enhanced one-way carsharing that reduces access walks to the vehicle through the autonomous vehicle's ability to approach its passenger. Researchers like Andréasson (n.d.) see in autonomous vehicle technology the possibility to implement Automated Transit Networks like Personal Rapid Transit (PRT) systems without the current need for a separated track. These systems would bring non-stop origin to destination and on-demand trips to public transport, removing the temporal constraints by schedules and the increased travel time due to intermediate stops or transfers of today's PT systems.[15] Depending on the perspective, SAVs would be integrated in PT services as a complement to mass transit systems or would operate competing to the existing services.[16]

Krueger/Rashadi/Rose (2016 p. 343 f.) distinguish two types of SAV operations. The regular SAVs would be shared intertemporally like today's car sharing or taxi services with the whole vehicle being used by one party at a time. With the addition of dynamic ride-sharing (DRS)

[14] cf. Krueger/Rashadi/Rose 2016, p. 344
[15] cf. Hosse/Neumann (2015, pp. 2-5)
[16] cf. scenario A versus scenario B in VDV 2016, p. 13 f.

schemes, parties with matching rides could be carried simultaneously, thus creating a collective transportation solution.

The studied implementation scenarios of SAVs as well as first tests of SAV services on the road are shown in this chapter.

2.2.1. Pilot operations

The pilot operations in place today show two distinct business models of SAV manufacturers. While the French firms navya and easymile as well as the US-based local motors offer their autonomous minibus vehicles as *white service providers* to transportation agencies for demonstration operations, companies from the Silicon Valley such as Waymo and uber test their self-developed SAVs for their own services on the roads.[17] In terms of operational design, the following examples of SAV testing show the scope of different use cases for SAVs.

Waymo (2017) announced in late 2017 that they started operating their vehicles in their public testing area without an engineer present on the vehicle. They state that all driving on these vehicles is done by the cars' software systems, giving them true level 4 autonomy. The company offers taxi-like ride sharing services free of charge to registered test riders in their modified Chrysler Pacifica Minivan vehicles in the Phoenix metro area with a fleet of 600 vehicles.[18] It is unclear if they apply a DRS scheme.

The first SAVs operating on public roads in Germany are the autonomous minibuses of the German railway company **Deutsche Bahn AG** in the Bavarian small town Bad Birnbach.[19] According to the company's fact sheet[20], the electric minibus EZ10 made by the company EasyMile runs daily on a short line from the market to the thermal bath in a fixed interval with a speed limited for test purposes to 15 km/h. The vehicle sits six passengers and it is constantly supervised by a trained attendant. The operation as a bus line on a fixed schedule could be seen as the most basic ride sharing scheme. The above-cited fact sheet promises, however, a later implementation of an on-demand service with a DRS scheme.

Andéasson (2016, p. 1) describes that in the five Automated Transit Networks in public operation, ride-sharing between people with the same destination occurs naturally.

2.2.2. Research on shared autonomous vehicle traffic impact

Hörl/Ciari/Axhausen (2016, pp. 8-11) aggregate the available research of the impact of SAVs on mobility. Assuming the emergence of SAVs as a new mode of transport as described above, they find the following main research results concerning their traffic impact. An SAV fleet would

- reduce the number of vehicles needed to cover today's traffic demand.

[17] Own assessment based on the companies' self-presentation on: NAVYA 2017, EasyMile 2017, local motors 2017, Waymo 2017, and Harris, 2015
[18] cf. Krafcik, 2017
[19] cf. DB 2017a
[20] DB 2017b

- increase the traffic capacity,
- induce additional demand, and
- lead to a significant increase in vehicle kilometres travelled.

Numerous studies take simulation-based approaches to determine the possible fleet size reduction resulting from a total substitution of private cars with SAVs. Bischoff/Maciejewski (2016, p. 243) suggest, that a citywide replacement of private cars with autonomous taxis (without DRS) in the city of Berlin would be feasible with 10% of the current private car fleet. Similarly, Fagnant/Kockelman (2014, p. 8) find a substitution rate of one autonomous taxi for twelve private cars in their agent-based simulation in the area of Austin, Texas. Both abovementioned studies show an increase in vehicle kilometres travelled (VKT) of 17% in the former and above 10% in the latter study. Hörl/Ciari/Axhausen (2016, p. 9 f.) expect even more induced traffic through the introduction of SAVs as the convenience of the mode (no constraints to stations and timetables) would attract former public transport riders and people that used to walk or cycle.

The ITF (2015, p. 21) simulates the impact of full private car replacement by SAVs in the city of Lisbon and estimates that the VKT could more than double if no DRS schemes were installed and no high-capacity public transport network would be in place. However, with both factors in place, the model estimates VKT similar to the baseline scenario without SAVs. This emphasises the importance of integrating PT with SAV fleets in an urban environment.

Davidson/Spinoulas (2016, p. 11-15) equally show that a SAV fleet would have synergies with the existing PT system. Since the marginal costs of the SAV use would be higher than PT, they expect the latter mode to become more attractive. They add that SAVs would especially complement PT in offering an access and egress option in the case of origins and destinations remote from PT stops.

Hosse/Neumann (2015 p. 13 f.) study the impact of replacing the whole PT network in Cottbus, Brandenburg with a PRT system of small automated vehicles. They estimate similar per-passenger-kilometre costs to the existing bus and tram operation with a PRT fleet of 1 000 vehicles and a mean waiting time of about twelve minutes while offering trips without intermediate stops or transfers. With the introduction of a DRS scheme, they estimate a reduction of the necessary fleet size of about 37% and subsequently much lower costs. However, the studies' cost calculation should be seen as incomplete, as it encompasses only the energy consumption, and insurance, and tax write-off costs. Maintenance costs are not taken into account.

All studies focus on urban and suburban traffic. Studies specifically exploring implementation scenarios of autonomous vehicles in rural areas could not be found, even though survey respondents in rural areas were significantly more open towards this new technology[21]. This might be

[21] cf. Cyganski 2015, p. 254

since the low population density of rural areas would prevent SAV systems to become economically viable for private operators in rural areas[22]. One option to deliver this new transport mode to rural areas could be the integration into the subsidised rural PT. This scenario shall be investigated in this thesis.

[22] cf. Fagnant/Kockelman 2014, p.2

3. Mobility in rural Germany

Mobility is, as Brenck/Gipp/Nienaber (2016, p. 9 f.) pointed out, often differently defined in the literature. Following their definition, spatial mobility is the individual ability to fulfil desires or necessities by change of place. They state that the mobility of the individual is dependent on the availability of systems for change of place and the individual usability of them. Steinrück/Küpper (2010, p. 5) add that the factor of distance in time taken to reach the locations of the desired or necessary activities further influences the individual mobility.

3.1. Challenges to rural public transport

This chapter focuses on the challenge to serve the inhabitants of rural areas with public transport[23] (PT) as this mode seeks to provide an alternative to the MIT especially in the cases were the latter cannot be used[24].

3.1.1. Defining rural areas

A definition of rural areas in Germany is given by the German Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR, 2017a). It classifies district regions according to their population density and their share of urban population. District regions can contain either a district or a medium sized city with its surrounding district. This definition is used as comprehensive standard for official analysis and studies.

For their analysis of the mobility chances and traffic behaviour in rural areas, Wehmeier/Koch (2010, p. 457) relied on an older BBSR definition for rural areas, which took also the location favourability of district regions (proximity to large centres of population) into account. District regions with a population density below 150 inhabitants (inh.)/km² and district regions that were considered to have a peripheral location were considered *rural districts*. As the overall district region population density is measured, also mid-sized cities can be considered as part of the rural areas.

To allow a more detailed analysis geographically, Brenck/Gipp/Nienaber (2016 p. 16 f.), define rural areas according to the population density in the communities setting the 150 inh./km² limit in accordance to the criteria for rural district regions from the BBSR. To get an overview of the rural areas in Germany, the communities with their respective inhabitation density is shown in the appendix at A 1.

3.1.2. Structural deficits of rural public transport

In rural areas, the low population density leads to distances that are often too long to walk or to cycle.[25] To be mobile, in these cases, the availability of a motorized system for change of place is

[23] Public transport shall be defined for this thesis (following §2 RegG) as publicly accessible transport of people in a regular service on short and regional distances.
[24] cf. Kirchhoff/Tsakaretos 2007, p. 20
[25] cf. BMVI 2013, p. 4

required. Following the analysis of Wehmeier/Koch (2010, p. 461-463)[26], the availability of passenger cars is with 86% equally high as the availability of PT stops within a 15-minute walk or a 1 km radius from the residence with 85%. The modal share of trips for motorised private transport both as drivers and passengers is, however, with 61,6% much higher than the 5% of trips taken by local PT. This difference is likely to be explained by the temporal and local constraints of public and relative freedom of individual transport[27]. According to Wehmeier/Koch (2010, p. 459 f.) 46% of the inhabitants of rural districts need more than 30 minutes to reach the next medium-level centre[28] by PT, while only 1% need the same amount of travel time using MIT.

In this context, PT cannot compete with the private car. Kirchhoff/Tsakaretos (2007, p. 20) describe thus the role of PT in rural areas as a tool to secure access to essential service facilities for PT captives[29]. They highlight the importance of its role in guaranteeing social participation for those, that out of financial or health reasons cannot drive.

As a result, rural PT has distinct target demographics. Steinrück/Küpper (2010, p. 17 f.) identify pupils and the elderly as the main users of rural PT. They further show that in many cases their demand is not fully met by classic PT in rural areas. As its main task is seen to be school transport, other transportation demands by pupils are often not served. They pointed out that this results in the paradox that PT service is low when it is needed by its main demand demographic. As young people tend to be very active on the weekends and at night when PT service is usually low or non-existent, this leads to an early feeling of car dependence. The elderly on the other hand tend to rely on services in proximity to their home. As service facilities are gradually thinned out, PT needing to compensate often fails to do so, causing the persons affected to stop their (social) activities, often without replacement.

3.1.3. Challenges from demographic change

Demographic change is bringing additional challenges to rural PT in Germany. Boehler-Baedecker et al. (2010, p. 477) describe the effects of the simultaneous aging of the population and additional losses of young workers towards urban areas due to job losses. As a result, the population declines at high rates, especially affecting rural areas in the new federal states[30] with population reductions of more than 10% expected over 20 years. Subsequently, service facilities frequently cannot be supported resulting in a thinned-out offer. PT, relying on bundling demand, is fewer used as there are increasingly fewer commuters and pupils. Elderly on the other hand are increasingly used to the private car and thus tend to stay car-reliant. Thus, demand from the increasing number of elders does not compensate for the passenger loss. To still be able to operate within budgetary

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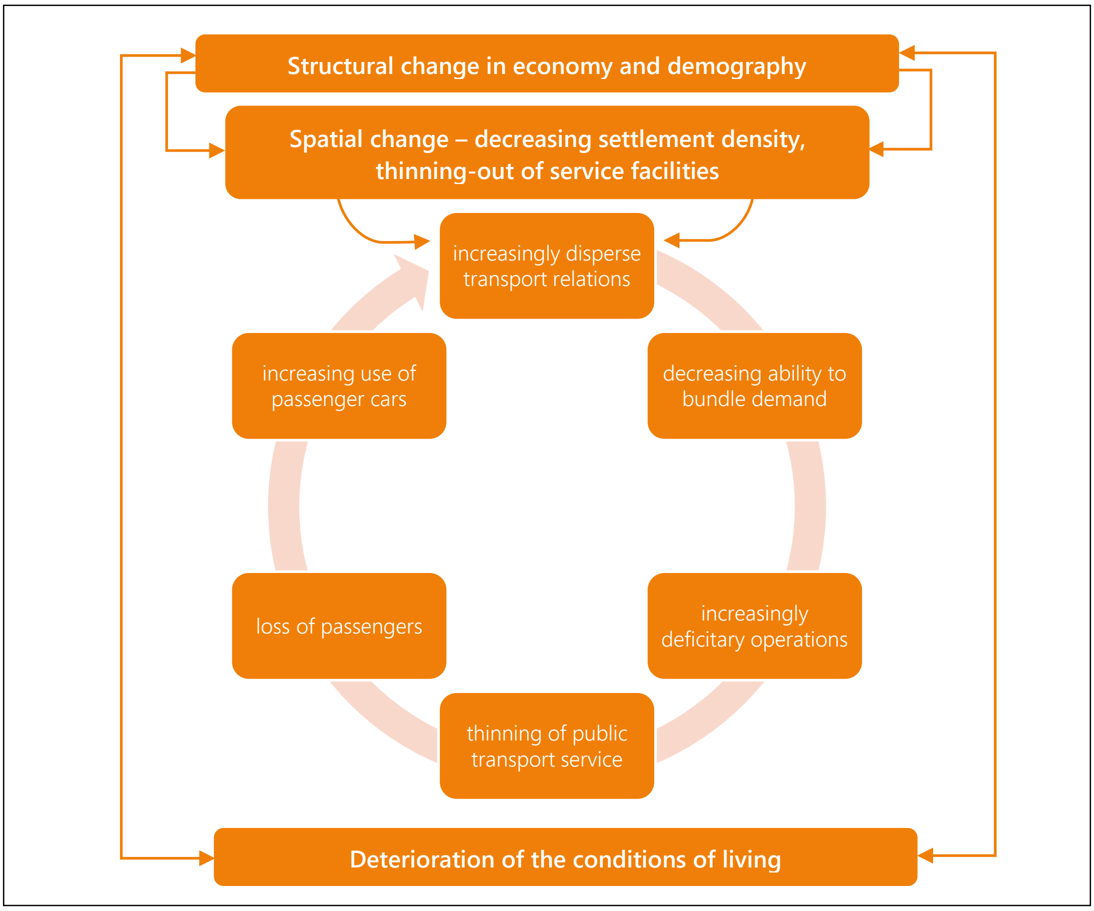
[26] Wehmeier/Koch (2010, p. 458-463) base their findings on data from a reachability study from 2009, as well as Mobilität in Deutschland 2008 (infas/DLR 2010), a deeply differentiated nationwide mobility study. These represent the latest available state and will therefore be used subsequently.
[27] cf. Reinhardt 2012, p. 565
[28] German spatial planning sets a system of central places to bundle supplies for securing the livelihoods (ROG §2 Art. 2 Ziffer 2). According to Wehmeier/Koch (2010, p. 458) it is assumed that business, employment and supplies are centred in medium- and high-level central places.
[29] Reinhardt (2012, p. 189) defines public transport captives as public transport passengers without possession or access to a car.
[30] New federal states comprise the states within the boundaries of the former GDR.

restrictions, PT agencies needs to cut some services leading to further promotion of car useage. This structural and economic change and its effects on PT are displayed in Figure 1.

Figure 1: Basic conditions for rural public transport



Own figure based on Boehler-Baedecker et al. (2010, p. 478)

To address these challenges, Boehler-Baedecker et al. (2010, p. 478) subsequently advocates for a "comprehensive regional mobility management-concept"[31] as part of an integrated transportation system.

3.2. Concepts for securing mobility in rural areas

In its study for securing supplies and mobility in rural areas in the long-term, the Federal Ministry of Transport and digital Infrastructure (BMVI 2013, p. 17) promotes a two-dimensional approach. It is based on the principle, that both the availability of essential service facilities as well as their reachability is important for securing mobility. Through intermunicipal cooperation, essential service facilities would be bundled in one town as the supply centre to the cooperation area. The reachability of this supply centre is to be guaranteed by a comprehensive mobility concept supporting the sustainability of its facilities by bundling the demand.

[31] Boehler-Baedecker et al. 2010, p. 478, own translation

3.2.1. Differentiated transport services

In its underlying mobility concept, the aforementioned BMVI study (2013, pp. 23-26) recommends a multi-layered PT network, differentiated according to its functional level, thus separating connective, secondary, and supportive services. While connective services ought to link all central places at frequent intervals and secondary services would supply centres with medium and higher-level centres on a regular schedule, the supportive services ought to supply basic local transport coverage and link the town in the cooperation area to their supply centre. For the latter network level, the study recommends a differentiation of transport offers. The usage of mobility solutions outside of PT is encouraged to satisfy demands that would not be servable by PT at reasonable expenses. Aside from those solutions, a combination of flexible and line-bound services is suggested. In those scenarios where demand cannot be bundled temporarily and locally, demand-responsive services should be implemented. Their advantage being that vehicle movement costs only occur according to the passenger demand and their advantage to cover a greater service area due to flexible routing.

3.2.2. Demand-responsive public transport

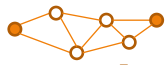
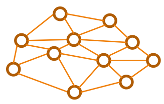
Reinhardt (2012, p. 589 f.) describes the first experiences with demand-responsive PT services in Germany. In 1978 the "Rufbus" (dial-a-bus service) was implemented in Friedrichshafen (Bodensee). It was the first exploration of its kind in Europe. The system completely abandoned a fixed timetable and relied instead on a real-time scheduling based on passengers' ride requests both spontaneous and scheduled. The system was overly successful to such extend that the system was unable to handle and barely able to bundle the demand. As a result, the system was decommissioned in 1981. The idea of a demand-responsive PT service, however, was pursued and differentiated.

Kirchhoff/Tsakaretos (2007, pp. 53-59) describes the successful exploration project *MOBINET* that was implemented around the turn of the millennium in the district of Erding (Bavaria). Different service strategies were tested including an extensive array of demand-responsive corridor lines. 18 places got new access to PT and travel times were reduced. As a result, the demand for PT increased at around 30% with new stops contributing 10%. At demand responsive covered stops, demand even increased at 50% over the course of the three-year study period, while the number of intentionally false claimed demand was negligibly low. This success caused the district to continue its operation.

The Federal Ministry of Transport, Building and Urban Development (BMVBS) (today BMVI) issued a handbook on the planning of flexible service forms in PT. The BMVBS[32] differentiates demand-responsive PT service according to its degree of spatial and temporal flexibility. Their classification of existing flexible PT offers is shown in the table below.

[32] BBR/BMVBS 2009, p.26

Table 2: Forms of demand-responsive public transport services in Germany

	Spatial flexibility			Temporal flexibility
service form indication	Line-shape		Access point	Pre-existing timetable
L-Bus	Line		Bus stop	yes
R-Bus	Corridor		Bus stop	yes
R-AST[33]	Corridor		Bus stop, Exit: doorstep	yes
F-Bus	Area		Bus stop	no
RF-Bus	Area		doorstep	no
		● regular stop, ○ stop only on demand		

Own figure based on the definitions of BBR/BMVBS (2009 pp. 26-30).

The handbook[34] recommends distinct service forms for different types of operation areas, based on its assessment of the service forms. For instance, a big service area (> 100 km²) with a low relevant[35] population density (< 100 inh./km²) is recommended to be served by an L-Bus service or with disperse settlement structures by an F- or RF-Bus.

However, the handbook[36] states that in certain cases, e.g. in the case of low demand in the given area, demand responsive PT is not capable of serving the mobility needs more economically than potentially even a taxi service. In those cases, it recommends mobility services outside of the PT frame, e.g. privately organized bus services. Inhabitants in those areas would then not be served or underserved by PT. This would imply that the livelihood of the inhabitants in those areas would soley rely on private initiatives and pro-bono work. The role of public transport to ensure social participation is not fulfilled in these areas.

[33] *Anrufsammeltaxi,* a call and collect taxi service
[34] BBR/BMVBS 2009, pp. 34-36
[35] Relevant population in this circumstance is that part of the population that is underserved by essential facilities in their surroundings and therefore has a need for displacement.
[36] BBR/BMVBS 2009, p. 67

4. New service concepts through autonomous vehicle technology in rural areas

Kirchhoff/Tsakaretos (2007, p. 20) argue, that even with the above cited improvements to rural PT efficiency, under reasonable budgetary constraints, its spatial and temporal restrictions would not make it competitive to MIT.

Given the estimation by Frank/Friedrich/Schlaich (2008, p. 22) for the conductor cost of over 40% of the total costs for classical bus line services, the savings from introducing vehicle automation to PT could be significant. Those gains could be reinvested in improving the services in previously underserved areas. Without the requirement of a conductor, smaller and cheaper vehicles in a greater number could further increase the service level.

This chapter evaluates implementation scenarios for autonomous vehicles in rural PT. For those scenarios, the availability of autonomous driving systems capable of SAE level 4 or higher is presumed. It is further assumed that the driving automation system would allow the reliable operation on public roads in a given service area, if it were restricted.

4.1. Operational scenarios

Fagnant/Kockelman (2014, p.2) expect that commercial operations of SAV systems could reject serving rural areas because it would not be economically viable. To prevent a scenario were that mobility option would only be available in areas where the demand would support commercial services, regulatory intervention could be considered. An alternative scenario would be the integration of SAV services in public transport.

Lenz/Fraedrich (2015, pp. 189-192) lay down three different operational scenarios in which rural PT would benefit from an integration of SAV services.

> In a scenario they call '**redesign of intermodality and flexibilization of public transport**', SAVs would provide a feeder service to arterial PT route stops. On the one hand, they would replace the need for private car shuttle services to the stops by family members or friends, on the other hand they could replace the local system of PT on the supportive level (following the network layer model elucidated in chapter 3.2). In this scenario, PT, apart from its arterial routes, would be served by a fleet of differently sized SAVs that would carry out a fully demand-responsive service without fixed routes or schedules (like the F- or RF-Bus service shown in Table 2). The authors emphasize the complex nature of the needed vehicle logistics resulting in particular from the requirement that a connection to the presumably scheduled arterial services should be guaranteed. As the service of local rural PT by a SAV fleet would enable nationwide comparable service levels, the authors pointed out that this would strengthen the argument for a completely publicly financed PT service.

In the scenario '**individualization of public transport**', the authors introduce to the scenario above the possibility of booking different vehicles of differentiated comfort levels (similar to the class-system in trains or airplanes today but in separate vehicles). Further, a possibility of opting-out of the DRS scheme would provide the option of a truly private mobility in a PT service. However, the authors pointed out, that a differentiation of the vehicle fleet would lead to a further increase of the logistical challenge of vehicle allocation.

The scenario '**increasing ability to provide public transport services**' emphasises the possibility of SAVs to increase not only the spatial but also the temporal density of PT services. Within a set of economic boundaries, a SAV fleet could possibly provide even continuous PT service.

The above-cited handbook on the planning of flexible service forms in PT[37] lists advantages and disadvantages of different possible operational strategies. It suggests that the omission of fixed schedules and stops might have disadvantages for the passengers. For instance, no schedules and fixed stops might increase the entry barriers to the PT system due to the unfamiliar system structure. No stations reduce the visibility of PT and might, in the case of ride-sharing, increase travel times. Furthermore, no stations would complicate the task to serve persons with reduced mobility without barriers[38] .

4.2. An autonomous minibus on-demand system for rural public transport

For this thesis' purpose, an own scenario of the integration of SAVs in rural PT is devised. It is based on the scenario "increasing ability to provide PT services" described in the previous chapter and the integrated rural mobility concept model described in chapter 3.2. Lenz/Fraedrich (2015, p. 189-192) describe in their scenario the role of SAVs in rural PT as a mode to provide shuttle services to arterial PT lines. Thereby they would fulfil the role of the supportive network layer in the integrated rural mobility concept model. In the latter model, the supportive network layer would bundle the transport demand in a supply centre, where connections to secondary or connective services would be offered. To provide public visibility and accessibility for persons with reduced mobility, fixed barrier-free accessible stops should be implemented.

An autonomous minibus on-demand system in rural PT could thus be characterized by

- Serving the local demand of a cooperation area,
- providing arrival-time oriented shuttle services to the supply centre and the local regular scheduled connective and secondary PT line stops,
- offering direct services within the cooperation area,
- operating on-demand without pre-defined call times for the passenger,
- shared rides with a guaranteed maximum deviation for all passengers of 30%,
- densely distributed barrier-free stops with accessible means of booking a ride,

[37] BBR/BMVBS 2009, p.28 f.
[38] cf. Brenck/Gipp/Nienaber 2016, p. 24

- optional door-to-door services, and
- offering continuous mobility service around the clock.

The vehicles would operate on public roads within the cooperation area as its operational design domain. For fully autonomous operations, the vehicles would be equipped with a SAE level 4 or higher driving automation system. To be able to bundle demand and accommodate larger groups while staying at a reasonable cost per unit, the vehicles would be minibuses. These vehicles should seat ten passengers while offering space for luggage, strollers, and wheelchairs, similarly to the *Mercedes Sprinter City 35*[39]. Electric propulsion would enable the omission of local pollution. To fulfil the role of PT of ensuring mobility for everyone, the vehicles would be equipped to meet the standards of barrier-free accessibility. A maintenance site and depot should be erected near the central attraction point of the served area to reduce the travel time of the vehicles to their maintenance location.

The on-demand system would ideally feature waiting vehicles at every station, so that the waiting time for passengers at stations would be eliminated. The vehicles would be approached by foot, called to the next station, or to the passenger's doorstep by an application on a connected device, by an order at a station, or by a phone call to a central operator. The vehicle call would include the information of the passenger's desired destination and the required arrival time there. The passenger would then receive a notice of the expected arrival time of the autonomous minibus.

Following the argument of Jie et al. (2010, p. 301), a scenario of vehicles waiting at every station would require a large and thus expensive fleet of vehicles, especially in the times of peak demand. They hence propose a methodology of estimating a fleet size that would optimize the total benefit of the system with a total system cost approach considering both the passengers and the operator. This methodology is used in the present thesis to obtain an optimal fleet size regarding the demand scenario. Waiting times in the stations on the proposed system should therefore be expected. With no vehicle at a station, the system would provide the passenger with an estimated waiting time for a vehicle. Ideally, the vehicle call would be made from the passenger's home so that even longer waiting times would be acceptable.

The scenario described above will be referred hereinafter to as the proposed system and it will provide the operational scenario for the feasibility and benefit assessment.

[39] cf. Mercedes Benz 2017

5. Exploration preliminary

The proposed autonomous minibus system is explored regarding its feasibility using a simulation based analysis. The simulation provides an estimation of performance level figures concerning the operator and the passengers depending on various input factors. By optimising the combined cost for the operator and the passengers over the vehicle fleet, a total cost optimum of the system can be estimated.[40] The optimized system is then subject to the feasibility and benefit evaluation.

In this chapter the input factors necessary for the simulation are discussed. A rural study area is devised and its peak hour demand matrices for three demand scenarios are estimated. The cost components for passengers and the operator for the fleet size optimization are determined and evaluation criteria for the feasibility and benefit assessment are set.

5.1. Study area

The study area is picked in the German district of Ostprignitz-Ruppin in the north-west of Brandenburg state. This district is one of 18 federal model regions for securing supplies and mobility in rural areas in a long-term perspective that are described in BMVI 2017. The project's aim is to "[…] ensure equal living conditions in rural areas"[41]. To achieve this goal, mobility concepts that integrate public service facilities, local supplies, and mobility are devised. In the short term, the project aims at implementing mobility concepts which improve the connection to the existing public service and local supplies facilities. The strategic goal is to bundle these facilities in supply centres through intercommunal cooperation as described in chapter 3.2. Such a cooperation area is picked as the study area for this thesis' analysis.

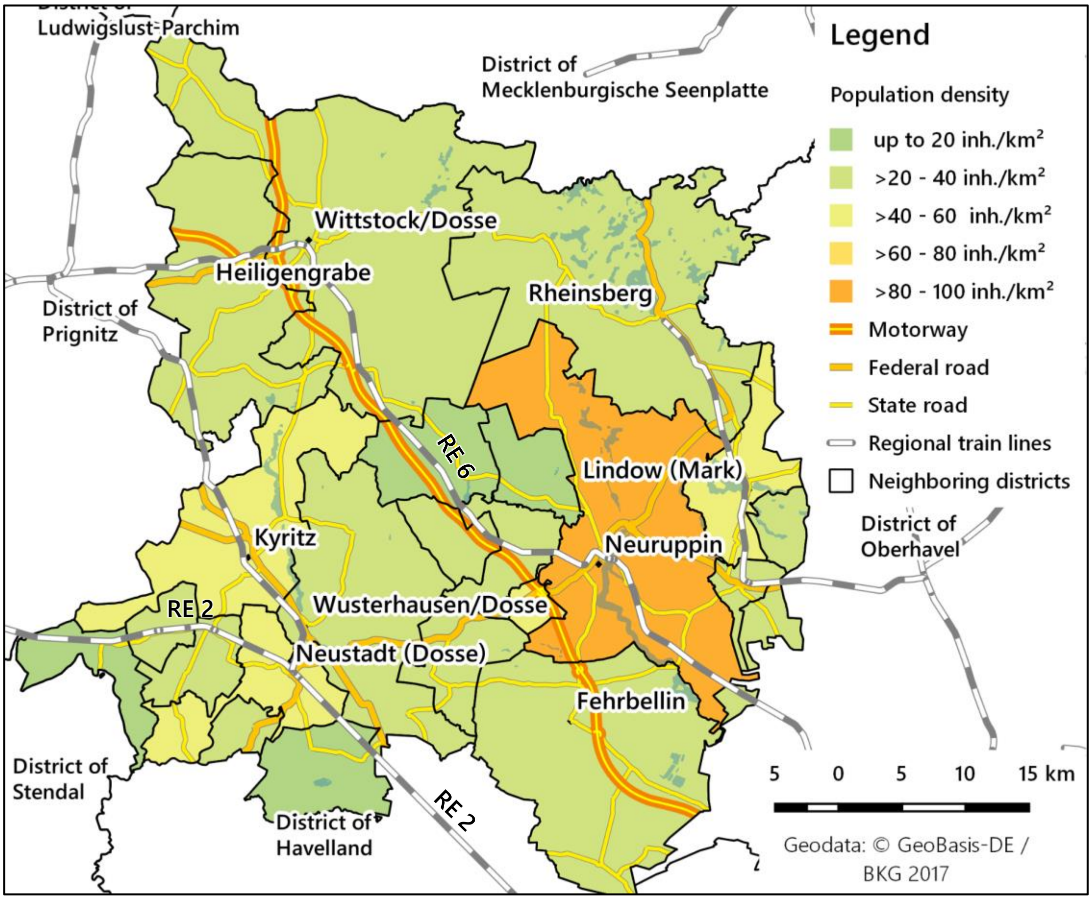
5.1.1. Study area district analysis

The district of Ostprignitz-Ruppin is located adjacent to the district of Mecklenburgische Seenplatte in the state of Mecklenburg-Vorpommern in its north, the district of Oberhavel in its east, the district of Havelland in its south, the district of Stendal in the state of Saxony-Anhalt in the south-west, and the district of Prignitz in the west. It is divided into 23 communities and its administration is located in the city of Neuruppin.[42] With 30,345 inhabitants it is the biggest city in the district followed by Wittstock/Dosse, Kyritz, and Fehrbellin.[43] The district has a surface area of around 2,500 km² and as of the 31st December 2013 a population of 98,944 inhabitants[44]. This results in a population density of about 39 inh./km² falling significantly under the BSSR limit of 150 inh./km² for the rural area definition (as described in chapter 3.1.1).

The population density in the communities as well as the main routes of transport and the neighbouring districts are depicted in the map below.

[40] cf. Jie et al. 2010, p. 304
[41] BMVI 2017
[42] LK OPR 2015, p. 19
[43] LK OPR 2015, p. 19
[44] LBV 2015 appendix 3 sheet 4

Figure 2: Population density and main routes of transport in Ostprignitz-Ruppin



Own figure, population data from 31/12/2015 by Statistische Ämter des Bundes und der Länder (2017)

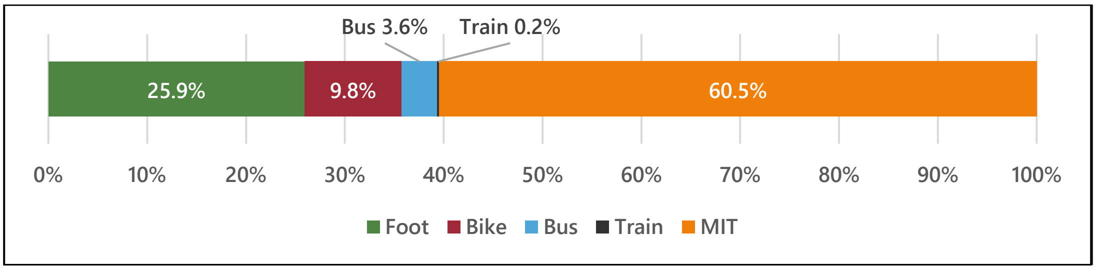
The district is served by the national motorway network in a north-west/south-east direction connecting the district to Berlin, Hamburg, and Rostock while serving as a fast route for the MIT inside Ostprignitz-Ruppin. Regional trains equally serve the district in the north-west/south-east direction. While the RE 6 (connecting Wittstock/Dosse and Neuruppin with Berlin) and the RE 2 (connecting Neustadt (Dosse) with Berlin and Wismar in the state of Mecklenburg-Vorpommern) run on a regular schedule, most other lines in the district operate on a seasonal basis or are oriented towards school transport schedules.[45]

The local public bus operator, Ostprignitz-Ruppiner Personennahverkehrsgesellschaft mbH (ORP), carried about 3.3 Million passengers in 2013.[46] Over 70% thereof have been pupils and apprentices[47] showing the importance of school transport for the local bus system. The local transportation plan[48] conceptualizes the PT network based on a layered system, differentiating between main routes, secondary routes, and supplementary routes. Main bus routes are the city bus in Neuruppin and the routes connecting the cities of Rheinsberg, Kyritz, Wusterhausen (Dosse), and Neustadt (Dosse) to Neuruppin.

[45] Based on own timetable analysis of vbb 2017a
[46] cf. LK OPR 2015, p. 44
[47] cf. LK OPR 2015, p. 46
[48] LK OPR 2015, p. 56 ff.

Using the data from the nationwide transport interconnectivity study's traffic matrix for 2010 from the Federal Ministry of Transport and Digital Infrastructure (BMVI)[49], an estimate of the modal share in Ostprignitz-Ruppin regarding the number of trips is possible. The study estimates that PT (rail and bus combined) have a share of about 3.8% of all trips. The estimated modal share is shown below.

Figure 3: Estimated modal share of annual trips in Ostprignitz-Ruppin



Own figure, data source: Intraplan Cosult 2014a

5.1.2. Study area analysis

Within the model region project, intercommunal cooperation areas have been conceptualized. Supply centres are classified into medium-sized central places (set in LEP-BB[50] being Wittstock (Dosse), Kyritz, and Neuruppin), larger supply centres, and smaller supply centres. One or more of these centres provide local supply and public service facilities for the cooperation area. The outlines of the cooperation areas in the district are shown in the appendix at A 1.

The cooperation area of Fehrbellin, Wustrau, and Linum (referred to as Fehrbellin area onwards) in the south of the district is chosen as the study area. The area is chosen because of

- its polycentric nature with one larger supply centre in the town of Fehrbellin and two smaller supply centres in Wustrau and Linum,
- its train station outside of town limits requiring a comprehensive shuttle service, and
- the potential for a strong scheduled bus route from Fehrbellin to the next medium-sized central place, Neuruppin.

The area is largely equivalent to the community of Fehrbellin, excluding the community district of Wall in the east and including the community districts of Buskow and Karwe belonging to the city community of Neuruppin. The city of Neuruppin itself is located in the north of the area. In the south, the area is limited by the borders of the district of Ostprignitz-Ruppin. Apart from the city of Neuruppin, important medium-sized central places[51] around the area are Kremmen to the east of the district and Nauen, situated in the south.

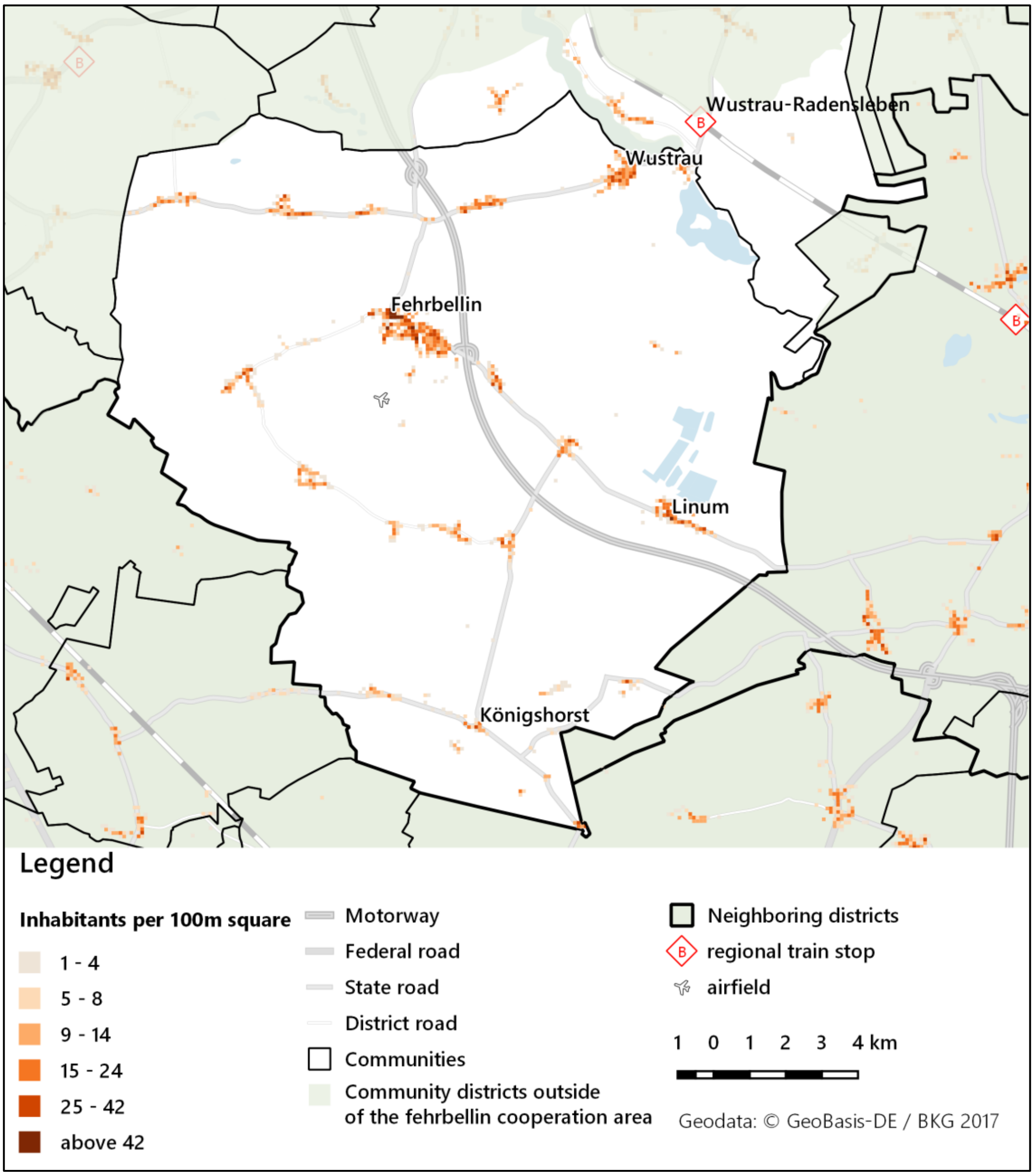
In 2011 the Fehrbellin area as shown in Figure 4 had a population of 9,146 inhabitants, 2,627 of which were living in the town of Fehrbellin. The towns with a population above 500 inhabitants

[49] Intraplan Consult 2014a
[50] Landesentwicklungsplan Berlin - Brandenburg (Gemeinsame Landesplanungsabteilung Berlin-Brandenburg 2017)
[51] cf. Gemeinsame Landesplanungsabteilung Berlin-Brandenburg 2017

are, apart from Fehrbellin, the two smaller supply centres Wustrau and Linum. The remaining inhabitants reside mainly along a linear east-west settlement band in the north of Fehrbellin and scattered in the south part of the area.

The Fehrbellin area is crossed by the A24 motorway with two access points north and south of the town of Fehrbellin offering fast connections to the MIT in north-west and south-easterly directions. Smaller state and community roads provide the access to the state roads in the area.

Figure 4: Population in 2011 and road network of the Fehrbellin cooperation area



Own figure, population data soure: Census 2011[52]

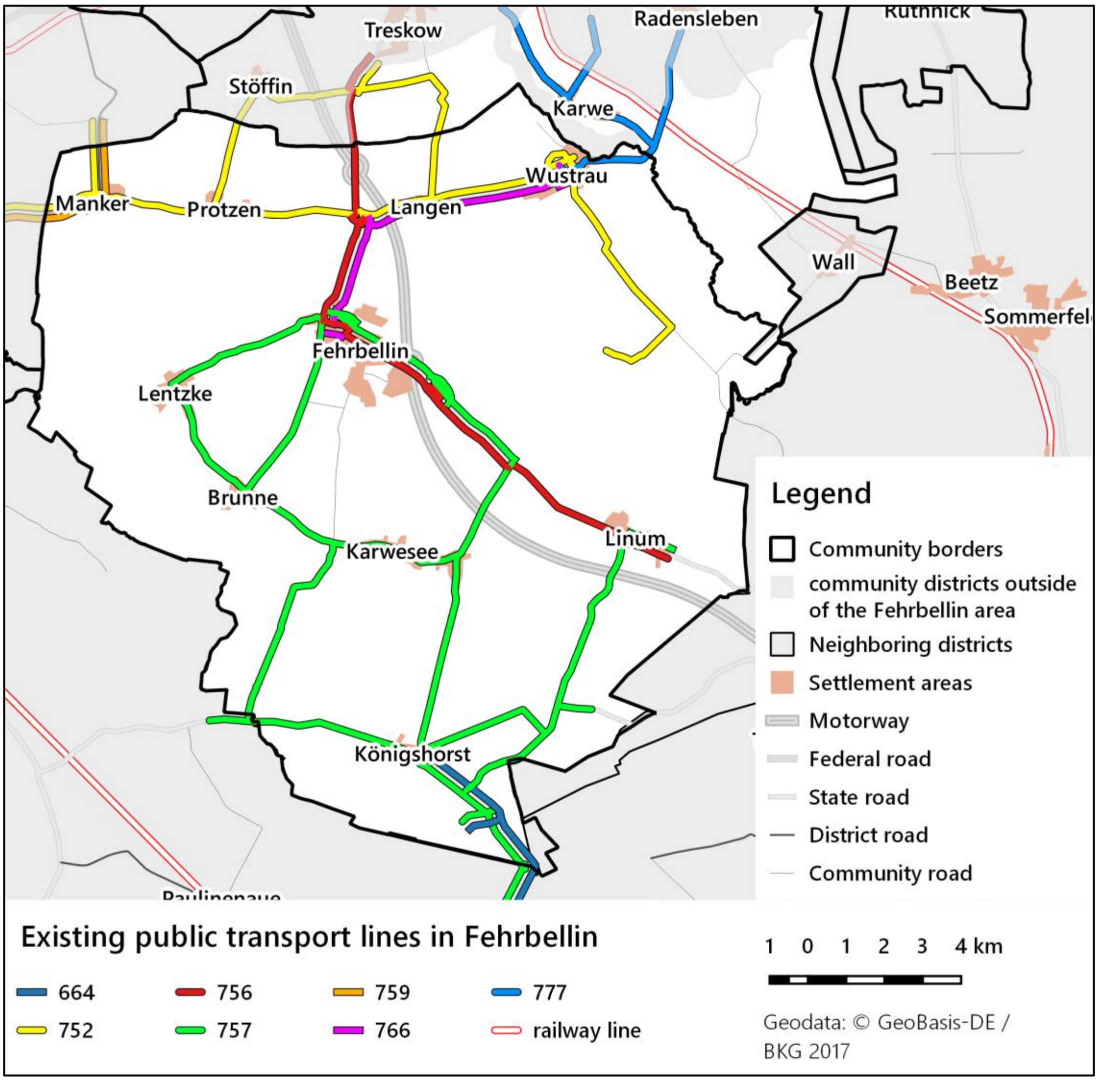
The railway stop Wustrau-Radensleben at the north-east border of the area is served by every second train of the regional train line RE 6. The line serves the station with every second train of

[52] Statistische Ämter des Bundes und der Länder 2014

its hourly service.[53] It connects the area in about an hour to Berlin and serves several different medium sized central places of the region.

Except for the railway stop at the north-east limit of the area, PT services in the area is provided by bus services. In the local transportation plan's network conception[54], the area is served by a secondary route connecting the city of Fehrbellin to Neuruppin and by supportive routes. The local transportation plan sets minimum requirements for the operating hours of the network levels. The secondary route ought to operate Monday to Friday once every two hours from 6 am to 6 pm. The supplementary routes ought to be served Monday to Friday at least twice per direction on school holidays and three times per direction on school days.

Figure 5: Existing public transport services in the Fehrbellin cooperation area



Own figure, line data based on own timetable analysis of vbb (2017a)

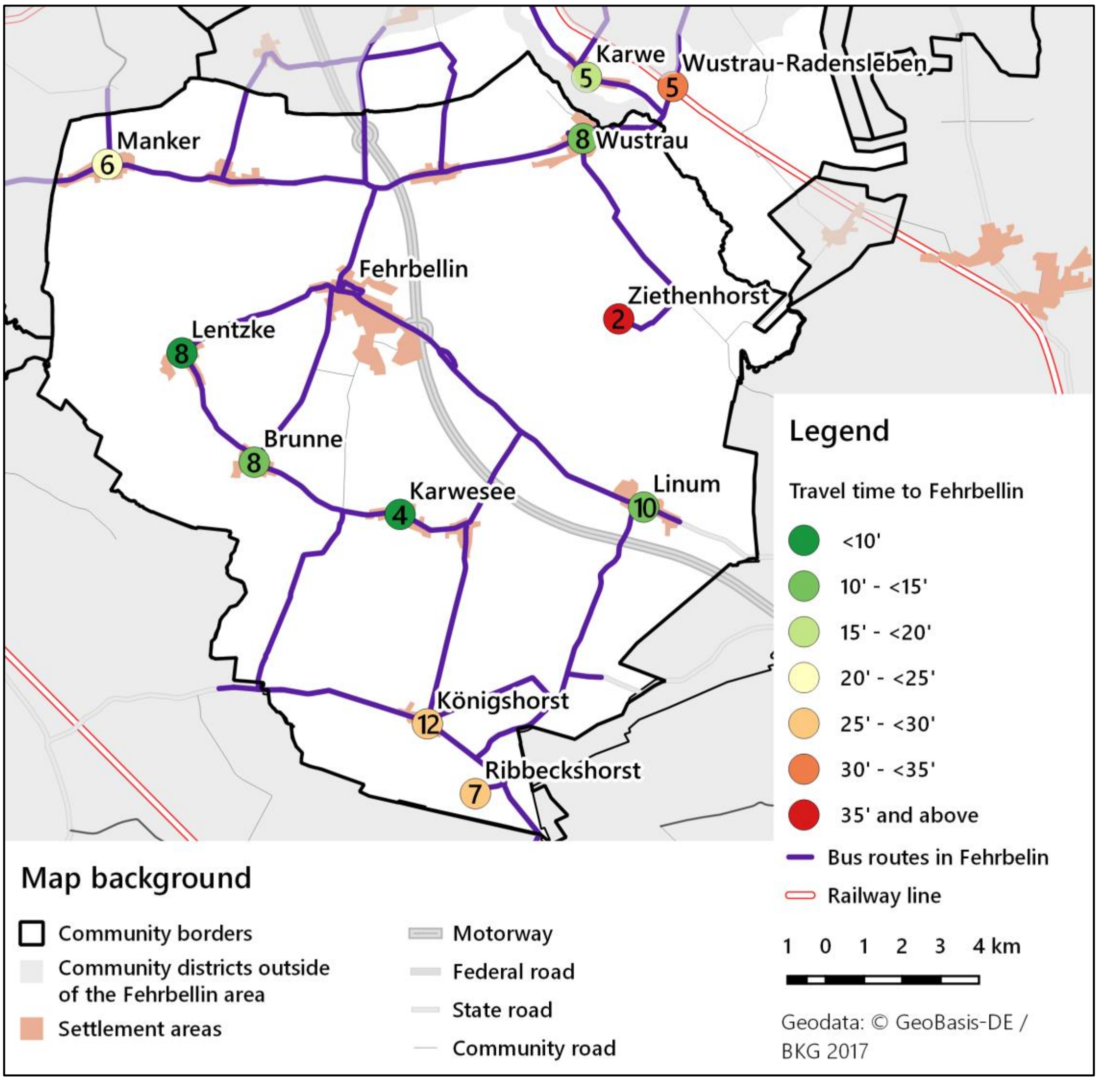
The area is currently served by the bus lines shown in Figure 5. An analysis of the timetables[55] shows that six of the seven lines do not run on regular intervals and are mainly optimized for school transport. There is repeatedly low to no overlap between line missions on one line leading

[53] Based on own timetable analysis of vbb 2017a
[54] LK OPR 2015, p. 56 ff.
[55] analysis of ORP 2017

to complicated timetables. Service gaps between 9 and 12 am as well as in the evening occur regularly. Parts of line trips are frequently served for disembarking passengers only. Several scheduled trips are call-a-bus services to be called 90 minutes in advance and/or carried out by non-fully-accessible line taxis. Weekend service is only found on the line 756 between Fehrbellin and Neuruppin on Saturdays. On Weekdays this section is served every hour between around 6 am and 7 pm.

Travel times with the current PT system between the big supply centre Fehrbellin and select towns in the study area, as well as the train station are analysed for the 6th December 2017 and displayed in Figure 6.

Figure 6: Connection analysis of local public transport towards the big supply centre Fehrbellin on a weekday (minimum travel time and number of connections)



Own figure based on analysis of the 06/12/2017 timetable. Number of daily connections towards Fehrbellin under one hour of travel time in the circles (colour in the circle represents the minimum travel time); timetable data source: vbb (2017b)

While most of the analyzed stations have a reasonably high number of of connections towards Fehrbellin compared to the minimum standards embedded in the local transportation plan,[56] service gaps and complex timetable structures characterise the PT in the area. Furthermore, the obtained minimum travel times frequently do not represent the average travel times as they can be extremely varying. The railway station Wustrau-Radensleben, offering direct trains to Berlin, is poorly connected to the area. On Sundays, the area is currently not served by PT.

A potential for an attractively scheduled bus route can be identified in connecting the two medium-sized central places Neuruppin and Nauen via Fehrbellin and Linum. Such a line is presumed to be in existence in the scenario for the exploration. With the proposed system being a comprehensive shuttle service to the train station Wustrau-Radensleben, the necessary demand should be generated to let every train stop at that station.

This would create central transfer points from the proposed system to the schedules regional train- and bus services at Wustrau-Radensleben, Fehrbellin, and Linum.

5.2. Travel demand assumption

To simulate the operation of the proposed autonomous minibus system, a system demand must be determined. The used simulation software PRTsim simulates a constant demand over a given exploration time based on an OD demand matrix in trips per hour. To determine the optimal fleet size, the system's operation is explored at its peak demand hour. The demand is estimated for Fehrbellin area internal trips, as well as incoming, and outgoing traffic.

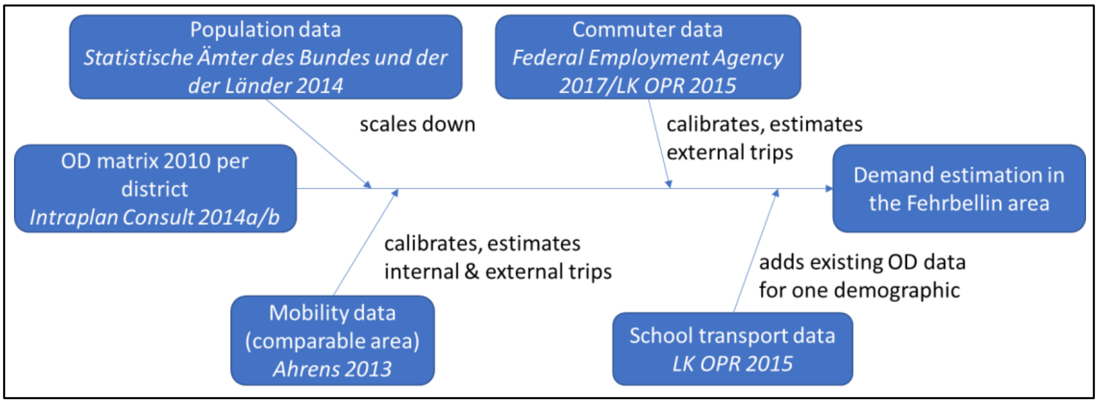
This transport demand matrix is estimated based on:

- Census 2011[57] population data per 100x100 m quadrant (visualized in Figure 4),
- commuter data for the Fehrbellin community from the Federal Employment Agency[58],
- school transport and additional commuter data from the Ostprignitz-Ruppin local transportation plan[59],
- the nationwide transport interconnectivity study's baseline 2010 annual trip matrix from the BMVI[60], and
- the SrV Mobilität in Städten mobility study[61].

This estimation is done for the simulation and is not based on a transport model. It is obtained by scaling secondary data of different years and is not validated by traffic counts. The used heuristic method of generating the transport demand matrix for the peak hour is subject of this chapter. The figures are calculated in the Microsoft Excel calculation table *demand estimation.xlsx* and can be found in the digital attachment to this thesis.

[56] cf. LK OPR 2015, p. 59
[57] Nationwide Census from 2011: Statistische Ämter des Bundes und der Länder 2014
[58] Federal Employment Agency 2017
[59] LK OPR 2015
[60] Intraplan Consult 2014a
[61] Ahrens 2016

Figure 7: Process of the demand estimation for the study area with data sources

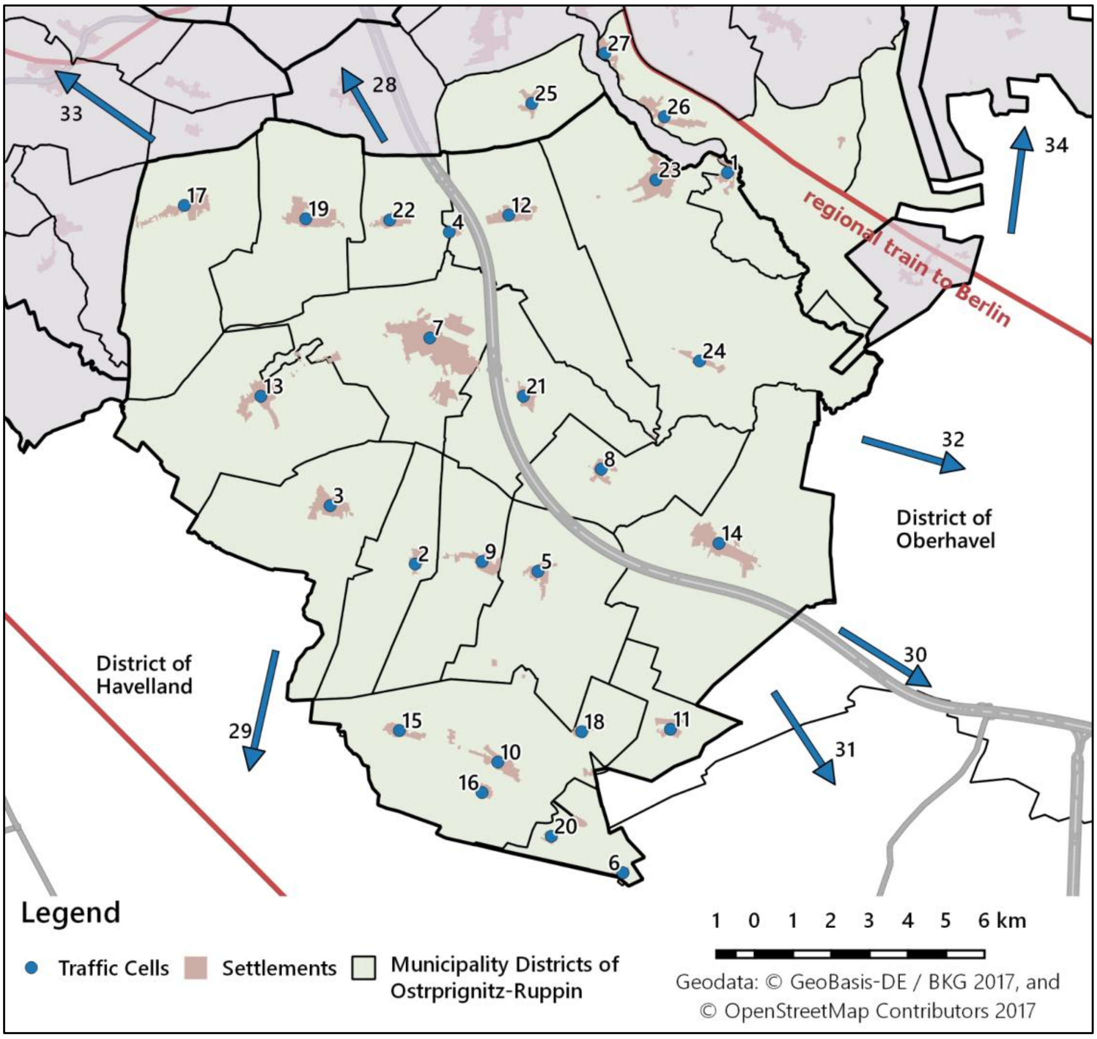


Own figure, data sources displayed in italic letters

5.2.1. Traffic cells

27 traffic cells were devised in the Fehrbellin cooperation area as well as seven additional traffic cells around the study area. The location and properties of the cells are shown in Figure 8.

Figure 8: Map of the traffic cells for the demand estimation matrix



Own figure, description of the numbers in Table 3

Table 3: Traffic cells for the demand estimation matrix

id	name	population	id	name	populaion
1	Altfriesack	201	18	Nordhof	97
2	Betzin	116	19	Protzen	432
3	Brunne	320	20	Ribbeckshorst	65
4	Dammkrug	41	21	Tarmow	290
5	Dechtow	241	22	Walchow	190
6	Dreibrück	121	23	Wustrau	883
7	Fehrbellin	2,627	24	Ziethenhorst	51
8	Hakenberg	264	25	Buskow	214
9	Karwesee	238	26	Karwe	348
10	Königshorst	162	27	Seehof	67
11	Kuhhorst	101	28	remaining Ostprignitz-Ruppin district [Neuruppin]	
12	Langen	448	29	district of Havelland [Nauen]	
13	Lentzke	391	30	city of Berlin [Zoo station]	
14	Linum	697	31	city of Potsdam	
15	Lobeofsund	182	32	district of Oberhavel [Kremmen]	
16	Mangelshorst	48	33	district of Prignitz [Pritzwalk]	
17	Manker	311	34	Former district of Müritz [Röbel/Müritz]	

Own figure, population data based on the Census 2011[62] 100m grid;
In brackets: target point for distance estimation, if not given: town centre.

The traffic cells in the area are set based on own analysis of the settlement areas and the community districts. Outside of the Fehrbellin area the cells represent the surrounding and additional traffic cells from the national mobility study[63] and the remaining part of the district of Ostprignitz-Ruppin.

5.2.2. Non-school-transport demand estimation

Comprehensive mobility figures are not available for the study area. However, the SrV Mobilität in Städten mobility study[64] delivers mobility data for an area that is comparable to the Fehrbellin area. This area, the local authority association[65] of Beetzendorf-Diesdorf, is situated in the north of the state of Saxony-Anhalt. Geographical analysis[66] of the areas shows a similar settlement structure. Both areas have some larger towns and near-by central places outside of the area.

While Beetzendorf-Diesdorf has a larger area and population than the Fehrbellin area, it has a lower population density. For this estimation it is presumed that the traffic behaviour in both areas is equal. A numeric comparison of the areas is shown in Table 4.

[62] Statistische Ämter des Bundes und der Länder 2014
[63] Intraplan Consult 2014a
[64] Ahrens 2016
[65] Own translation of "Verbandsgemeinde"
[66] Based on Geodata by Geobasis-DE / BKG 2017

Table 4: Comparison of Beetzendorf-Diesdorf and the Fehrbellin area

criteria	Beetzendorf-Diesdorf	Fehrbellin area
population	13,819	9,146
area in km²	535	275
Population density in inh./ km²	25.8	33.3

Own figure based on data from Beetzendorf-Diesdorf (2017) and own calculations based on Statistische Ämter des Bundes und der Länder (2014)

The SrV mobility study[67] estimates the peak hours and the trip volume share of the trips on a working day[68] in the peak hours for Beetzendorf-Diesdorf. The peak hours occur in the morning between 7:01 am to 8 am and in the afternoon between 4:01pm to 5 pm. The morning peak hour comprises $w_{BD}^{peak} = 10\%$ and the afternoon peak 10.7% of the total weekday trips. The trip amount per inhabitant on a working day in Beetzendorf-Diesdorf is stated in the study as $t_{BD}^{wd} = 3.4$ trips. Of those trips, $t_{int\,BD}^{wd} = 1.7$ have their destination inside the local authority association.

Although the afternoon peak in Beetzendorf-Diesdorf is higher, it is presumed that the school transport traffic peak is higher in the morning as schools start at a similar time. Given the significant share of school transport passengers of all PT passengers (as shown in 5.1.1), it can thus be presumed that the morning peak is the peak hour of demand for PT. Therefore, a demand matrix for the morning peak hour is devised.

The national mobility study for the BMVI[69] estimates the nationwide traffic for different modes and trip purposes based on traffic cells that are, in Germany, equivalent to the districts. The study encompasses two traffic matrices. It makes a prediction for the national traffic levels in 2030 for the national transport plan and, to calibrate the variables in the methodology, a trip matrix for the year 2010 is generated.[70] The latter matrix is used for the demand estimation on the system in the Fehrbellin area.

The 2010 trip matrix is filtered regarding the MIT commuter trip volume from Ostprignitz-Ruppin. Traffic cells with an attraction of less than 100,000 annual MIT commuting trips are not taken into the demand estimation to reduce complexity. As the trip matrix is symmetrical, outgoing and incoming traffic are the same for each origin-destination (OD) relation.

From the resulting simplified matrix, the following values are obtained:

- $v_{OPR,l}^{a}$ describes the total annual traffic volume from the district of Ostrprignitz-Ruppin to the traffic cell l,
- $\mathrm{v}_{\mathrm{OPR},l}^{a,PT}$ describes the annual PT (train and bus) trip volume from the district of Ostrprignitz-Ruppin to traffic cell l, and

[67] Ahrens 2016, Tab 1 (d), Tab 2(e)
[68] hereby subsequently defined as a typical day of Monday to Friday
[69] Intraplan Consult 2014a
[70] cf. Intraplan Consult 2014b, p.

- $v_{OPR,l}^{a,edu,PT}$ describes the annual educational trip volume on PT from the district of Ostrprignitz-Ruppin to traffic cell l

With the traffic cells $l \in \{B; P; HVL; OHV; OPR; PR; MÜR\}$[71].

The above values are scaled down by the population ratio of the district and the Fehrbellin area P_{Fb}/P_{OPR} and the ratio of the travel disutility measured in MIT trip duration[72] $U_{OPR,l}/U_{Fb,l}$ between the traffic cells and the district of Ostprignitz-Ruppin and the Fehrbellin area respectively. This process can be explained by the term $\left(\frac{U_{OPR,l}}{U_{Fb,l}}\right)^{k_r} \cdot \frac{P_{Fb}}{P_{OPR}}$ with l denoting the traffic cells as above and $k_r = 3$ the disutility exponent following the scaling principle for disutility variables of Intraplan Consult (2014b p. 59, eq. (3)).

Combining the data from the SrV study and scaled down district data from the national mobility study, the originating peak hour traffic volume in the Fehrbellin area is estimated as shown in equation (eq.) (1). This step is based on the presumption that the population in Ostprignitz-Ruppin is homogenous regarding their mobility patterns and that mobility patterns in the Fehrbellin area are the same as in Beetzendorf-Siersdorf.

(1) $$O_{Fb} = \sum_l \left(v_{OPR,l}^{a} \cdot \left(\frac{U_{OPR,l}}{U_{Fb,l}}\right)^{k_r} \cdot \frac{P_{Fb}}{P_{OPR}} \cdot \rho_{all}^{peak} \right)$$

The resulting value O_{Fb} denotes the number of trips in the morning peak hour. The ratio ρ_{all}^{peak} describes as shown in eq. (2) the trips per inhabitant in the peak hour on week days (obtained from the SrV study) per mean trips per inhabitant and year. The remaining necessary values are obtained from the SrV study as shown above and from the national mobility study Mobilität in Deutschland[73]. From the latter source the value of average trips per person on a mean day in Germany ($t_{MiD}^{md} = 3.4$)[74] and the average trips per person on a week day in Germany ($t_{MiD}^{wd} = 3.7$)[75] is gained.

(2) $$\rho_{all}^{peak} = \frac{w_{BD}^{peak} \cdot t_{BD}^{wd}}{t_{BD}^{wd} \cdot \frac{t_{MiD}^{md}}{t_{MiD}^{wd}} \cdot 365{,}25}$$

This originating traffic volume is allocated to the traffic cells inside the Fehrbellin area ($i \leq 27$) by their population ($p_i^{pop} = P_i/P_{Fb}$, values of P_i as in Table 3, and P_{Fb} denoting the population in the Fehrbellin area). This step is based on the presumption that the population in the cells $i \leq 27$ is homogeneous regarding their originating traffic volume.

[71] B: city of Berlin, P: city of Potsdam, HVL: district of Havelland, OHV: district of Oberhavelland, OPR: district of Ostprignitz-Ruppin, PR: district of Prignitz, and MÜR: former district of Müritz
[72] Obtained in Google Maps (Google 2017), figures in the appendix at A 3
[73] infas/DLR 2010
[74] infas/DLR 2010 p. 23
[75] Fraction of the sum of the number of weekday trips (from infas/DLR 2010 p. 143) devided by the population of Germany and the number of weekdays.

Combining the total originating traffic in the morning peak hour from the Fehrbellin area (O_{Fb}) with the ratio of the trip amount per inhabitant and working day in Beetzendorf-Siersdorf with a destination outside the area ($1 - t_{int\,BD}^{wd}$) and the total trip amount per inhabitant and weekday in the area (t_{BD}^{wd}), the commuter volume in the morning peak hour from the Fehrbellin area

(3) $$C_{-Fb}^{BMVI} = \frac{1-t_{int\,BD}^{wd}}{t_{BD}^{wd}} \cdot O_{Fb}$$

can be estimated.

The originating traffic estimate of the remaining cells outside of the Fehrbellin area considers only the trips that have their destination inside the Fehrbellin area. The total traffic volume of all non-Fehrbellin area traffic cells is estimated using the total commuter volume[76] on a weekday to the community of Fehrbellin (C_{Fb}^{BA}) in 2016, obtained from the federal employment agency [77], scaled by

(4) $$r^{commuters} = \frac{C_{-Fb}^{BMVI}}{C_{-Fb}^{BA}}.$$

In eq. (4) $\mathrm{C}_{-\mathrm{Fb}}^{\mathrm{BA}}$ denotes the total commuter volume from the community of Fehrbellin in 2016, obtained from the federal employment agency [78], C_{-Fb}^{BMVI} is taken from eq. (3) above. This scaling is based on the presumption that not all commutes are taken in the peak hour and corrects for the different areal reference.

The local transportation plan of Ostprignitz-Ruppin[79] provides commuter data from the federal employment agency for the community of Fehrbellin. This data is used where available as $O_i^{commuters}$ for $i > 28$ and is scaled by $r^{commuters}$ as above. Where this data is not available, the data from the national interconnectivity study is scaled as in eq. (5) to

(5) $$v_{Fb,i}^{peak} = v_{OPR,l}^{a} \cdot \left(\frac{U_{OPR,l}}{U_{Fb,l}}\right)^{k_r} \cdot \frac{P_{Fb}}{P_{OPR}} \cdot \rho_{all}^{peak}$$ (with l matching the traffic cell i).

The originating traffic from the remaining areas of the Ostprignitz-Ruppin district (traffic cell $i = 28$) is set to the remaining originating traffic volume of all non-Fehrbellin area traffic cells.

The estimate for the total originating traffic O_i^* per traffic cell is generated as shown in the following equation.

[76] Data from the Federal employment agency and the local transportation plan encompasses only employees who are subject to mandatory social insurance contributions,
[77] Federal Employment Agency 2017, table sheet Fehrbellin
[78] Federal Employment Agency 2017, table sheet Fehrbellin
[79] LK OPR 2015, pp. 24-27

(6)
$$O_i^* = \begin{cases} O_{Fb} \cdot p_i^{pop}, i \leq 27 \\ C_{Fb}^{BA} \cdot r^{commuters} - \sum_{i=29}^{34} O_i^*, i = 28 \\ O_i^{commuters} \cdot r^{commuters}, i > 28 \land O_i^{commuters} \neq null \\ v_{Fb,i}^{peak}, i > 28 \land O_i^{commuters} = null \end{cases}$$

The total traffic attraction of the traffic cells inside of the Fehrbellin area D_{Fb} is estimated by the sum of the non-outgoing traffic volume originating in the Fehrbellin area ($O_{Fb} - C_{-Fb}^{BMVI}$ as in eq. (1) and eq. (3) respectively) and the originating traffic volume outside of the Fehrbellin area ($C_{Fb}^{BA} \cdot r^{commuters}$ as above and in eq. (4)):

(7)
$$D_{Fb} = O_{Fb} - C_{-Fb}^{BMVI} + C_{Fb}^{BA} \cdot r^{commuters}$$

The total traffic attraction of the Fehrbellin area is allocated to its traffic cells ($i \leq 27$) by the weight p_i^{attr}. It considers the population P_i of the cells as well as a factor for the added attraction of the supply centres in the cooperation area ($c_s, s \in \{big, small\}$) following the additional weighting of central places in the national interconnectivity study[80] as following. The weights are heuristically set at $c_{big} = 5{,}000$ and $c_{small} = 2{,}000$ respectively.

(8)
$$p_i^{attr} = \begin{cases} \frac{P_i + c_{big}}{c_{big} + 2c_{small} + P_{Fb}}, i = 7 \\ \frac{P_i + c_{small}}{c_{big} + 2c_{small} + P_{Fb}}, i = 14 \land i = 23 \\ \frac{P_i + c_{big}}{c_{big} + 2c_{small} + P_{Fb}}, else \end{cases}$$

The traffic attraction for the traffic cells outside of the Fehrbellin area is similarly estimated as their originating traffic. The estimate only considers attraction on traffic originating from the Fehrbellin area. The total traffic attraction volume of all non-Fehrbellin area traffic cells is estimated using the total commuter volume on a weekday originating in the community of Fehrbellin (C_{-Fb}^{BA}) in 2016, obtained from the federal employment agency[81], scaled by $r^{commuters}$ as above.

Where available commuter data from the local transportation plan $D_i^{commuters}$ is taken and scaled with $r^{commuters}$. Traffic attraction in cells without this data available is estimated by the scaled values obtained from the national interconnectivity study $v_{Fb,i}^{peak}$ as above. The traffic attraction of the remaining areas of the Ostprignitz-Ruppin district (traffic cell $i = 28$) is set to the remaining traffic attraction volume of all non-Fehrbellin area traffic cells.

The estimate for the total traffic attraction D_i^* per traffic cell is generated as shown in the following equation

[80] Intraplan consult 2015, p. 60 f.
[81] Federal Employment Agency 2017, table sheet Fehrbellin

(9)
$$D_i^* = \begin{cases} D_{Fb} \cdot p_i^{attr}, i \leq 27 \\ C_{-Fb}^{BA} \cdot r^{commuters} - \sum_{i=29}^{34} D_i^* \ , i = 28 \\ D_i^{commuters} \cdot r^{commuters}, i > 28 \ \wedge D_i^{commuters} \neq null \\ v_{Fb,i}^{peak}, i > 28 \ \wedge D_i^{commuters} = null \ . \end{cases}$$

As shown in chapter 5.1.1, school transport has a significant share in current PT demand in the district of Ostprignitz-Ruppin. A school transport OD-matrix of pupils entitled to public school transport can be obtained out of the provided graphics in the local transportation plan of the district[82]. The number of school-transport entitled pupils for each origin-destination pair is given in various ranges. Based on the presumption of an equal distribution of the trip numbers in the ranges, the average value in the given range of values is taken to estimate the trip numbers. The obtained school trip OD estimation matrix is displayed in the appendix A 4.

To obtain an estimation for the non-school transport traffic, the school transport trips (O_i^{pupils} for the originating school transport trips in cell i and D_j^{pupils} for school transport trips with their destination in cell j) are subtracted from the cells originating traffic and their traffic attraction respectively:

(10)
$$O_i = O_i^* - O_i^{pupils}$$

(11)
$$D_j = D_i^* - D_j^{pupils} \text{ (with traffic cell } i \text{ matching } j\text{)}$$

The trip distribution is obtained with the gravitational traffic distribution model that Intraplan Consult use in the national interconnectivity study[83]. A first trip estimation between cell i and j, $\left(T_{ij}\right)_0$ is described in eq. (12).

(12)
$$\left(T_{ij}\right)_0 = O_i \cdot \frac{D_j \cdot U_{ij}^k}{\sum_j \left(D_j \cdot U_{ij}^k\right)}$$

The disutility of trips between cells i and j (U_{ij}) is measured as the travel time by MIT[84] between the traffic cells. The travel time within the cells is estimated as the time to travel half of the diameter of the built-up area in the traffic cell. The disutility between the traffic cells outside of the Fehrbellin area was set to 1,000 to prevent trips solely outside of the Fehrbellin area. Those trips are not subject of this estimation and the originating traffic and the traffic attraction estimates in the cells outside of the Fehrbellin area are adapted accordingly (as described above). The disutility exponent was set to $k = -3$ like $-k_r$ in eq. (1) approximating a mean value used in Intraplan Consult (2014b, p. 60).

[82] LK OPR 2015, pp. 112-116
[83] Intraplan Consult 2014b, p. 59, eq. (3)
[84] obtained from Google maps (Google 2017), figures displayed in the appendix at A 3

The resulting matrix is scaled by the Furness-Algorithm (eq. (13)). After seven iterations, a sufficient equality[85] is obtained between the matrix row and O_i and the column sums and D_j respectively:

(13)
$$\left(T_{ij}\right)_n = \begin{cases} \left(T_{ij}\right)_{n-1} \cdot \frac{\Sigma_i \left(T_{ij}\right)_{n-1}}{O_i}, \frac{n}{2} \notin \mathbb{N} \\ \left(T_{ij}\right)_{n-1} \cdot \frac{\Sigma_j \left(T_{ij}\right)_{n-1}}{D_j}, \frac{n}{2} \in \mathbb{N} . \end{cases}$$

5.2.3. Demand scenarios

Future passenger demand is uncertain. Thus, to assess the feasibility of a new system, different realistic demand scenarios should be studied. The used scenarios s are:

- *Scenario 0* ($s = 0$): The introduction of the new system does not change the traffic demand on PT.
- *Scenario call-a-bus* ($s = cb$): PT demand in the Fehrbellin area reacts similar to the demand development observed in the MOBINET study described in 3.2.2 with the introduction of call-a-bus services.
- *Scenario public transport* ($s = pt$): The high level of service triggers a PT modal share that is comparable to PT shares in urban centres.

The scenarios are outlined in more detail below.

The used peak hour demand matrices combine the school transport and non-school transport demand matrices for each demand scenario as described in the following equation.

(14)
$$T_{ij}^s = \left(T_{ij}\right)_7 \cdot \sigma^s + T_{ij}^{pupils} \cdot \varphi^s$$

In eq. (14) $\left(T_{ij}\right)_7$ denotes the estimated value for non-school-transport trips between cells i and j in all modes as obtained from eq. (13), σ^s is the modal share of the system among all trips in scenario s, T_{ij}^{pupils} are the morning peak trips of pupils entitled to school transportation (estimated from school transport data in the local transportation plan[86]), and φ^s represents the share of trips entitled to school transportation taken on the system in scenario s. The modal share is applied to all OD-relations equally. The scenario dependent modal share variables σ^s and φ^s are set as explained below and shown in Table 5.

Scenario 0

The existing PT trip share (bus and train combined) in the district of Ostprignitz-Ruppin can be estimated as shown in chapter 5.1.1 to be at 3,8% of all trips. However, σ^0 is set as 5,1% which represents the estimated PT modal share excluding pedestrian trips on the

[85] ratio rounded to one decimal digit equals one
[86] LK OPR 2015, pp. 112-116, estimate in the appendix at A 4

same base data. This is done to prevent an overestimation of long pedestrian trips. The simulated network will be designed in a way that excludes pedestrian trips in the given OD-matrix.

The estimation of φ^0 is obtained by the fraction of the district educational trips in PT scaled down to the Fehrbellin area and the amount of annual school trips entitled to school transport as shown in eq. (15).

(15) $$\varphi^0 = \frac{\frac{P_{Fb}}{P_{OPR}} \cdot \left(\sum_l v_{OPR,l}^{a,edu,PT}\right)}{2 \cdot sd^a \cdot \sum_{ij} T_{ij}^{pupils}}$$

In eq. (15), P_{Fb}, P_{OPR}, and T_{ij}^{pupils} are as described above eq. (1) and after eq. (14) respectively. The variable $v_{OPR,l}^{a,edu,PT}$ describes the annual educational trip volume on PT from Ostrprignitz-Ruppin to traffic cell l (as described above) and sd^a represents the number of school days per year[87].

Scenario call-a-bus

As presented in 3.2.2, ridership volume in the district of Erding increased by 50% after the introduction of call-a-bus services. This example is not fully applicable in the Fehrbellin area, as call-a-bus-services to some extend are already in place. However, these services are not frequent and there are large service gaps in the service hours. It is though presumed that the introduction of an around-the-clock available on-demand service would have a similar impact as the introduction of the call-a-bus service in the district of Erding.

Thus, the PT modal share of school-transport and non-school-transport trips is scaled up by the factor 1.5 in relation to the *scenario 0* values.

Scenario public transport

This scenario is based on the presumption that autonomous vehicle technology enables the nationwide introduction of high quality PT services that can be compared to the PT service levels currently found in urban centres. The modal share for non-school transport trips is thus set at the modal share value among all trips that is currently found in the city of Berlin[88]. Traffic survey data from the SrV Mobilität in Städten mobility study estimates the modal share of PT among all taken trips at 26.9%[89], thus σ^{pt} is set as that value.

It is further presumed that more pupils entitled to school transport take a trip on the system than in the previous scenario. The value φ^{pt} is set at 80% considering that some

[87] used value: $sd^a = 189$ own calculation based on analysis of school holidays in Brandenburg State on MBJS (n.d.) for the year 2017
[88] Presumption: The high public transport modal share in Berlin correspondents with a high level of service that would be matched by the introduction of the proposed system.
[89] Ahrens 2016, Tab 11 (a)

pupils will still get to school on other modes of transport (e.g. brought to school by their parents on their way to work).

Table 5: Public transport modal share of school-transport and non-school-transport trips per scenario

scenario s	σ^s	φ^s
0	5.1%	47.6%
call-a-bus (cb)	7.6%	71.3%
public transport (pt)	26.9%	80%

Own figure, values obtained as explained above

The resulting demand matrices are displayed in the appendix at A 5.

5.3. General cost component assumption

The simulation aims to optimize the number of vehicles in the proposed system's fleet by finding the global minimum of the generalized cost for the users and the operator over the fleet size. Thus, the global minimum of the following function of the annual total costs for the users C^a_{user} and the operator $C^a_{operator}$ over the fleet size v shall be minimized.

$$C^a_{total}(v) = C^a_{user}(v) + C^a_{operator}(v) \quad (16)$$

The calculation follows the case study on the fleet size optimization of a Personal Rapid Transit system in the port of Rotterdam by Jie et al. (2010, p. 304 f.) and is executed in the Microsoft Excel calculation table *fleet size optimization.xlsx* which can be found in the digital attachment to this thesis.

5.3.1. Generalized costs for the passengers

Jie et al. (2010, p. 304 f.) propose that the cost to the user of taking the system has two components: the perceived disutility of the travel time and the riding fare. To monetize the travel time's disutility, they use the concept of multiplying it by the passengers' estimated value of time (VoT) m_w. For the fleet size optimization, Jie et al. set the fare at a fixed level since ticket prices in PT are determined by political decision and not directly based on the system cost. They further presume that the passenger riding time on the system is not or only negligibly influenced by the number of vehicles as long as there is no congestion due to an oversized fleet on the system. As access and egress times are also presumed not to be influenced by the fleet size, the perceived annual cost for the user can be modelled by the following equation.

$$C^a_{user} = m_w \cdot t_w \cdot T^a + X \quad (17)$$

In eq. (17), X represents the generalized cost components to the users that are assumed to be fixed regarding the fleet size variations, t_w denotes the average waiting time that is taken from the simulation and is presumed to be similar over the day compared to the peak hour figures, T^a describes the number of annual trips on the system and is derived for *scenario 0* from summing the national transport interconnectivity study data set $v^{a,PT}_{OPR,l}$ scaled as explained in eq. (18) by the same principles as shown in eq. (1). This is based on the presumption that PT demand per inhabitant is equal in the Fehrbellin area compared to the district of Ostprignitz-Ruppin.

(18) $$T^a = \sum_l v_{OPR,l}^{a,PT} \cdot \left(\frac{U_{OPR,l}}{U_{Fb,l}}\right)^{k_r} \cdot \frac{P_{Fb}}{P_{OPR}}$$

The above value is scaled equally to the scenario variable σ^s to match the passenger numbers expected in the different demand scenarios.

The value of time for the passengers m_w is obtained by combining the low-end estimate VoT values per trip purpose from the national transport interconnectivity studies final report[90] and the share of trip purposes among all trips in Ostprignitz-Ruppin on PT for existing passengers and on the remaining modes (excluding walking) for new passengers. The VoT figures are shown in the following table.

Table 6: Value of time for existing and new public transport passenger in Ostprignitz-Ruppin

trip purpose (assigned VoT trip purpose)	Work (working commute)	Education (educational commute)	Shopping (private)	Business (business)	Vacation (private)	Private (private)
VoT per person and hour	6 €	1 €	5 €	20 €	5 €	5 €
Share of existing public transport trips	16%	35%	22%	1%	0%	26%
Share of non-public-transport trips excluding walking	18%	3%	33%	7%	0%	39%
VoT existing passengers:		3.87 €	VoT new passengers:			6.13 €

Own figure based on data for trip purpose shares: Intraplan Consult 2014a; for VoT values per trip purpose: Intraplan Consult (2014b, p. 69)

5.3.2. System cost components for the operator

The definition of the system operator follows Jie et al. (2010, p. 304) who describe it as "the companies and agencies that are responsible for the financing, construction and operation"[91] of the transport system. They divide the fleet size dependent costs to the operator into the annual capital cost of the vehicles C_v^a, the annual energy cost for running the vehicles C_e^a, and the annual maintenance cost C_m^a. Frank/Friedrich/Schlaich (2008, p. 22) propose a more detailed estimation for bus systems' costs based on their timetable kilometrage. However, as the proposed system offers no timetable, their cost estimation could not be applied.

To model the full operator's cost, a cost component Y for fixed costs regarding fleet size adjustments and the factor α as an overhead-and risk premium is added. The total annual system cost for the operator is described by the following equation.

[90] Intraplan Consult 2014b, p. 69
[91] Jie et al. 2010, p. 304

(19) $$C_{operator}^{a} = (1 + \alpha) \cdot (C_v^a + C_e^a + C_m^a + Y)$$

The annual capital cost for the vehicles is estimated by the following equation.

(20) $$C_v^a = v \cdot C_v \cdot A_v = v \cdot C_v \cdot \frac{ir}{1-(1+ir)^{-n}}$$

In eq. (20) v denotes the fleet size in number of vehicles, C_v the vehicle purchase cost, and A_v the amortisation factor comprised of the annual interest rate ir (assumed to be at 4%) and the average vehicle life expectancy n (assumed to be 15 years).

The vehicle purchase cost C_v is set following Jie et al. (2010, p. 304) at the purchase cost for the Heathrow Airport pod-car, a level-4 autonomous vehicle, of 140,000 €. Considering cost estimations for fully accessible conventional minibuses in Reuter (2015, p. 30) of 110,000 €, and a prime of 10,000 € for the automated driving system (as proposed in chapter 2.1.2), the remaining 20,000 € for the electric propulsion would be reasonable.

The annual energy cost C_e^a for the vehicle movements is estimated deviating from Jie et al. (2010, p. 304) by the following equation. Electric propulsion is assumed.

(21) $$C_e^a = P_v^{peak} \cdot l_{peak} \cdot C_e \cdot u_e \cdot \frac{T^a}{t^{peak}}$$

In eq. (21) P_v^{peak} denotes the peak hour vehicle performance in vehicle-kilometre obtained from the simulation results, l_{peak} denotes a load factor that corrects for the different system loads in on- and off-peak hours, C_e the average commercial energy cost in Germany assumed to be at 0.12 €/kWh[92], u_e the estimated energy usage of the vehicles assumed to be at 0.8 kWh/km[93], and t^{peak} the trips taken in the peak hour on the system taken from the simulation results. This energy usage estimation presumes that the vehicle-kilometre per transported passenger on the system can be estimated by the peak-hour system performance multiplied by a load factor (here presumed to be $l_{peak} = 2$).

Jie et al. (2010, p. 304) further presume that the annual maintenance cost can be modelled as a fraction of the vehicle purchase cost. Their presumption of $C_m^a = 0.05 \cdot C_v$ is used here as well.

Following Reuter (2015, p. 30) and Frank/Friedrich/Schlaich (2008, p. 22), the overhead and risk prime α is set at 15%.

The variable Y is kept empty out of the lack of a reliable source for an estimation. For instance, in this estimation, the only cost component directly considering vehicle performance is the energy cost. Further, no taxes and no insurance costs are specifically considered. It should therefore be

[92] cf. Destatis 2017, sheet 5.9.3
[93] cf. Lajunen 2014, p. 11

measured as a representation of the uncertainty of this cost prediction. The assumed cost components are displayed in Table 7.

Table 7: Assumed operator's cost components

Cost component	symbol	indication	assumptions	
vehicle annuities	C_v^a	purchase cost	140000	€
		life expectancy	15	years
		interest rate	4	%
		annual cost	12591.75	€ p.a.
maintanance	C_m^a	generalized annual cost	7000.00	€ p.a.
energy cost	C_e^a	energy usage	0.8	kWh/VKT
		energy cost	0.12	€/kWh
		annual cost	0.096	€/VKT

Own figure based on above explained assumptions and own calculations

5.4. Feasibility and benefit evaluation criteria

For the consideration of the autonomous minibus on-demand system to be feasible, it should propose a benefit to the passengers while being economically sensible for the operator.

For assessing the benefits for the passengers, the quality of service criteria of Kirchoff/Tsakaretos (2007, p. 56) can be used. They consider

- number of served stops,
- the number of daily services, and
- the travel-time

to be the most important factors to determine PT service quality. Due to incomplete data, only the travel time component can be assessed numerically in this thesis. The current travel time from selected stations to the big supply centre of the area, Fehrbellin, is compared to the travel times obtained from the simulation. The other two factors are assessed qualitatively.

As the proposed system would offer on-demand services, the average and maximum waiting times for a vehicle would replace the second criterium. The mandatory minimum call time in advance for the scheduled on-demand services on the current system would act as a reference variable to the maximum waiting time on the proposed system.

To assess the economic sensibility of the proposed system, the evaluation criteria of BBR/BMVBS (2009, p. 66 ff.) is taken. The paper proposes to evaluate

- the passengers served per ride,
- the necessary subsidies per ride,
- and the cost recovery ratio.

Those factors are compared against existing conventional demand-responsive PT systems given in BBR/BMVBS (2009, p. 66 ff.), Reuter (2015), and the available data for the existing PT system in the Fehrbellin area.

To evaluate the latter two factors, a revenue prediction is necessary. The average revenue per passenger trip is assumed at today's level. It is further presumed that on average 75% of the Fehrbellin traffic performance per trip is carried out by the proposed system. This assumes half of the Fehrbellin area trips to have an origin or a destination outside of the area[94] and that on average half of the traffic performance of those trips is provided within the Fehrbellin area.

Through substracting the subsidy of the district of Ostprignitz-Ruppin in 2015[95] from the ORP gross profit in 2015[96] and dividing this difference though the carried passengers in 2015[97], an average revenue per passenger of 0.58€ is obtained. As 75% of traffic performance is estimated to be carried out by the proposed system, an average revenue per passenger of 0.44 € is presumed.

With districtwide subsidies of around 4.5 million Euro in 2015 (including the ORP company loss as the ORP is owned by the district),[98] the per capita subsidy for bus transport in the district of 45.61 € is estimated. Assuming constant subsidies, the equal distribution of PT subsidies on the basis of the population numbers, and a performance share of 75% of local PT among all PT services in the Fehrbellin area (as in the revenue estimation), a subsidy budget for the proposed system of 0.31 million Euro is identified.

In the studied cases, it is presumed that all vehicles would be operational in the peak demand hours. Maintenance works are presumed to be carried out in the off-peak hours when less vehicles are needed to serve passenger demands.

[94] Value taken from to the traffic figures of the SrV study presented in 5.2.2 (Ahrens 2016)
[95] cf. LK OPR 2016, p. 42
[96] cf. ORP 2016
[97] cf. ORP 2016
[98] cf. LK OPR 2016, p. 42 and ORP 2016

6. Simulation

The proposed autonomous minibus on-demand system is simulated in the chosen study area to obtain an estimation of the total-cost-optimal fleet size in the peak time of the demand scenarios. The optimized systems' properties are then subject to the feasibility and benefit evaluation.

6.1. The used software

The used software *PRTsim* was developed by Andréasson (2009) to simulate generic Automated Transit Systems. The software simulates both passenger and vehicle traffic on a microscopic level[99]. Andréasson (2016, p. 4) describes that *PRTsim* assumes a system network of one-directional guideways with stations on or off-line and asynchronous vehicle control. He describes that the software uses merge controllers to allocate the order and time of vehicles at the convergence of two guideways and diverge controllers that direct vehicles on their fastest route to their destination. This approach of a vehicle control by the infrastructure allows for fast computational times[100].

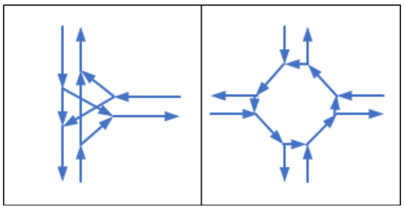
The software offers a network editor, an animation of the simulation and possibilities to display different simulation results.[101] The simulation inputs are set in an input file; results are presented in a result file. Excerpts of these files are presented in the appendix at A 7 and A 8.

6.1.1. Modelling of the operational scenario

The operational scenario described in chapter 4.2 is modelled for the simulation purpose as an Automated Transit System. These systems are characterised by on-demand and direct services between its stations by small vehicles on designated guideways.[102] The proposed system is represented by modelling the roads in the service area as designated guideways and the areas of door-to-door services as stations.

As the designated guideways in the software PRTsim are one-directional, a road is modelled by two guideways with opposite directions. Intersections are modelled as shown in Figure 9 as a branched-design for three-way crossings, or as a roundabout for larger intersections.

Figure 9: Detail of the model network design – used solutions to model intersections



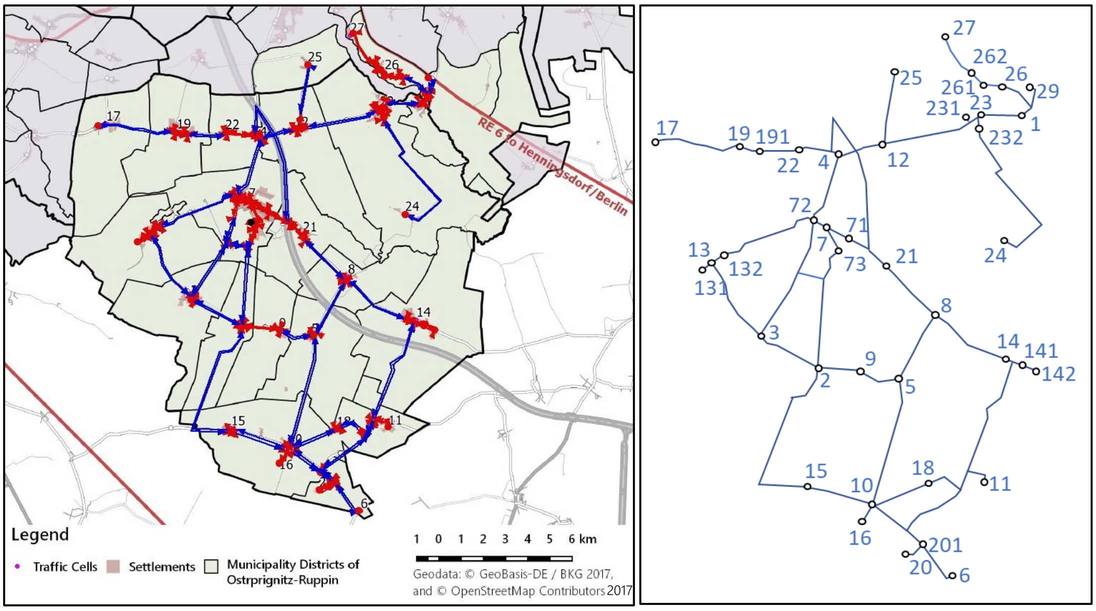
Own figure: Branched-design on the left and roundabout-design on the right

Every traffic cell in the study area is provided with at least one station. Depending on the size and distribution of the settlement area in the traffic cells, up to four stations are allocated. The stations

[99] cf. Coulombel et al. 2016, p. 8
[100] The system simulation could be completed in few seconds.
[101] cf. Anréasson 2009, p. 32
[102] cf. Andréasson 2016, p. 1

are used to model door-to-door service and stops in the traffic cell. All stations are modelled off-line so that vehicles can pass a possibly occupied station, and within a closed loop enabling vehicles to make a turn after each station. In traffic cells with one station, traffic demand is taken from the demand matrix. In this instance, internal traffic in the cell is not considered. Traffic demand for stations in traffic cells with more than one station is distributed by a heuristic method based on their position in the settlement area and their proximity to public facilities like schools. Traffic demand from outside the study area is allocated to the most likely main transfer points at the train station Wustrau-Radensleben and at the presumed scheduled bus service stops at Fehrbellin and Linum. The positioning of the stations as well as the network design is shown in Figure 10. The allocation of the traffic demand from the traffic cells to the stations is shown in the appendix at A 6.

Figure 10: Network design in PRT sim to model the proposed system



Own figures: Left: grid of guideways with speed profiles (red – slow, blue – fast); right: network with station id

The software PRTsim allows for two different speed-levels in the network[103]. As shown in Figure 10, two speed profiles were devised for tracks inside and outside of built-up areas. The used mean speed values are oriented towards the values in the reachability model of the Federal Institute for Research on Building, Urban Affairs, and Spatial Development[104]. The medium average speed on federal streets of 18 m/s is set as mean speed outside the built-up areas and 10 m/s is set as the mean lower speed equalling medium to fast average city speeds.

Network demand in PRTsim is treated as a constant. A network performance analysis over the day is not possible within one simulation run. For optimising the fleet size, the presumed demand peak hour in the morning was used. An additional 60 minutes with 60% demand before the ana-

[103] cf. Andréasson 2009, p.29
[104] cf. BBSR 2017b

lysed peak hour was simulated as the modelled vehicles start in a central depot. Operational performance indicators of this simulation period were presumed to be able to describe the general system performance.

Arrival-time oriented trips were not possible to simulate, and the possibility of modelling scheduled arrivals at selected stations in the software was not used due to uncertain external schedules.

6.1.2. Embedded operational strategies and presumptions in the software

The software has an embedded strategy for the distribution of vehicles. Andréasson (2002, p. 3-8) describes the development of this strategy. He pointed out that the efficiency of vehicle distribution is directly affecting service performance. In large networks, vehicle distribution in anticipation of expected demand would lead to faster call times but vehicles en route would need to also react to unexpected demand. The developed vehicle distribution algorithm can be described as a three-step process.

- Ex ante, based on predicted passenger demand, stations with expected vehicle surplus, as well as vehicle deficit are identified and a list of their best respective vehicle sources and send stations is generated with the standard optimization method Transportation Simplex. If possible, empty vehicles are allocated according to that list in real time operations. Vehicles are called if queuing passengers and expected short-term demand exceed the sum of the vehicles in the station and on their way to the station.
- In a second step, running vehicles may swap their destination to react to current demand. The longest waiting passenger gets her, or his nearest empty running vehicle allocated. The second longest waiting passenger gets her, or his nearest empty running vehicle assigned and so on until all waiting passengers are served.
- The remaining running empty vehicles are redistributed to the stations with the highest expected deficit of demand and vehicle supply.

This dispatch strategy in the simulation software *PRTsim* is tailored to create a state in which the passenger would ideally find an empty vehicle already waiting at the station, so that the passenger would not have to wait.[105] This leads to the fact that before boarding, the modelled transport system in the software does not know the passengers' desired destination. Potentially, in a situation of a vehicle deficit on the whole system, this algorithm carries out the second step only. Andréasson (2002, p. 5) describes that this process would ensure an optimal solution to the longest waiting passenger only.

The software has embedded DRS schemes. As the system is a public service, following the observation of Andréasson (2016, p. 1), it is assumed that all passengers are willing to share rides. The software allows for adjusting

- the number of acceptable intermediate stops per passenger ride (set to two stops),

[105] cf. Anréasson 2002, p. 5

- the acceptable detour for these stops for the passengers in the vehicle (set as demanded in 4.2 to 30%), and
- if the vehicle would stop to pick up new passengers on the way (set to yes).

Furthermore, the software allows a delay of vehicles in the station to wait for additional passengers if the vehicle is loaded with less than the required number of passengers to depart. This waiting time for potentially shared rides was set to one minute and the number of required passengers to depart immediately was set to eight.

As the software models a situation in which the system, until boarding, would not know the passenger's desired destination, it is likely that the empty vehicle management, as well as the DRS system in the model is more inefficient than it could be on the proposed system. Passenger's waiting times would therefore be overestimated.

Andréasson (2016, p. 4) describes assumptions regarding the passengers embedded in *PRTsim*. The software presumes random passenger arrivals in a Poisson distribution and various passenger party sizes distributed binominal around a mean value. Boarding and egress times are presumed to be distributed normally according to measurements taken at the pod-car system at Heathrow.

6.1.3. Additional input factors

The mean passenger party size is presumed to equal the mean occupancy rate of private cars in the study area. As described in chapter 5.2.2, it is presumed that the mobility data for the district of Beetzendorf-Diesdorf can describe the mobility patterns in the study area. Thus, the mean private car occupancy rate of 1.3 for Beetzendorf-Diesdorf[106] is assumed as the average party size.

The boarding and egress times measured on the pod-car system in Heathrow are presumed to be comparable to the passenger behaviour in the study area. Further, system factors of the proposed system explained in chapter 4.2 were applied. A list of the simulation input factors is displayed in the appendix at A 7.

6.2. Fleet size optimisation

The simulation aims to optimize the vehicle fleet by finding the global minimum of the generalized cost for the users and the operator over the fleet size. The fleet size was set to ten vehicles and then increased in ten-vehicle steps. The proposed system was optimized for the three demand scenarios and based on the cost component assumptions explained in chapter 5.3. The combined cost calculation tables are listed in the appendix at A 6

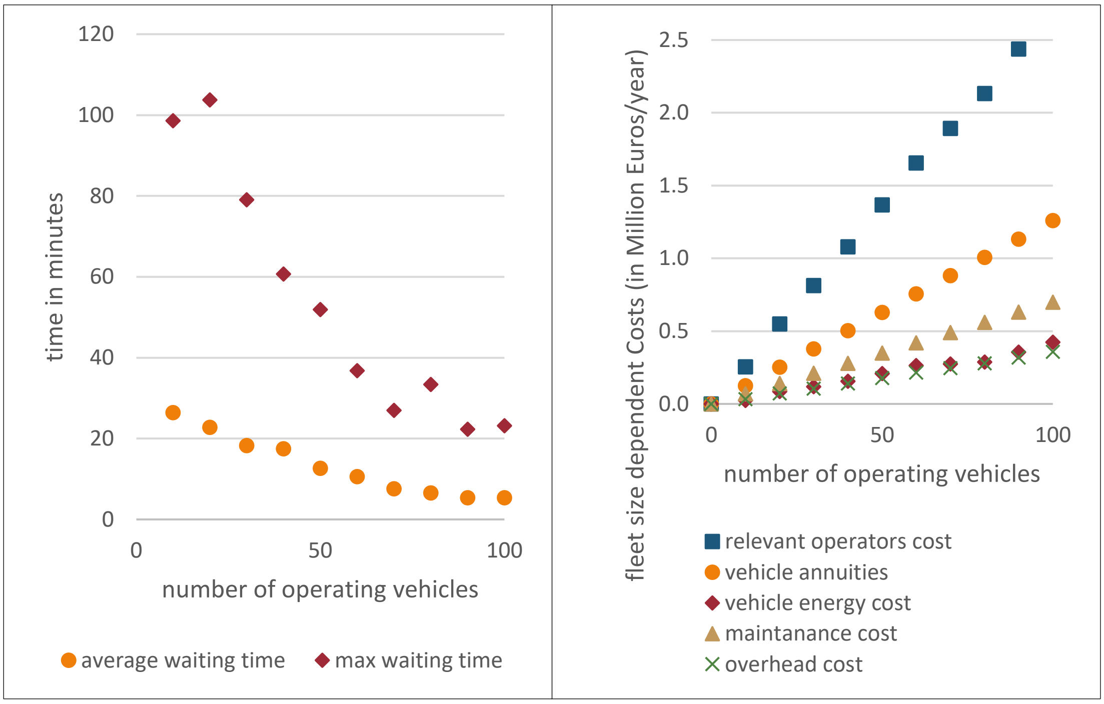
6.2.1. Scenario 0 and scenario call-a-bus

Scenario 0 represents a baseline scenario in which the introduction of the proposed system has no influence on the traffic demand on the PT system in the study area. *Scenario cb* presumes an increase in traffic demand for the PT system in the study area by 50%, reacting similarly to the

[106] Ahrens 2015, Tab 7 (e)

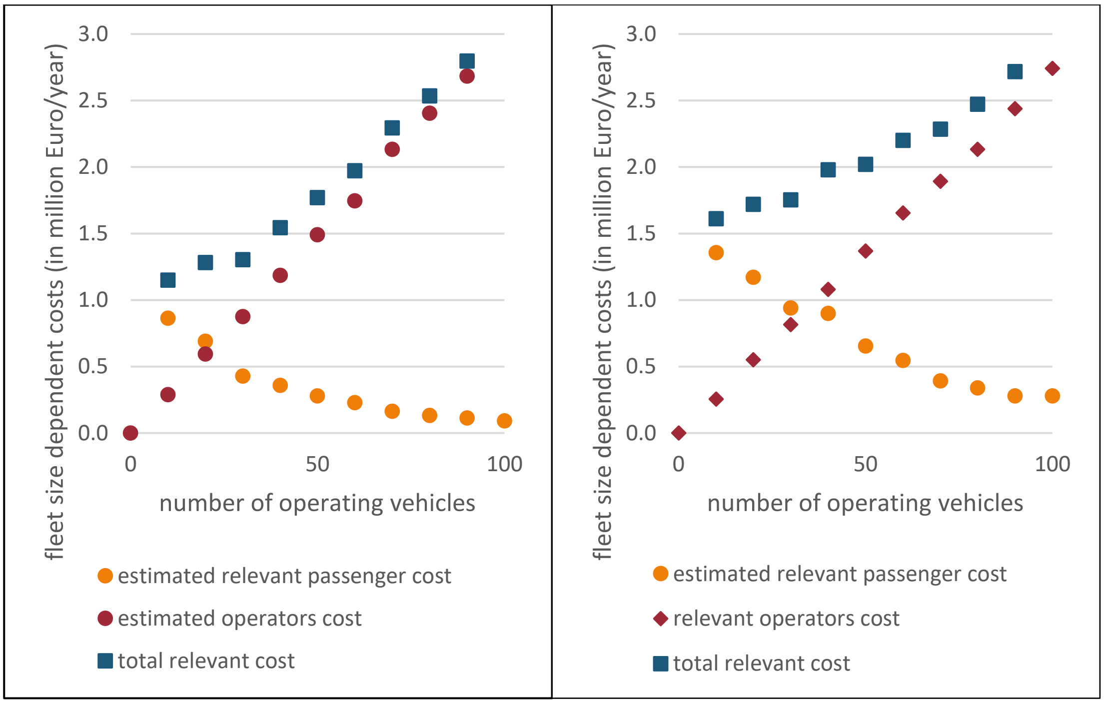
introduction of a classic call-a-bus system. The simulation software identifies 499 passenger trips in the morning peak hour on the system in *scenario 0* and 733 passenger trips in *scenario cb*.

Figure 11: Average and maximum waiting time (left) and cost components for the operator in *scenario cb* over the fleet size



Own figures, graph calculation based on simulation output and cost component presumptions in chapter 5.3

Figure 12: Estimated total fleet size dependent system costs over the fleet size in *scenario 0* (left) and *scenario cb* (right)



Own figures, graph calculation based on simulation output and cost component presumptions in chapter 5.3

With the presumptions from chapter 5.3, a graph (Figure 12) of the total cost of the system to the passengers and the operator is obtained. The estimated relevant passenger cost refers to the estimated perceived cost in lost VoT by waiting time since the other cost factors are presumed to be constant regarding the fleet size.

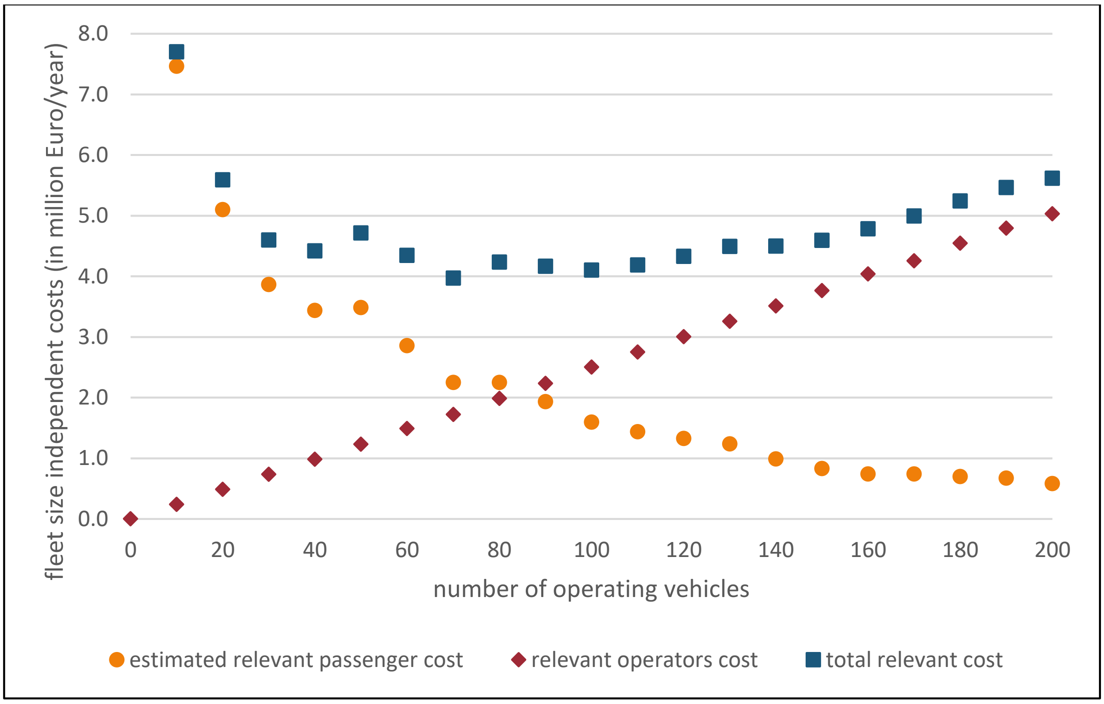
The average and maximum waiting time, as well as the cost components for the operator are plotted over the fleet size for *scenario cb* in Figure 11. In the cost component model for the operator the vehicle purchase cost has a high significance. Vehicle annuities generate almost half of the system's costs to the operator under all studied fleet sizes.

As shown in Figure 12 the total cost minimum of the system in both *scenario 0* and *scenario cb* is obtained with 10 vehicles.

6.2.2. Scenario public transport

In *scenario pt*, the proposed system serves a much-increased PT demand. The scenario presumes that the increased PT service level would attract as many passengers as urban PT systems regarding its modal share. In the morning peak hour, the system would transport 1,396 passengers.

Figure 13: Estimated total fleet size dependent system costs over the fleet size in *scenario pt*



Own figures, graph calculation based on simulation output and cost component presumptions in chapter 5.3

As displayed in Figure 13, the global minimum of the combined total cost to the passengers and the operator of the proposed system is at a fleet size of 70 vehicles. The different efficiency of the ride sharing scheme due to the randomness of the passenger arrivals could explain the non-constant curve of the relevant passenger cost.

7. Feasibility and benefit assessment

The feasibility and benefit assessment of the proposed system rests on the criteria set in chapter 5.4 and the performance of its simulated model. The analysis will consider the perspective of the riders and of the operator. The feasibility and benefits of the system will be analysed for the total-cost optimal fleet size per scenario estimated in the previous chapter. As the *scenarios 0* and *cb* have shown similar outcomes in the fleet size optimization, they will be reviewed together.

7.1. Scenario agnostic factors

The following chapter considers factors that are not dependent on the demand scenarios. To prevent repeating these factors, they are assessed separately.

7.1.1. Passenger perspective

For the passenger perspective, an analysis of the change in the service level of the local PT system in the study area is proposed in chapter 5.4 as indicator of the beneficial nature of the proposed system.

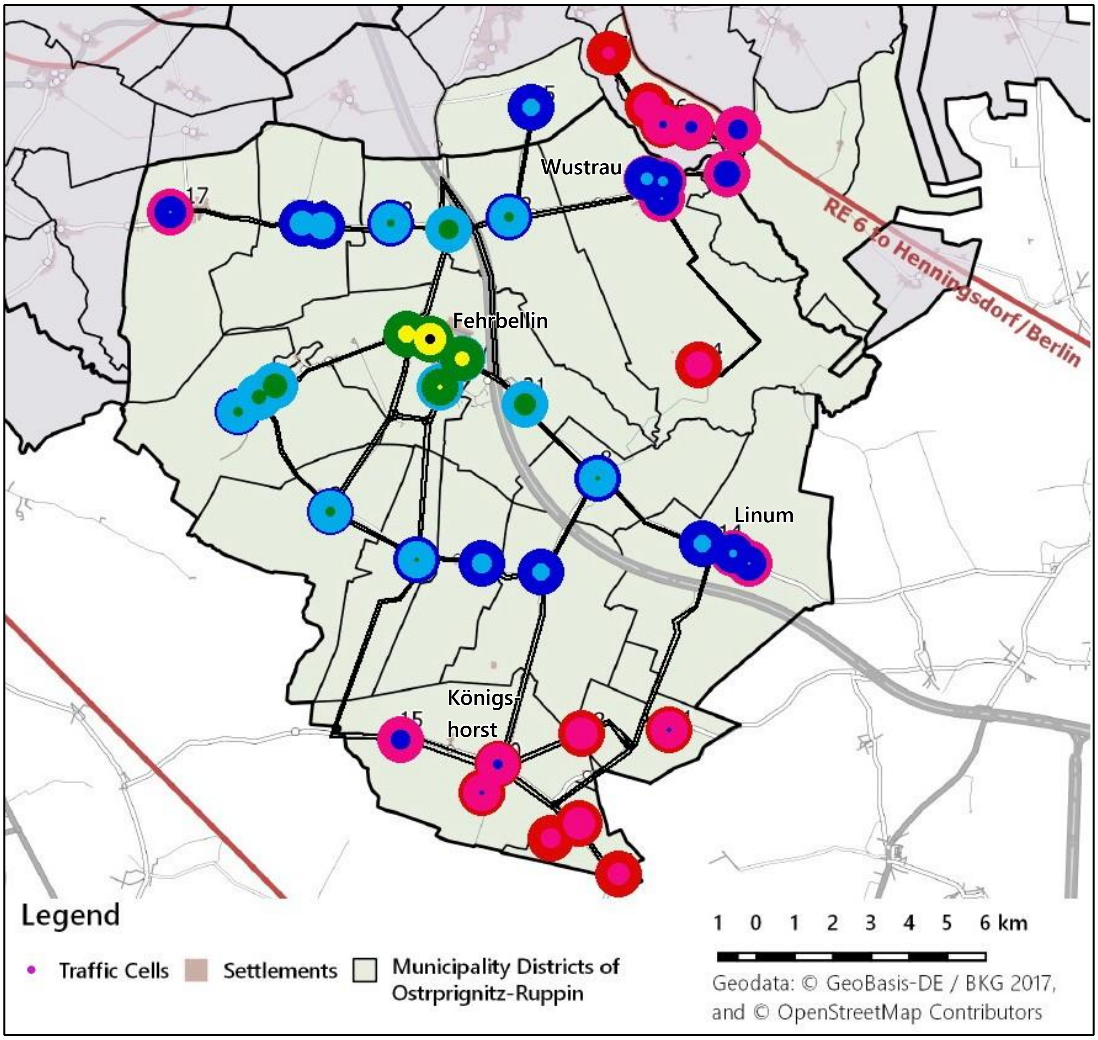
As the proposed system would add the option of door-to-door trips, it would practically enable the densest network of stops possible. To provide for a fully accessible system, the current bus stops would be kept as barrier-free access points to the system. Thus, regarding the **number of served stops**, the proposed system would provide significant benefits to the passengers.

Considering the **travel time to the big local supply centre Fehrbellin**, the direct services on the proposed system allow significant service improvements. The current shortest possible travel times displayed in Figure 6 were compared to the simulated minimum travel times on the proposed system in Figure 14. Reduced travel times of up to nine minutes on today's direct services and up to 19 minutes on today's services with a transfer are observed. Of the analysed origins, only Karwesee would have higher travel times which could indicate an underestimation of the travel times on the system. A numerical comparison is given in the appendix at A 9.

From the pupil's perspective, the proposed system would eliminate current direct services to schools in Neuruppin with arrival times coordinated with the start of school. However, the system would be able to react more flexible to changes in school schedules and could enable individual return trips.

A significant factor of service performance are the service intervals or the number of services per day and station. As the proposed system would offer on-demand services, in theory, there could be an immediate departure for every passenger. As described in chapter 4.2, this scenario would be more expensive. Therefore, waiting times between a vehicle call and its arrival are to be expected. This would potentially prohibit spontaneous trips that would be possible on a scheduled service and the vehicle call ahead of the ride would add complications.

Figure 14: Isochrones from Fehrbellin to the modelled stations with a walking radius of 600m



Passenger isochrones from the modelled station 7 in Fehrbellin to the other stations (<5 min: yellow, <10 min: green, <15 min: light blue, <20 min: dark blue, <25 min: pink, <30 min: red); presumed walking speed: 1 m/s; screen capture of PRTsim.

Even with long waiting times, a service around the clock would eliminate the service gaps on the current system. Local transport demand on the weekend and in the evening, could be fulfilled on the proposed system, providing a significant benefit.

7.1.2. Operator perspective

The proposed system's operation is based on the presumption that level-4 compliant autonomous vehicles would be available to the operator. Recent developments around autonomous mobility (as described in 2.2.1) show that the technology is approaching its readiness. Given that neither the availability of the proposed vehicles nor their purchase cost is available yet, the cost estimations have a high risk of deviating in a real system. In the cost model, the marginal cost of added VKT is low so services in times of very low demand should be feasible.

7.2. Scenario 0 and scenario call-a-bus

Considering the fleet size optimization graphs displayed in Figure 12, it can be deduced that the operators' cost per new vehicle would be greater than the expected passenger benefits per new vehicle in both *scenario 0* and *scenario cb*. This results in an optimum of the total system cost in the minimum of the studied fleet sizes at ten vehicles for both scenarios.

7.2.1. Passenger perspective

In the considered scenarios, the passengers benefit from the introduction of the proposed system as described in 7.1.1. However, in both scenarios, the average and the maximum waiting times obtained in the simulation are significant. These times are displayed in Table 8.

Table 8: **Average and maximum waiting time in minutes on the proposed system in *scenario 0* and *cb***

Scenario	Average waiting time	Maximum waiting time
0	29.8	107.9
call-a-bus	26.4	98.6

Own figure, waiting times obtained from the simulated model systems described in 6.1

Waiting times for the *scenario 0* are generally higher than on the higher demand *scenario cb*. Presumably, the higher trip demand enables a more efficient DRS scheme. However, in both instances, the maximum waiting time exceeds the current mandatory call time in advance for the current scheduled call-a-bus scheme in the area of 90 minutes. In the simulated cases, 24% of *scenario 0* passengers and 33% of scenario call-a-bus passengers could get waiting times below ten minutes.

7.2.2. Operator perspective

For the operator's perspective, the economic feasibility and effectiveness of the proposed system is assessed according to the criteria set in chapter 5.4.

In the explored morning peak demand hour, the DRS scheme of the proposed system could bundle the demand in such a way, that loaded vehicle trips had on average 7.1 passengers in *scenario 0* and in the case of scenario call-a-bus had on average 9.6 passengers. The highest number of average **passengers per ride** were 4.25 on a scheduled by-call service and 2.1 on a non-scheduled on-demand service among the systems studied in BBR/BMVBS (2009, p. 41).

Based on the revenue prediction of 0.44 € per passenger made in chapter 5.4 and the operator's cost estimation in chapter 6.2.1, the **necessary subsidies per ride** on the proposed system as well as the **cost recovery ratio** of the proposed system are estimated. This estimate is compared to the economic performance figures of the best performing system provided in BBR/BMVBS (2009, p. 70) in Table 9.

Table 9: **Necessary subsidies per ride and cost recovery ratios for the scenarios 0, cb, and for an existing system in the state of Hessen**

System figures	Scenario 0	Scenario cb	Hessen system
Necessary subsidies per ride	1.51 €	0.78 €	2.87 €
Cost-recovery ratio	22%	36%	41%

Own figure based on simulation results. Data for the existing system from BBR/BMVBS (2009, p. 70): call-a-bus-system with the best economic performance of the given examples in the source

As the revenue of 2 € per passenger on the Hessen system[107] is much higher than the estimated 0.44 €, the cost recovery ratio is not comparable. With estimated costs for the operator of 1.95 € in *scenario 0* and 1.22 € in *scenario cb* per passenger, a revenue of 2 € per passenger would turn a profit without any subsidy.

The total system cost for the operator is estimated at around 0.87 million Euro for *scenario 0* and 0.81 million Euro for *scenario cb*. Compared to the estimated cost of 1.3 million Euro by Reuter (2015, p. 31) for a new call-a-bus system with ten vehicles in the German rural district of Nordfriesland, a cost advantage of at least 33% can be estimated. The annual passenger revenue would account for 0.20 million Euro in *scenario 0* and 0.29 million Euro in *scenario cb*. Assuming the subsidy budget of 0.31 million Euro (as estimated in chapter 5.4), **additional annual funding of 0.37 million Euro in *scenario 0* and 0.21 million Euro in *scenario cb* would be needed**. Alternatively, an added fee for the system or an increase of ticket prices of 0.81 € in *scenario 0* and 0.31 € in *scenario cb* could be introduced.

7.2.3. Feasibility and benefit finding

Relative to the rural PT on-demand systems in operation studied in BBR/BMVBS (2009 p. 70), the cost per passenger trip of the proposed system is very low. However, additional funding and/or a rise of ticket prices would be needed to sustain the proposed system. From the passenger's perspective, services during the simulated morning peak demand hour would be worse than today for many passengers, as on the one hand waiting times would be partially higher than the mandatory call time of 90 minutes for bus-by-call services and peak hour headways of the scheduled services[108] in the area today, and on the other hand reliable schedules would disappear. Outside the peak demand times though, the proposed system could close existing service gaps and provide local PT services on weekends and at night.

The high waiting times in the simulated peak demand hour propose that in those times of the day, a scheduled service would be more effective in serving the demand in the area. Scheduled services can better bundle higher passenger demand and thus operate more efficiently. In case local politics would decide that the additional service quality of the off-peak-operations of the proposed system would be worth the additional funding, the anticipated ten vehicles could run on a schedule in the peak demand times and in the proposed on-demand manner in off-peak hours.

An analysis of today's timetables for the bus lines in the Fehrbellin area[109] excluding the corridor Linum-Fehrbellin-Neuruppin which proposedly would feature a frequent scheduled service outside of the proposed system, shows that five vehicles would be needed to fulfil today's morning peak demand hour schedule. The additional five autonomous vehicles could be used to increase the service performance in the morning. Alternatively, only five larger autonomous vehicles could be purchased, potentially reducing the cost of the system to such an extent, that the ticket revenue

[107] cf. BBR/BMVBS 2009, p. 70
[108] Timetable analysis on ORP 2017
[109] Timetable analysis on ORP 2017

and the current subsidies would sustain the system's cost. In both alternative cases, on-demand services in the off-peak hours could be provided. The quality of those services should be subject of further studies.

7.3. Scenario "public transport"

In the scenario "public transport" the ridership on the proposed system would be significantly higher than in the scenarios studied above. To serve the higher number of riders, within the simulation 70 vehicles were identified as the optimal solution considering the total system cost to the passengers and the operator.

7.3.1. Passenger perspective

In the considered scenario, the passengers benefit from the introduction of the proposed system as described in 7.1.1. Furthermore, the passengers would profit from an average waiting time of 10 minutes with a maximum waiting time of 52.4 minutes in the simulated morning peak demand hour. Over 66% of the passengers would not have to wait more than the average ten minutes in the morning peak demand hour; 12% of the passengers would be served almost immediately (vehicle call-time in less than one minute).

7.3.2. Operator perspective

As above, the economic feasibility and effectiveness of the proposed system from the operator's perspective is assessed according to the criteria set in chapter 5.4.

In the explored morning peak demand hour, the DRS scheme of the proposed system could bundle the passenger demand, so that, on average, five passengers would share a vehicle mission. Considering that the DRS scheme would be less successful in the off-peak times, the system should match the number of **average passengers per ride** of today's non-scheduled on-demand services 2.1 and below[110].

Based on the revenue prediction of 0.44 € per passenger made in chapter 5.4 and the operator's cost estimation in chapter 6.2.2, the necessary subsidies per ride on the proposed system as well as the cost recovery ratio of the proposed system are estimated.

The operation of the proposed system would cost the operator an estimated 1.72 million Euro while the estimated 2.36 million passengers would amount to 1.04 million Euro in ticket revenue. The system would thus have a **cost recovery ratio** of 60% resulting in **necessary subsidies per passenger** ride of 0.29 €. The economic figures provided in Table 9 for the best performing conventional rural PT on-demand system studied in BBR/BMVBS (2009, p. 70) suggest that these figures are not achievable without autonomous vehicle technology.

[110] cf. BBR/BMVBS 2009, p. 41

With the subsidy budget for the local Fehrbellin area PT system estimated in chapter 5.4 at 0.31 million Euro, the proposed system would **need an additional 0.16 € per passenger ride or 0.37 million Euro in total**.

7.3.3. Feasibility and benefit finding

The cost per passenger trip in the scenario „public transport" is significantly lower than in the other studied scenarios, as well as all the given examples of rural PT on-demand and call-a-bus services provided in the BBR/BMVBS handbook. Most of those systems levy a convenience charge of 0.50 € per ride or higher on top of the common fare.[111] With such a prime for the added system cost on the ticket fares, a political decision to increase the local PT subsidy, or both, the system would be economically feasible. The relatively high level of service could also facilitate the introduction of alternative financing policies such as a general PT tax as suggested in chapter 4.1.

In this scenario, the simulated waiting times for the passengers are significantly lower than today's mandatory minimum call-time for call-a-bus services in the study area of 90 minutes. However, the waiting times are still significant. Thus, as discussed in 7.2.3, a service that would differ between peak demand times and off-peak times should be considered. The relatively high number of vehicles in the proposed system could run based on a schedule in the peak times to increase reliability for commuters while providing on-demand shuttle services in off-peak times to more spontaneous passengers. In the former case, the system would lose some direct services and travel times would be increased by a significant margin due to scheduled stops and necessary detours. On the other hand, the number of vehicles on the proposed system could deliver significantly denser schedules than today's PT offer.

[111] cf. BBR/BMVBS 2009, p. 75

8. Conclusion and Outlook

This thesis develops and explores an operational scenario for the introduction of autonomous vehicles in German rural public transport. It was shown that research expects high driving automation systems to enable a new transport mode of shared autonomous vehicles. This mode could significantly reduce the number of cars in cities and increase the convenience and affordability of individual travel. While the application of such systems in urban environments is well studied, research suggests that the application to rural areas would be uneconomical for fleet operators. However, with an integration into the subsidised PT, this travel mode was identified to have the potential to significantly increase rural PT efficiency.

It was equally shown that PT fulfils a vital role of ensuring social participation for rural inhabitants that have no access to alternative travel modes. Current rural PT is challenged by demographic change, sprawl of settlements and facilities, as well as budgetary restrictions and can frequently not fulfil its passengers' demand. The bundling of service facilities and differentiated transport services are identified as a current comprehensive concept to sustainably secure the livelihood of rural communities. However, the latter part of the concept implies that transport services should rely on private initiatives and pro-bono work instead of PT, where budgetary restrictions make PT services uneconomical. Operational scenarios of introducing SAVs to rural PT were explored that could prevent the underserving of rural areas with PT.

The operational scenario for the introduction of SAVs to rural PT studied in this thesis transfers the operational design of urban ride-sharing services to rural PT on a local level. Within its operational area, this system would bundle passenger flows to transfer-stations of scheduled arterial PT services and provide direct door-to-door services within the area. The system would run around the clock and on-demand. It was explored if such a system would be economically feasible and which benefits it would bring to its passengers based on the simulation of an operational model. Their respective optimal fleet size for the system regarding the combined cost to the operator and the passengers was determined in its peak demand hour. The analysis of the operational figures obtained by the simulation evinced mixed results.

The assumed all-day service would close temporal PT service gaps and reduce the car reliance of the local inhabitants. Especially, the young rural population would profit from services late into the night. The proposed door-to-door service would eliminate spatial PT service gaps and significantly improve the accessibility of remote settlements. Direct services with a limited number of intermediate stops and detours would reduce travel times for almost every explored local connection. On the other hand, the layered model of local on-demand services and interlocal scheduled arterial routes would omit several direct routes to destinations outside the local area. As school transport was assumed to be integrated in the proposed system, pupils would have to plan, when to call a vehicle to reach the school on time. Longer waiting times could reduce the advantages of fully on-demand versus time-table based operations.

In the two lower demand scenarios, the number of passengers would be so low, that within the modelled scenario the added cost of a vehicle would be greater than the total monetized benefits in reduced waiting time to the passengers. The modelled system with ten vehicles showed significantly long waiting times, partially exceeding the current mandatory call time in advance for scheduled on-demand services of 90 minutes with 30 and 26 minutes on average. In the higher demand scenario, 70 vehicles were identified as the total cost optimal fleet size on the proposed system and waiting times could be kept under 60 minutes with ten minutes on average. Those waiting times were presumed to be too high for peak hour traffic and a need for an alteration of the operational scenario was identified.

The revenue volume per passenger and the annual subsidies of 2015, all studied scenarios would require additional funding between 0.21 and 0.37 million Euro. Although, the costs are higher than for the current service in the area, significant cost reductions could be identified in comparison to conventional rural PT on-demand systems with the same fleet size. Thus, this thesis could not find, that within budgetary restrictions, the explored system would be feasible and deliver significant benefits to the passengers.

This thesis could not find that the explored autonomous minibus on-demand system for rural public transport would be feasible under current budgetary restrictions, and that its benefits to the passengers would outweigh its disadvantageously passenger waiting times. Different factors were identified that should be studied regarding their potential to increase the efficiency of the studied operational scenario. Alternative dispatch strategies for long-distances and low demand ride-sharing networks should be further investigated as the studied system was modelled with a dispatch strategy developed for urban Automated Transit Systems. It should be investigated how the system's efficiency could be increased if the system would be aware of the passengers' destinations upon their vehicle requests.

As an alternative to a full on-demand system, the feasibility of a partial on-demand system that would alternate between scheduled mode in peak times and on-demand mode in off-peak times should be further explored. This thesis' results support the idea that such a system could be feasible.

Other factors regarding the feasibility of rural schedule-free on-demand systems that could not be accessed in this thesis include the performance of such the system's performance in off-peak times, and the interaction between scheduled and non-scheduled modes in PT especially with long scheduled intervals. Regarding the use of autonomous vehicles in PT, different aspects of passenger amenities have not been discussed in this thesis e.g. the intrinsic value of the interaction with a human bus conductor to the passengers or a change of subjective passenger safety in absence of a human driver. These subjects should equally be studied in further research.

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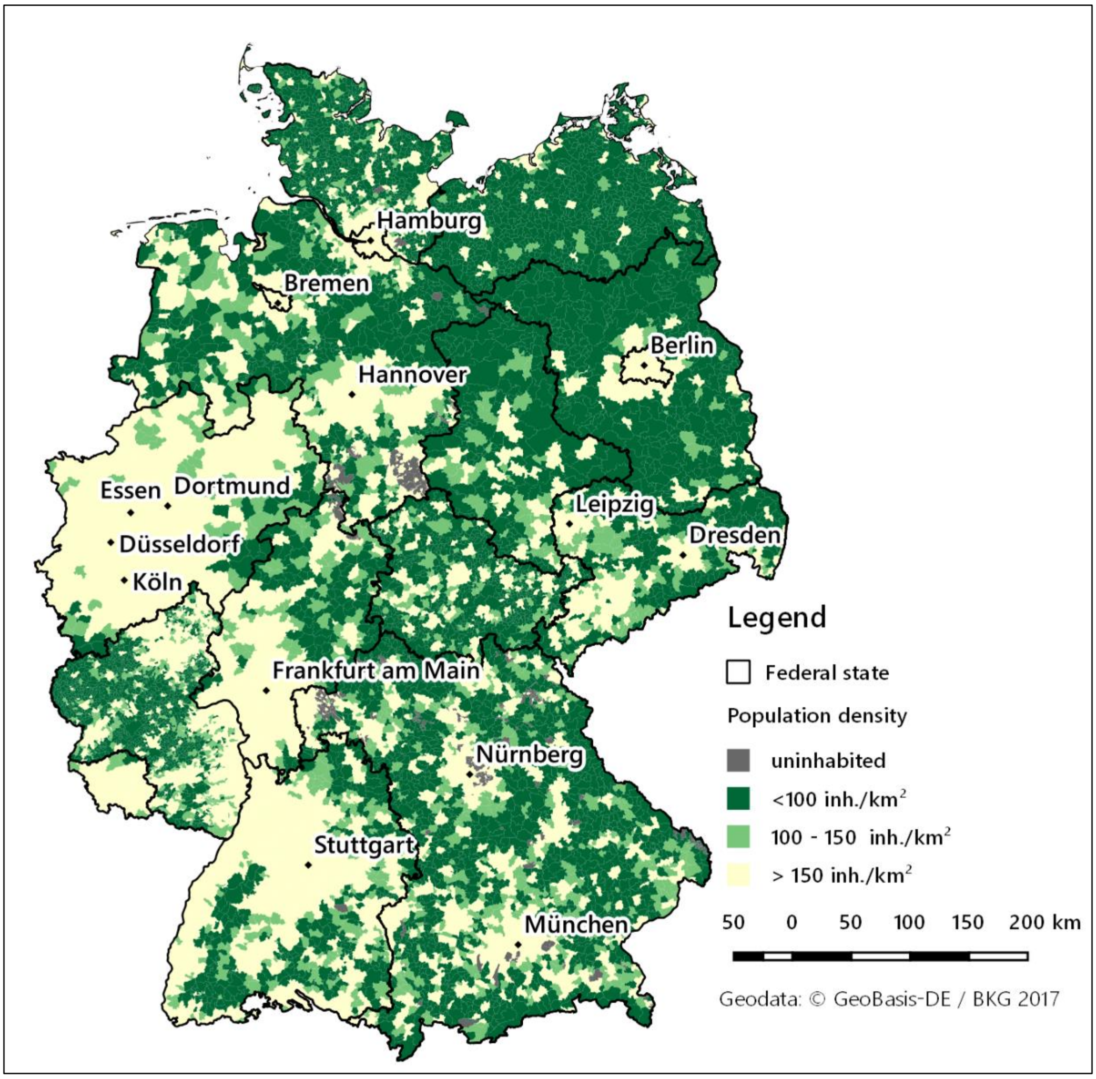
Files in the digital attachment on the compact data disk:

- *demand estimation.xlsx*: calculation table for the estimation of the passenger demand on the proposed system in chapter 5.2
- *fleet size optimisation.xlsx*: calculation table for the fleet size optimization and cost estimation in chapter 6 and 7
- folder *BVWP_Nachfrage_2010-2030*: Origin-Destination matrices of the movement of persons (Intraplan Consult 2014a)
- pdf file of this thesis

A 1 Rural Communities in Germany

Figure 15: Population density of German communities



Own figure based on population data from Statistische Ämter des Bundes und der Länder (2017)

A 2 Cooperation area concept for Ostprignitz-Ruppin

Figure 16: Cooperation area concept for Ostprignitz-Ruppin

Source: LK OPR 2017, P. 25, with own translation for the legend, (grey highlighted area in the north of the district: former military grounds; *Orientierung in Richtung* … translates to: orientation towards …, *Orientierung aus Richtung* … translates to: orientation from …)

A 3 Travel disutility figures

Table 10: Travel disutility in MIT trip duration between the surrounding district traffic cells and the district of Ostprignitz-Ruppin and the Fehrbellin area respectively

Traffic cells	MIT travel time to OPR [centroid] in minutes	MIT travel time to Fehrbellin [town] in minutes
district of Havelland [Nauen]	44	29
city of Berlin [Zoo station]	69	55
city of Potsdam	68	52
district of Oberhavel [Kremmen]	37	22
district of Prignitz [Pritzwalk]	47	48
Former district of Müritz [Röbel/Müritz]	52	55

Own figure based on travel times obtained on the trip planner in Google (2017) on the 12/07/2017, Locations in brackets: target point for distance estimation

Table 11: Travel disutility in MIT trip duration between the traffic cells

Cell id	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	23	24	25	26	27	28	29	30	31	32	33
1	2	19	20	8	21	30	13	16	21	26	25	6	16	20	26	28	16	28	13	30	16	10	4	15	11	3	6	20	38	58	61	26	51	58
2	19	1	4	11	5	14	7	8	3	10	16	13	8	11	6	10	19	13	15	14	10	13	18	29	16	23	25	25	29	57	54	24	52	59
3	20	4	1	9	8	17	6	11	6	13	19	11	5	14	10	14	16	17	12	17	10	11	15	26	15	21	23	27	32	58	55	25	52	59
4	8	11	9	1	12	22	5	9	14	18	18	2	9	12	18	20	8	20	5	22	8	2	6	17	6	12	14	18	36	54	51	21	43	50
5	21	5	8	12	1	10	10	3	2	6	12	13	12	7	10	8	18	9	14	10	6	13	18	29	14	24	26	25	25	56	53	19	51	58
6	30	14	17	22	10	1	20	13	12	4	7	23	23	11	8	7	28	8	25	4	16	23	28	39	25	34	36	35	14	57	47	23	61	68
7	13	7	6	5	10	20	3	7	9	16	16	6	7	11	12	16	12	18	9	20	6	6	11	22	10	15	17	21	27	50	49	21	48	55
8	16	8	11	9	3	13	7	1	5	9	9	10	13	4	13	11	15	11	12	13	3	9	15	26	15	21	23	22	27	49	48	16	48	55
9	21	3	6	14	2	12	9	5	1	8	14	15	10	8	9	10	20	11	17	12	8	14	19	30	16	24	26	26	26	53	51	20	53	60
10	26	10	13	18	6	4	16	9	8	1	6	19	18	10	4	2	25	4	22	5	12	19	25	36	21	30	32	30	18	57	48	22	57	64
11	25	16	19	18	12	7	16	9	14	6	1	19	23	6	10	8	25	4	22	7	12	19	25	36	21	30	32	30	21	50	49	17	56	63
12	6	13	11	2	13	23	6	10	15	19	19	1	10	14	19	21	9	22	7	23	9	4	5	16	5	10	12	20	29	52	52	22	45	52
13	16	8	5	9	12	23	7	13	10	18	23	10	2	17	15	20	11	21	9	22	12	11	15	26	14	21	23	24	35	55	54	27	51	58
14	20	11	14	12	10	11	11	4	8	10	6	14	17	2	13	12	19	8	16	11	7	13	19	30	19	25	27	24	25	51	49	12	51	58
15	26	6	10	18	10	8	12	13	9	4	10	19	15	13	1	5	25	7	22	8	16	19	24	35	22	30	32	31	22	59	52	25	57	64
16	28	10	14	20	8	7	16	11	10	2	8	21	20	12	5	1	26	5	24	6	14	20	26	37	26	32	34	33	21	60	53	24	63	70
17	16	19	16	8	18	28	12	15	20	25	25	9	11	19	25	26	1	28	3	29	14	6	14	25	13	20	22	19	35	56	54	27	48	55
18	28	13	17	20	9	8	18	11	11	4	4	22	21	8	7	5	28	1	25	8	15	22	28	39	24	34	36	33	23	55	53	20	58	65
19	13	15	12	5	14	25	9	12	17	22	22	7	9	16	22	24	3	25	1	27	11	3	12	23	10	18	20	19	32	53	52	23	47	54
20	30	14	17	22	10	4	20	13	12	5	8	23	22	11	8	6	29	8	27	1	18	25	30	42	26	36	38	35	18	57	48	24	61	68
21	16	10	10	8	6	16	6	3	8	12	12	9	12	7	16	14	14	15	11	18	1	8	14	25	10	20	22	19	26	48	45	18	45	52
22	10	13	11	2	13	23	6	9	14	19	19	4	11	13	19	20	6	22	3	25	8	1	9	20	7	15	17	16	29	51	48	22	44	51
23	4	18	15	6	18	28	11	15	19	25	25	5	15	19	24	26	14	28	12	30	14	9	3	14	9	9	11	20	34	56	53	27	49	56
24	15	29	26	17	29	39	22	26	30	36	36	16	26	30	35	37	25	39	23	42	25	20	14	1	21	20	22	31	46	68	65	38	61	68
25	11	16	15	6	14	25	10	15	16	21	21	5	14	19	22	26	13	24	10	26	10	7	9	21	1	15	17	15	31	52	50	24	45	52
26	3	23	21	12	14	34	15	21	24	30	30	10	21	25	30	32	20	34	18	36	20	15	9	20	15	1	2	14	39	61	58	29	55	62
27	6	25	23	14	26	36	17	23	26	32	32	12	23	27	32	34	22	36	20	38	22	17	11	22	17	2	1	12	41	63	60	31	56	63
28	20	25	27	18	25	35	21	22	26	30	30	20	24	24	31	33	19	33	19	35	19	16	20	31	15	14	12							
29	38	29	32	36	25	14	27	27	26	18	21	29	35	25	22	21	35	23	32	18	26	29	34	46	31	39	41							
30	58	57	58	54	56	57	50	49	53	57	50	52	55	51	59	60	56	55	53	57	48	51	56	68	52	61	63							
31	61	54	55	51	53	47	49	48	51	48	49	52	54	49	52	53	54	53	52	48	45	48	53	65	50	58	60							
32	26	24	25	21	19	23	21	16	20	22	17	22	27	12	25	24	27	20	23	24	18	22	27	38	24	29	31							
33	51	52	52	43	51	61	48	48	53	57	56	45	51	51	57	63	48	58	47	61	45	44	49	61	45	55	56							
34	58	59	59	50	58	67	55	55	60	64	63	52	58	58	64	70	55	65	54	68	52	51	56	68	52	62	63							

Own figure based on travel times obtained on the trip planner in Google (2017) on the 13/07/2017, no measurement for connections between traffic cells outside of the Fehrbellin area

A 4 Estimation for the OD-trips of school transport entitled pupils

Table 12: Estimation for the OD-trips of school transport entitled pupils

id	Traffic cell name	Altfriesack	Betzin	Brunne	Dammkrug	Dechtow	Dreibrück	Fehrbellin	Hakenberg	Karwesee	Königshorst	Kuhhorst	Langen	Lentzke	Linum	Lobeofsund	Mangelshorst	Manker	Nordhof	Protzen	Ribbeckshorst	Tarmow	Walchow	Wustrau	Ziethenhorst	Buskow	Karwe	Seehof	Neuruppin/	HVL/Nauen
1	Altfriesack							2,5																5					12,5	
2	Betzin							5																					6,5	
3	Brunne							18,5																					33,5	
4	Dammkrug																							1					4,5	
5	Dechtow							7,5																					31	
6	Dreibrück																												4,5	
7	Fehrbellin																												167	
8	Hakenberg							18,5																					17	
9	Karwesee							11																					21,5	
10	Königshorst							7,5																					9,5	
11	Kuhhorst							6																					4,5	
12	Langen							6																20					29,5	
13	Lentzke							25,5																					22,5	
14	Linum							27																					45	
15	Lobeofsund							8,5																					12,5	
16	Mangelshorst							2																						
17	Manker							1																13					30	
18	Nordhof							5																					4,5	
19	Protzen							7																20					23	
20	Ribbeckshorst							1																						1
21	Tarmow							7,5																					9,5	
22	Walchow							2,5																2,5					6,5	
23	Wustrau							14,5																					96,5	
24	Ziethenhorst																							2,5						
25	Buskow							2,5																5,5					12	
26	Karwe							1																2,5					61,5	
27	Seehof																												8	

Own figure based on own analysis of the figures in LK OPR 2015 pp. 112-116; mean value of the limits of the given value range, empty when 0

A 5 Estimated public transport demand per scenario

Table 13: Estimated PT demand in *scenario 0*

Cell id	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	7	0	0	0	0	0	0
2	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
3	0	0	2	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0
5	0	0	0	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
7	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	86	3	5	1	3	0	0
8	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0
9	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0
10	0	0	0	0	0	0	4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	0	0	0	0	0
11	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
12	0	0	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	15	0	1	0	0	0	0
13	0	0	0	0	0	0	13	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	1	0	0	0	0
14	0	0	0	0	0	0	13	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	1	0	2	0	0
15	0	0	0	0	0	0	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0
16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	6	0	0	0	0	15	0	0	0	0	0	0
18	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
19	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	9	0	0	0	0	13	0	1	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
21	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	6	0	1	0	1	0	0
22	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	4	0	0	0	0	0	0
23	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	49	1	2	0	1	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	7	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	31	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0
28	1	0	0	0	0	0	10	0	0	0	0	0	1	5	0	0	0	0	0	0	0	0	7	0	0	1	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Own calculation based on presumptions in chapter 5.2

Table 14: Estimated PT demand in *scenario ed*

Cell id	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	10	0	1	0	0	0	0
2	0	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0
3	0	0	3	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	0	0	0	0	0	0
5	0	0	0	0	2	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0
7	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	130	4	8	1	4	1	0
8	0	0	0	0	0	0	13	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	1	0	1	0	0
9	0	0	0	0	0	0	8	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	1	0	0	0	0
10	0	0	0	0	0	0	5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	0	0	0	0	0
11	0	0	0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
12	0	0	0	0	0	0	5	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	23	0	1	0	1	0	0
13	0	0	0	0	0	0	19	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	2	0	1	0	0
14	0	0	0	0	0	0	19	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	33	1	1	0	3	0	0
15	0	0	0	0	0	0	6	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	9	1	1	0	0	0	0
16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	9	0	0	0	0	23	0	1	0	0	0	0
18	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
19	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	14	0	0	0	0	19	0	1	0	1	0	0
20	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
21	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	8	1	1	0	1	0	0
22	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	6	0	1	0	0	0	0
23	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	74	1	2	0	1	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	0	0	11	0	1	0	0	0	0
26	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	47	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0
28	1	0	0	0	0	0	16	0	0	0	0	0	1	7	0	0	0	0	0	0	0	1	10	0	1	1	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Own calculation based on presumptions in chapter 5.2

Table 15: Estimated PT demand in *scenario pt*

Cell id	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	15	1	2	0	1	0	0
2	0	3	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	1	0	1	0	0
3	0	0	10	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	1	2	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5	0	0	0	0	0	0
5	0	0	0	0	6	0	6	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	27	1	2	0	2	0	0
6	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	1	0	1	0	0
7	0	0	0	0	0	0	125	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	1	0	0	0	0	171	14	29	4	15	2	1
8	0	0	0	0	0	0	16	6	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	16	1	2	0	2	0	0
9	0	0	0	0	1	0	9	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	1	2	0	2	0	0
10	0	0	0	0	0	0	6	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	4	2	0	1	0	0
11	0	0	0	0	0	0	5	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	1	0	1	0	0
12	0	0	0	0	0	0	7	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	30	2	4	0	2	0	0
13	0	0	0	0	0	0	23	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	2	6	1	2	1	0
14	0	0	0	0	0	0	22	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	39	2	3	0	10	0	0
15	0	0	0	0	0	0	7	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	11	3	2	0	1	0	0
16	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
17	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	10	0	0	0	0	30	1	3	0	1	0	0
18	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	4	1	1	0	1	0	0
19	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	16	0	0	0	0	27	1	4	1	2	0	0
20	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	3	1	0	1	0	0
21	0	0	0	0	0	0	8	0	0	0	0	0	0	1	0	0	0	0	0	0	8	0	0	0	0	0	0	13	2	4	1	3	0	0
22	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	0	0	0	0	12	1	2	0	1	0	0
23	1	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	94	3	8	1	3	1	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	1	0	1	0	0	0	0
25	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	4	0	0	18	1	2	0	1	0	0
26	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	7	0	59	0	1	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
28	3	0	1	0	1	0	55	1	1	0	0	2	3	26	0	0	2	0	2	0	1	2	37	0	3	5	2	0	0	0	0	0	0	0
29	0	0	0	0	0	1	6	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	5	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	3	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Own calculation based on presumptions in chapter 5.2

A 6 Allocation of the traffic demand from the traffic cells to the stations

Table 16: Allocation of the traffic demand from the traffic cells to the stations

Traffic cell (id)	Station id	share of cell demand at station	Traffic cell (id)	Station id	share of cell demand at station
Fehrbellin (7)	7	50%	Wustrau (23)	23	50%
	71	23%		231	30%
	72	17%		232	20%
	73	10%	Karwe (26)	26	40%
Lentzke (13)	13	60%		261	30%
	131	20%		262	30%
	132	20%	remaining OPR (28)	7	60%
Linum (14)	14	50%		29	40%
	141	30%	Havelland (29)	14	100%
	142	20%	Berlin (30)	29	100%
Protzen (19)	19	50%	Potsdam (31)	29	100%
	191	50%	Oberhavel (32)	29	100%
Ribbeckshorst (20)	20	60%	Prignitz (33)	29	100%
	201	40%	Müritz (34)	7	100%

Own figure based on geographic analysis of the area

A 7 Excerpt from an exemplary simulation input file simin.txt

```
OPR 0
sim_b.jpg picturefile(<10 characters)
Nodes nodefile
OD_0.txt demandfile
R result file
 1 no zones(0), zones as listed below(1), zone=station(2)
 2 stn OD(1), zone OD(2), stn trip ends(3), zone trip ends(4),
Emme(5), transpose(-X)
 400 m minimum distance (crow-fly) for riding
 30 vehicles in fleet or -x mins demand (0=as called)
 0 minimum vehicles at station
 3 sec minimum headway
 3 sec high-speed headway
 10 m/sec normal speed
 18 m/sec high speed
 2 m/sec2 acceleration
 3.7 m vehicle spacing in stations and queues
 1.0 overspeed factor for empty cabs
 0 couple at departure if next ready(1), coming(2), loaded(3)
 2 secs to open or close door
 4.4 sec mean single passenger load
 1.1 sec standard deviation
 1.8 sec additional passenger load
 3.2 sec single passenger unload
 120 vehicle deps/hr per platform position p
 3 +p positions on station entry track
 -2 +p positions on station exit track, minimum 2 positions
 0 combined(0) or separate(1) unload positions before platform
 0.5 reallocation interval in mins (if>0)
 0.2 weight of last observation in smoothing call-times
 2 look-ahead in route choices (0-2 diverges)
 5 mins between recalculation of paths (if>0)
 2 weight of delay in path calculation
 2 weight of wait-time in travel disutility
 1.3 average group size
 10 passengers capacity per vehicle
 100 % willing to share
 8 passengers to depart
 1 mins wait limit for shared ride (-to list matchings)
 2 m/sec station speed
 30 % reduction of cabs in sharing relations
 -2 acceptable intermediate stops (0-2), - accept boarding (same
destinations)
 -30 % acceptable detour for ride-sharing, - stop to pick up
 60 % of matrix trips per hour in initial period
 100 % of matrix trips per hour in study period
 60 initial minutes without statistics
 60 minutes study period (0=no paths)
 0 list network code(1), Vision(2)
 1 sum matrix trips from/to (1)
 0 list all paths (1)
 2 log passenger pickups(1), sharing(2), arriving(3), queues(4)
 0 log cabs continuing(1), empty(2), in&out(3), passing nodes(4),
reallocated(5), pairs (6), Vision(7)
 0 log selected cab(c) at nodes/stations
 0 log selected node/station(n)
 2 list trips, riding-times, distances between zones(1) and sta-
tions(2)
13579 random seed
 5 plot steps per time step
[…] [only the number of vehicles was modified and the demandfile was
adjusted to the scenarios]
```

A 8 Excerpt of the simulation result files R.txt for the total-cost-optimal fleet size per scenario

```
OPR 0

 590 total zone trips in matrix

 499 total station trips in matrix

Party sizes %: 75 20 4 1 0 0 0 0 0 0

 499 trips in PRT matrix
Statn From To Sum demand
 1 11 1 12
 2 5 0 5
 3 24 0 24
 4 2 0 2
 5 17 0 17
 6 3 0 3
 7 40 222 262
 8 16 0 16
 9 15 0 15
 10 8 0 8
 11 5 0 5
 12 27 0 27
 13 15 1 16
 14 21 18 39
 15 11 0 11
 16 1 0 1
 17 21 0 21
 18 4 0 4
 19 13 0 13
 20 1 0 1
 21 11 0 11
 22 6 0 6
 23 30 21 51
 24 1 0 1
 25 10 0 10
 26 12 1 13
 27 4 0 4
 29 16 145 161
 71 26 27 53
 72 19 20 39
 73 11 12 23
 131 5 1 6
 132 5 1 6
 141 12 4 16
 142 8 3 11
 191 13 0 13
 201 0 0 0
 231 18 13 31
 232 12 9 21
 261 9 1 10
 262 9 1 10
sum 497 501

 39 % empty trips minimum


SUMMARY OPR 0
 […]
 10 vehicles
```

```
120 parties on+off per platform position
3+platform positions on entry track unless specified
0 minimum vehicles at station unless transfers
3.0 secs slot interval
10 m/sec normal speed
0.5 mins reallocation interval
5 minutes between path calculations
2 weight of delay in path calculation
1.0 max wait minutes for share matching
30 % reduction of vehicles in sharing relations
2 acceptable intermediate stops, boarding at drop-off
30 % acceptable detour for sharing, stopping to pick
no coupled vehicles
60 minutes in study period
100.0 % of input trips

86 passengers departed in initial period
221 passengers departed in study period, 1.31 in average party
498 passengers left waiting for vehicle =59.9 mins arrivals
38 % of all passengers matched, 38 % of willing and tried
37 % of loaded departures for 2 stops
7 % of loaded departures for 3 stops
2.19 stops per vehicle mission
16 stops en route to pick up passengers
80 passengers picked up at intermediate stops
1.42 stops per passenger trip
29.8 minutes waiting for vehicle, 24 % < 9.8, max107.9
8.1 minutes riding, max 26.9
0.0 minutes average passenger delay
6.3 kilometers average trip, max 23.8
47 kilometers/h average speed
24.3 minutes per empty trip, max 53.4
20.9 kilometers per empty trip, max 47.6
0.0 % of loaded vehicles waived-off, 0.0 % of empties
5.7 departures per vehicle hour
2.6 missions per vehicle hour
5 % of departures empty
9 % of departures with 1 passenger
9 % of departures with 2 passengers
5 % of departures with 3 passengers
11 % of departures with 4 passengers
14 % of departures with 5 passengers
4 % of departures with 6 passengers
4 % of departures with 7 passengers
40 % of departures with 8 passengers or more
7.1 passengers per loaded vehicle running, 10.0 on max link
22.1 passengers carried per vehicle hour
3 % of used fleet standing idle
44 % of used fleet running empty
53 % of used fleet running with passengers
2 vehicles/hour on average link, max 24
7 passengers/hour on average link, max 120
0.0 minutes delay of loaded on link, max 0.0 towards 0
146 vehicle kilometers empty
166 vehicle kilometers with passengers
1170 passenger kilometers
```
[…]

```
OPR ED

 907 total zone trips in matrix

 773 total station trips in matrix

Party sizes %: 75 20 4 1 0 0 0 0 0 0

 773 trips in PRT matrix
Statn From To Sum demand
 1 17 1 18
 2 9 0 9
 3 37 0 37
 4 4 0 4
 5 26 0 26
 6 5 0 5
 7 60 338 398
 8 28 0 28
 9 23 0 23
 10 13 0 13
 11 7 0 7
 12 42 0 42
 13 23 1 24
 14 34 34 68
 15 17 0 17
 16 1 0 1
 17 32 0 32
 18 6 0 6
 19 20 1 21
 20 1 0 1
 21 17 0 17
 22 11 1 12
 23 44 33 77
 24 2 0 2
 25 17 1 18
 26 19 1 20
 27 6 0 6
 29 27 221 248
 71 38 42 80
 72 29 31 60
 73 17 19 36
 131 8 1 9
 132 8 1 9
 141 18 7 25
 142 12 5 17
 191 20 1 21
 201 1 0 1
 231 27 20 47
 232 18 14 32
 261 15 1 16
 262 15 1 16
sum 774 775

 39 % empty trips minimum


SUMMARY OPR ED
[…]
 10 vehicles
 120 parties on+off per platform position
 3+platform positions on entry track unless specified
 0 minimum vehicles at station unless transfers
 3.0 secs slot interval
 10 m/sec normal speed
```

```
0.5 mins reallocation interval
5 minutes between path calculations
2 weight of delay in path calculation
1.0 max wait minutes for share matching
30 % reduction of vehicles in sharing relations
2 acceptable intermediate stops, boarding at drop-off
30 % acceptable detour for sharing, stopping to pick
no coupled vehicles
60 minutes in study period
100.0 % of input trips

170 passengers departed in initial period
241 passengers departed in study period, 1.31 in average party
865 passengers left waiting for vehicle =67.1 mins arrivals
26 % of all passengers matched, 26 % of willing and tried
33 % of loaded departures for 2 stops
13 % of loaded departures for 3 stops
2.38 stops per vehicle mission
11 stops en route to pick up passengers
55 passengers picked up at intermediate stops
1.48 stops per passenger trip
26.4 minutes waiting for vehicle, 33 % < 9.8, max 98.6
8.6 minutes riding, max 28.3
0.0 minutes average passenger delay
6.8 kilometers average trip, max 25.2
47 kilometers/h average speed
19.8 minutes per empty trip, max 30.2
17.6 kilometers per empty trip, max 27.8
0.0 % of loaded vehicles waived-off, 0.0 % of empties
6.2 departures per vehicle hour
2.6 missions per vehicle hour
3 % of departures empty
10 % of departures with 1 passenger
15 % of departures with 2 passengers
10 % of departures with 3 passengers
8 % of departures with 4 passengers
5 % of departures with 5 passengers
5 % of departures with 6 passengers
5 % of departures with 7 passengers
40 % of departures with 8 passengers or more
9.6 passengers per loaded vehicle running, 10.0 on max link
24.1 passengers carried per vehicle hour
5 % of used fleet standing idle
27 % of used fleet running empty
68 % of used fleet running with passengers
2 vehicles/hour on average link, max 24
13 passengers/hour on average link, max 204
0.0 minutes delay of loaded on link, max 0.1 towards 319
70 vehicle kilometers empty
156 vehicle kilometers with passengers
1496 passenger kilometers
```

[…]

```
OPR PT

 1641 total zone trips in matrix

 1396 total station trips in matrix

Party sizes %: 75 20 4 1 0 0 0 0 0 0

 1396 trips in PRT matrix
Statn From To Sum demand
 1 29 4 33
 2 15 0 15
 3 50 1 51
 4 6 0 6
 5 40 2 42
 6 12 1 13
 7 172 491 663
 8 40 1 41
 9 34 2 36
 10 22 0 22
 11 12 0 12
 12 63 2 65
 13 37 4 41
 14 58 129 187
 15 24 0 24
 16 4 0 4
 17 46 2 48
 18 11 0 11
 19 32 4 36
 20 4 0 4
 21 32 1 33
 22 21 2 23
 23 69 62 131
 24 4 0 4
 25 29 3 32
 26 27 4 31
 27 10 2 12
 29 98 384 482
 71 77 78 155
 72 58 59 117
 73 35 35 70
 131 13 2 15
 132 13 2 15
 141 30 25 55
 142 21 17 38
 191 32 4 36
 201 3 0 3
 231 43 39 82
 232 29 26 55
 261 20 3 23
 262 20 3 23
sum 1395 1394

 33 % empty trips minimum


SUMMARY OPR PT
 70 vehicles
 120 parties on+off per platform position
 3+platform positions on entry track unless specified
 0 minimum vehicles at station unless transfers
 3.0 secs slot interval
 10 m/sec normal speed
 0.5 mins reallocation interval
```

```
 5 minutes between path calculations
 2 weight of delay in path calculation
 1.0 max wait minutes for share matching
 30 % reduction of vehicles in sharing relations
 2 acceptable intermediate stops, boarding at drop-off
 30 % acceptable detour for sharing, stopping to pick
 no coupled vehicles
 60 minutes in study period
 100.0 % of input trips

 685 passengers departed in initial period
 1081 passengers departed in study period, 1.31 in average party
 564 passengers left waiting for vehicle =24.2 mins arrivals
 59 % of all passengers matched, 59 % of willing and tried
 34 % of loaded departures for 2 stops
 14 % of loaded departures for 3 stops
 2.49 stops per vehicle mission
 87 stops en route to pick up passengers
 283 passengers picked up at intermediate stops
 1.76 stops per passenger trip
 10.0 minutes waiting for vehicle, 66 % < 9.8, max 52.4
 7.9 minutes riding, max 35.1
 0.0 minutes average passenger delay
 6.1 kilometers average trip, max 30.0
 46 kilometers/h average speed
 19.8 minutes per empty trip, max 91.9
 16.9 kilometers per empty trip, max 79.9
 0.0 % of loaded vehicles waived-off, 0.0 % of empties
 5.8 departures per vehicle hour
 2.3 missions per vehicle hour
 11 % of departures empty
 13 % of departures with 1 passenger
 9 % of departures with 2 passengers
 12 % of departures with 3 passengers
 10 % of departures with 4 passengers
 7 % of departures with 5 passengers
 10 % of departures with 6 passengers
 7 % of departures with 7 passengers
 21 % of departures with 8 passengers or more
 5.0 passengers per loaded vehicle running, 10.0 on max link
 15.4 passengers carried per vehicle hour
 3 % of used fleet standing idle
 35 % of used fleet running empty
 62 % of used fleet running with passengers
 14 vehicles/hour on average link, max 108
 44 passengers/hour on average link, max 456
 0.0 minutes delay of loaded on link, max 0.1 towards 319
 758 vehicle kilometers empty
 1256 vehicle kilometers with passengers
 6265 passenger kilometres
[…]
```

A 9 Combined cost calculation tables per scenario

Table 17: Cost estimations for the passengers and the operator and for the total system in *scenario 0*

fleet size	average waiting time in minutes	maximum waiting time in minutes	est. relevant passenger cost in million Euro	est. operators cost in million Euro	est. total relevant cost in million Euro
10	29.8	107.9	0.86	0.29	1.15
20	23.8	83.3	0.69	0.59	1.28
30	14.8	57.2	0.43	0.87	1.30
40	12.4	44.8	0.36	1.18	1.54
50	9.6	31.5	0.28	1.49	1.77
60	7.9	28.8	0.23	1.74	1.97
70	5.6	21.5	0.16	2.13	2.29
80	4.5	18	0.13	2.40	2.53
90	3.9	17.7	0.11	2.68	2.80
100	3.1	12.8	0.09	3.03	3.12

Own figure based on simulation results and cost estimations in chapter 5.3

Table 18: Cost estimations for the passengers and the operator and for the total system in *scenario cb*

fleet size	average waiting time in minutes	maximum waiting time in minutes	est. relevant passenger cost in million Euro	est. operators cost in million Euro	est. total relevant cost in million Euro
10	26.4	98.6	1.36	0.25	1.61
20	22.8	103.8	1.17	0.55	1.72
30	18.3	79.1	0.94	0.81	1.75
40	17.5	60.7	0.90	1.08	1.98
50	12.7	51.9	0.65	1.37	2.02
60	10.6	36.8	0.54	1.65	2.20
70	7.6	27	0.39	1.89	2.28
80	6.6	33.4	0.34	2.13	2.47
90	5.4	22.3	0.28	2.44	2.72
100	5.4	23.2	0.28	2.74	3.02

Own figure based on simulation results and cost estimations in chapter 5.3

Table 19: Cost estimations for the passengers and the operator and for the total system in *scenario pt*

fleet size	average waiting time	maximum waiting time	est. relevant passenger cost	est. operators cost	est. total relevant cost
	in minutes		in million Euro		
10	33.2	104.6	7.46	0.24	7.701
20	22.7	110.4	5.10	0.49	5.591
30	17.2	99.3	3.87	0.73	4.600
40	15.3	92.2	3.44	0.98	4.419
50	15.5	83.6	3.48	1.23	4.713
60	12.7	65.9	2.85	1.49	4.343
70	10	52.4	2.25	1.72	3.967
80	10	45.5	2.25	1.99	4.233
90	8.6	44	1.93	2.23	4.165
100	7.1	36.8	1.60	2.50	4.100
110	6.4	34.5	1.44	2.75	4.187
120	5.9	30.1	1.33	3.00	4.330
130	5.5	71.3	1.24	3.26	4.494
140	4.4	22.5	0.99	3.51	4.499
150	3.7	21	0.83	3.76	4.594
160	3.3	17.2	0.74	4.04	4.782
170	3.3	17.2	0.74	4.25	4.995
180	3.1	17.9	0.70	4.54	5.241
190	3	16.4	0.67	4.79	5.465
200	2.6	16.8	0.58	5.03	5.615

Own figure based on simulation results and cost estimations in chapter 5.3

A 10 Comparison of selected minimum travel times to Fehrbellin on the current and on the proposed system

Table 20: Comparison of selected minimum travel times to Fehrbellin on the current and on the proposed system

Origin	Current minimum travel time	Currently transfer needed	Travel time on the proposed system
Lentzke	9	No	7
Brunne	15	No	7
Karwesee	9	No	11
Königshorst	27	No	18
Ribbeckshorst	27	No	21
Linum	12	No	11
Ziethenhorst	38	Yes	20
Wustrau-Radensleben	35	Yes	16
Karwe	20	Yes	17
Wustrau	13	No	13
Manker	21	Yes	14

Own figure based on the simulation results and analysis of vbb (2017b)