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# Identifying Key Factors in Planning and Implementing Autonomous Public Transport: An Investigation of Road- and Rail-bound Projects in Germany

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**Abstract**

Autonomous driving in public transport is becoming increasingly popular in Germany. The reasons for this are manifold – as are the challenges in the implementation. The aim of this article is to highlight these reasons and challenges and, in particular, to provide a deeper insight into the planning and implementation processes of various transport projects in Germany. This enables a comparison of road- and rail-bound transport systems and emphasises the differences between urban and rural project areas. Particular attention is paid to the formation of a stakeholder network in the case of the autonomous metro system in Nuremberg as well as to forms of cooperation in road-bound projects.

Keywords

autonomous public transport, autonomous driving, public transport, autonomous metro, autonomous bus

## Introduction

Autonomous driving has become an important topic in the field of mobility research. The discussion is not only focused on private cars but covers also public transport. Although the issue is complex and the challenges are many, automation is still associated with great hopes. While knowledge about potential contributions as well as technical, legal and ethical challenges has reached a reasonable level, the specific planning and implementation processes in autonomous public transport are rarely studied.

Most publications focus on the implementation of the national legal framework for road-bound (and mainly privately used) autonomous vehicles (such as Schreurs & Steuwer, 2015; Hansson, 2020; Smith, 2015; Iclodean et al., 2020) or on operational challenges in public transport (e.g. Beiker, 2015a; von Mörner, 2018). Researchers in the field of public transport planning and governance do not focus specifically on autonomous systems (e.g. Hirschhorn, et al., 2020). Specific (local and/or also informal) planning processes with regard

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to autonomous public transport services and infrastructure implementation have not yet been investigated. Thus, it remains unclear how autonomous public transport projects are implemented and in which way these processes can be improved. The aim of this article is to address this research gap and provide valuable insights for planning practice.

Based on existing literature and expert interviews, this article examines different autonomous transport projects in Germany to gain insights into how autonomous public transport is currently implemented and to identify factors that are relevant for a successful planning process. The article first presents the research methodology and the main objectives and challenges related to autonomous driving in public transport. Subsequently, it introduces the four case studies and explains why these cases were selected. In the results section, specific framework conditions related to autonomous rail-bound and road-bound systems, urban and rural settings as well as stakeholder cooperation are analysed and compared. These findings are then discussed. Finally, the findings are synthesised in the conclusions.

## Methodology

Based on an exploratory research approach, the aim of this article is to understand planning and implementation processes of autonomous public transport. Data was collected in 2018 and 2021. Seven expert interviews were conducted to generate primary qualitative data (Table 1). The expert interviews were conducted based on an interview guide (Hellferich, 2014). The basic rule was "as open as possible, as structured as necessary" (Hellferich, 2014, p. 560). By using interview guides that were individually created for each case, the research was exploratory and partially open. The expert interviews were conducted with local (public transport) authorities, transport companies as well as private planning companies and research institutions.

***Table 1:*** *Expert interviews*

| Number | Year | Employer | Projects |
|---|---|---|---|
| Interview 1 | 2021 | local authority | 'Rubin' metro project |
| Interview 2 | 2021 | transport company | 'Rubin' metro project |
| Interview 3 | 2021 | local authority | 'Bad Birnbach Shuttle' and 'Heal' bus projects |
| Interview 4 | 2021 | transport company | 'Bad Birnbach Shuttle' and 'Heal' bus projects |
| Interview 5 | 2021 | private planning office | 'First Mover', 'Pole Position' and 'Hub Chain' bus projects |
| Interview 6 | 2018 | private research and development company | 'First Mover' and 'Pole Position' bus projects |
| Interview 7 | 2018 | public transport authority | not involved in any autonomous transport projects |

The interviewees were selected to cover both a public transport authority and a transport company in a road-bound as well as a rail-bound case. This approach enabled perspectives on the projects from the planning and the implementing side. Thus, the two sides relevant on the European tender market were taken into account. The examples of Nuremberg and Bad Birnbach were selected as case studies (Interviews 1-4). Interviews 5 and 6 were conducted in order to gain additional perspectives on the implementation of road-bound projects on the one hand and on services implemented at an early stage on the other. This allowed an evolutionary view on the implementation of autonomous transport services. In addition, Interview 7 was conducted to discuss the potential contribution of autonomous public transport with a transport company that does not yet use the technology. This allowed to receive a (different) third party perspective on the topic. The derivation of possible contributions, but also hurdles in the use of autonomous driving in German public transport could thus be recorded in more detail.

The interviews centred around the following research questions, which also guide this article:

1. What are the main differences in the implementation of autonomous public transport compared to conventional public transport?
2. Do the implementation processes differ for bus and rail projects?
3. Do the implementation processes for bus projects differ in urban and rural areas?
4. Which actors are involved in the implementation process and how do they cooperate?

The interviews in 2018 were conducted in person, while the interviews in 2021 were conducted by telephone or video call. In case of Interview 6, the project location in Berlin was chosen for the conversation. It included a live demonstration of the vehicle. Interview 7 was conducted at the headquarters of a major public transport authority in Germany, which covers both urban and rural areas. All interviews were recorded and transcribed for further analysis. During the analysis, the various text passages were assigned to the research questions mentioned here. For use in this article, the interview transcripts were either quoted verbatim or paraphrased.

## Autonomous Driving in Public Transport

### Main objectives in the automation of transport services

Depending on the type of space as well as the type of transport system, different goals are pursued with regard to automation.

Maintaining public transport services in rural areas is often not possible in Germany due to the high costs. While flexible road-bound services are sometimes introduced as compensation, these services also often have to be discontinued for the same reason (Ahrens et al., 2010, p. 467; cf. also Holz-Rau et al., 2010, p. 499). A high degree of temporal flexibility means greater comfort for passengers, but also leads to higher costs, increasing timetable uncertainty and more complicated scheduling for the operator (BMVBS & BBSR, 2009, p. 29).

Therefore, the reduction of costs in a not profitable area is necessary to ensure the functioning of public transport as part of the provision of public services, especially in rural areas (Interview 7). The costs for the driving personnel in the area of the examined public transport authority account for 46% of the total costs for public transport (ibid.). With fully autonomous operation, it would therefore be possible to reduce operating costs by almost half.

Autonomous driving could, for example, offer the possibility to “reorganise on-demand transport, [and] offer something where it is normally not worth hiring a driver” (Interview 6). In addition, it is possible to provide slow-movement journeys when there is a lack of capacity utilisation, which would normally increase wage costs: “You can then do journeys with no passengers at all and no driver, where the vehicle just drives very slowly from one village to the next because it knows: ‘I'll pick the children up from school in an hour and then drive them somewhere else’. These are all transport cases that are probably cheaper in the long run with such a vehicle than if you always have a driver you have to hire. The vehicle can then also stand around for a day” (Interview 6). In summary, autonomous public transport can significantly reduce the costs of public transport and thus help to ensure the provision of public services in rural areas (Interview 6).

In urban areas, coverage of the first and last kilometres of a public transport journey is currently the main goal of autonomous transport services. The aim is to extend the catchment area of public transport and its stops (Interview 6). In case of metros, automation is used to increase the capacity of the transport system (Interview 1 & Interview 2).

In general, there is an increasing shortage of driving staff in the German labour market, which is already leading to a breakdown of services (ver.di, 2021, p. 2). It is also predicted that within the next ten years 50% of the German public transport driving staff will retire (ibid.). There is hope that automation can at least partially solve this problem. Fears that existing staff will be pushed into unemployment by the introduction of autonomous public transport systems are therefore unfounded.

### Main challenges on the way to implementation

While the previously described potential benefits encourage various actors, such as local (public transport) authorities and transport operators, to implement autonomous public transport projects, they also face various challenges. Apart from the individual local framework conditions, there are three main problem areas: Technology, law and ethics.

In the case of technology, capturing and mapping the vehicle environment (Minx & Dietrich, 2015, p. IV) is an important challenge. The mapping of human behaviour patterns (Maurer, 2014, p. 1) must also be taken into account. Last but not least, the safe networking of vehicles and infrastructure (Interview 6, 2018) is a topic in the ongoing debate. From a legal perspective, vehicle licensing (Jänich et al., 2015, p. 313f & Interview 6, 2018), allocation of liability (Reck, 2017, p. 2) and data protection (Minx & Dietrich, 2016, p. 128f) are the most important issues. Ethics in autonomous driving focuses primarily on the need to protect road users (BMVI, 2017, p. 10f & Lin, 2015, p. 70ff).

While technology and law are in an evolutionary process in the case of road-bound transport (and are only secondarily relevant in the case of fully autonomous metro systems, see Interview 1 & Interview 2), ethical concerns remain crucial for all autonomous transport. Federal German policy also recognises the need for action here. The Federal Ministry of Transport and Digital Infrastructure has set up an ethics commission for "automated and connected driving". The commission came to the conclusion that some ethical dilemmas of autonomous driving cannot be solved (BMVI, 2017, p. 10f). Furthermore, the priority of protecting human life over material assets is ethically justifiable in a weighing of legal interests (ibid.). However, in case of doubt, no ethically correct decision is possible: "Technical systems must be designed for accident avoidance, but cannot be standardised for a complex or intuitive accident consequence assessment in such a way that they could replace or anticipate the decision of a responsible vehicle driver capable of moral judgement" (BMVI, 2017, p. 11). This means that the human driver cannot be replaced as an actor. Consequently, fully autonomous driving is not justifiable from an ethical perspective. A final solution to the ethical dilemma therefore remains open, but it is a central building block for the successful and widespread implementation of autonomous driving in Germany. There is an urgent need for action here. In this context, the ethics commission recommends further systematic collection of experience by an "independent public body" (ibid.). The creation of a corresponding federal authority or a federal office for automated traffic is suggested (ibid.). Neither proposal has been implemented to date.

## Case Studies on Autonomous Public Transport in Germany

### Selection of Case Studies

Automated road-bound public transport is a widely discussed topic in Germany. In most of the sixteen federal states, initial projects have been implemented or are in operation (VDV, 2021a). However, most of the projects are limited in time. A large share of the projects had a duration of several months before operation was discontinued due to the end of the project (VDV, 2021b). One reason for the limited time span is the dependence of most projects on European, national or state funding (cf. VDV, 2021b). The autonomous bus in Bad Birnbach is the longest-running project in the country (ibid.), but to date also dependent on changing, time-limited funding (Interview 4).

The situation is quite different regarding fully independent and automated rail-bound public transport (mainly metro systems). Compared to road-bound public transport, the number of metro services is smaller, but also more stable. Worldwide, only about fifty fully automated metro systems (automation level four, cf. UITP, 2019, p. 8) are in operation (UITP, 2019, p. 1). Due to the need for a comprehensive infrastructural implementation, these services are put into operation with a long-term perspective. The only autonomous rail passenger transport project in Germany is being implemented in the city of Nuremberg (UITP, 2019, p. 1).

Differences can therefore be identified in the comparison between rail-bound and road-bound transport. While rail-bound transport is carried out on its own infrastructure, road-bound transport is more interlinked with external actors, such as pedestrians or animals. The open accessibility of the transport infrastructure as well as a broader mix of autonomous and non-autonomous vehicles in a transition phase leads to different challenges in the implementation of self-driving road-bound transport (Wachenfeld & Winner, 2015, p. 451). It is therefore necessary to compare rail-bound and road-bound autonomous public transport.

The cases of Nuremberg and Bad Birnbach are suitable for this purpose, as they were and are the first permanently automated public transport systems in Germany (see below). Their longevity and uniqueness in automated public transport are the main reasons for the selection. Due to the high number of projects in road-bound transport, further projects should be monitored.

Due to the available experts for this research project, further projects in Berlin, Osnabrück and Bad Essen were included. This made it possible to record development processes over the past years, especially in the case of learnings about different projects that were accompanied by the same expert. This feature could be of great importance: "Depending on the status and degree of implementation of a technology, different political implications and regulatory need for action arise. Different technology and use paths place different demands on the political system" (Schreurs & Steuwer, 2015, p. 153). In addition, with this selection of case studies, urban and rural test sites as well as projects on private and public land could be compared.

## Overview of the selected case studies

### Autonomous buses in Berlin: the 'First Mover' and 'Pole Position' projects

The "First Mover" project was carried out from November 2016 to September 2017 on the private premises of the "EuRef" science campus. The project was the first publicly accessible regular service with an autonomous bus in Germany. The main goal of the project was to establish the production of autonomous vehicles in Berlin (VDV, 2021a). The "Pole Position" project was also carried out on the "EuRef" campus from October 2017 to December 2018 (VDV, 2021a). Various goals were pursued through this follow-up project, such as demand-oriented connections to public transport, automated re-parking and inductive charging (ibid.).

### Autonomous buses in Bad Birnbach: the projects 'Bad Birnbach Shuttle' and 'Heal'

The first autonomous bus line in public road transport in Germany was introduced in Bad Birnbach on 25 October 2017. The railway station has been connected on an extended route since 7 October 2019. The total length of the route is two kilometres and several stops are served. The vehicles run on virtual rails and a supervisor accompanies all trips. The ride is free of charge (DB Regio Bus Bayern, 2021). The main aim is to test first and last mile transport in rural areas (VDV, 2021a). Until the outbreak of the Corona pandemic, an average of 120 passengers per day were transported, a total of 60,000 on line 7015 since the start of the project (Bad Birnbach 2022). The maximum speed of the vehicles is 17 km/h (ibid.). Since spring 2022, not only scheduled services between the village and the station (red line), but also on-demand services within the settlement (black network) have been offered as part of the “Heal” project (Figure 1). As with the previous project, “Heal” uses self-driving minibuses to serve Bad Birnbach and the surrounding area (Figure 2).

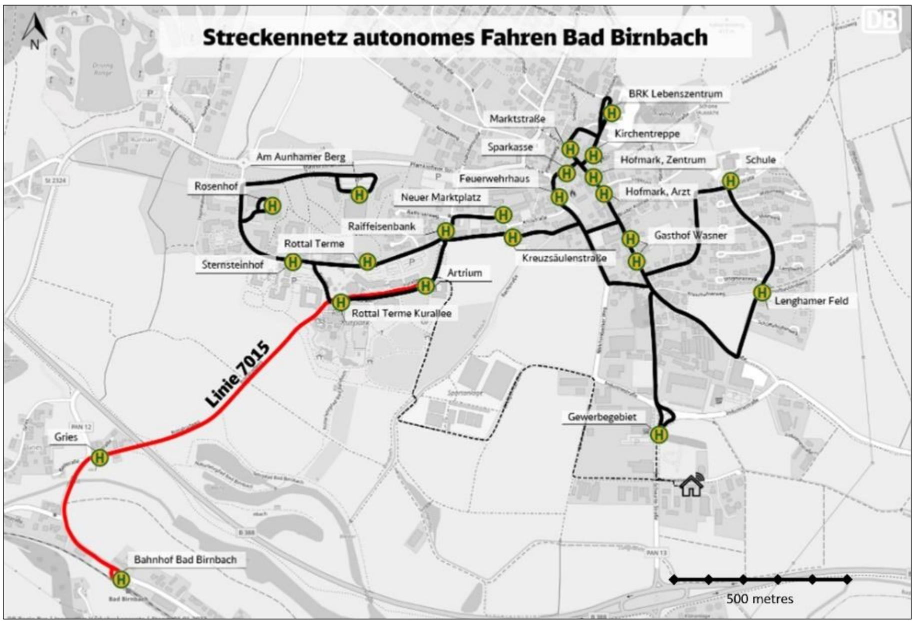


***Figure 1**: Network of Autonomous Bus Services in Bad Birnbach (© DB Regio Bus).*


***Figure 2**: Autonomous Bus Shuttle in Bad Birnbach (‘Heal’ project, © DB Regio Bus).*

## Autonomous buses in Osnabrück and Bad Essen: the "Hub Chain" project

The 'Hub Chain' project consists of two different parts: an urban test field in Osnabrück in the period from July 2019 to March 2020 (VDV, 2021a) as well as a rural test field in the municipality of Bad Essen from September 2020 to November 2020 (Hub Chain, 2021). The aim was to link scheduled transport with on-demand services and to set up a mobility platform to match these modes of transport (VDV, 2021a).

## Autonomous underground rail in Nuremberg: the "Rubin" project

In 2008, the first and only autonomous underground system in Germany was put into operation in the city of Nuremberg. The decision to automate the system was made due to the introduction of the new U3 line. This line had to share the existing tracks with the U2 line in the core of the network (Figure 3).

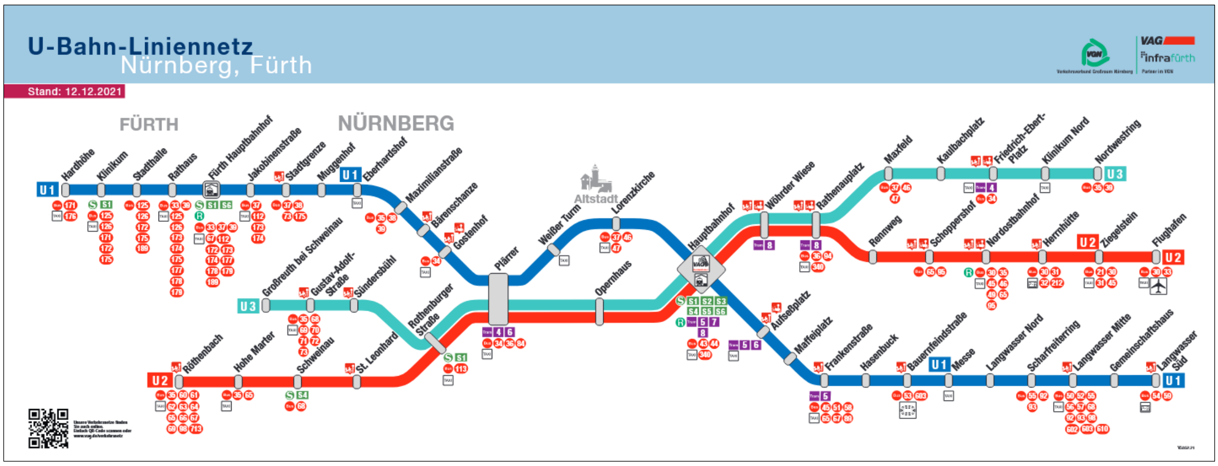


*Figure 3: The network of underground lines in Nuremberg and Fürth with the autonomous lines U2 (red) and U3 (turquoise) (© VAG).*

Unfortunately, the U2 line had already reached its maximum capacity in terms of the number of trains per hour. In order to increase the capacity of the existing infrastructure, automation was necessary. With the introduction of autonomous operation, the capacity of the rail infrastructure could be doubled. Trains can now run at 100-second intervals (Stadt Nürnberg, 2022). The changeover also brought other advantages. The autonomous trains are more punctual and the vehicles run more frequently which reduces waiting times. The optimised driving style reduces energy consumption and the number of defects and thus the maintenance costs are also lower. In addition, a more flexible adjustment to current demand is possible, especially at peak times (ibid.). The operation is monitored by the control centre of the local transport company (Figure 4).

The entire metro network (autonomous and conventional lines) carried about 400,000 passengers per day before the start of the Corona pandemic (Süddeutsche Zeitung, 2022). At the beginning of 2022, it carried an average of 260,000 passengers per day (ibid.).

***Figure 4**: Monitoring the autonomous underground in Nuremberg from the control centre (© VAG – Claus Felix).*

# Results

## Characteristics of implementation processes

The main purpose of the "Rubin" project Nuremberg was the targeted increase of network capacity (Interview 1 & Interview 2). Comparing the planning and implementation of conventional and fully autonomous metro systems, only minor differences can be found according to Interviewee 1: "As far as the planning process is concerned, (...) the time required for the construction of automatic metros is not much higher compared to non-automatic metros, because of course the planning, the approval process and so on, and then also the construction takes a lot of time. And the installation of the technology and the tests only take a certain amount of time". This finding is confirmed by Interviewee 2: "The difference [between conventional and autonomous projects] comes later with the [technical] equipment".

In all implemented road-bound projects in Germany, the funded testing of the technology was the main objective (VDV, 2021b). Significant improvements of the existing systems or a general improvement of the availability or quality of public transport on the road were not achieved (cf. VDV, 2021b). According to the European Regulation No. 1370/2007 on public passenger transport services by rail and road, regular public transport services are usually implemented by the competent authorities through a tendering procedure. In contrast, the implementation processes of the autonomous road-bound bus projects studied are very different and individual: specific framework conditions lead to individual permission and approval procedures for each project and each vehicle used (Interviews 3-6). Influencing factors that shape the implementation and authorisation scheme are the targeted level of automation, the type of space, the type of area and the type of service (ibid.). It can be concluded that each individual case has its own complex development, planning and implementation process.

### Comparison between road-based urban and rural projects

As highlighted earlier, there are high hopes that autonomous driving can secure or improve the provision of public services, especially in rural areas. Unfortunately, the use of the technology in such circumstances has not been feasible so far. A few projects in Germany have focused on rural areas, but they have not been successful: “The use of the vehicle and the use on the route has not been clarified at all in rural areas. That didn't work either” (Interview 5). The main problems were the approval procedure and the technical equipment of the vehicle and the track: “We wanted to do it (...) on a rural road and then you start all over again with this first approval issue that we had here on the “EuRef”campus. Um, because there are technical problems. The shuttle just drives great in its own field that it knows, orients itself, that's just not the case in the countryside. Then there's a field, the field is harvested, there are trees that lose their leaves, there are things that also move, sensors like this can't cope with that. Um, that means you should actually offer it something else as orientation, (...) it has to be a bit higher to be safe, and that means you actually have to build something like a guardrail or something along the whole route. Of course, that's way too time-consuming, so we didn't do that (...)” (Interview 5). Therefore, according to the qualitative data used in this article, the technology has only been successfully tested in urban areas.

### Comparison of autonomous rail-bound and road-bound public transport

Comparing autonomous road-bound and rail-bound public transport, it is clear that the deployment of autonomous rail, especially regarding fully autonomous metro systems, is several steps ahead of autonomous road-bound public transport. There are many existing fully autonomous mass transport systems around the world and also in Europe (UITP, 2019, p. 1). Autonomous metro systems with different levels of automation play an important role as part of public transport systems in London (Docklands Light Railway), Paris, Copenhagen and other large and medium-sized cities (UITP, 2019, p. 1; Allianz Pro Schiene, 2021). In 2016, one billion passengers were transported by autonomous metro systems in Europe (Allianz Pro Schiene, 2021).

In road-bound transport, mostly time-limited demonstrations can be found. In addition, there is a strong dependence on specific subsidies, which excludes these services from existing, reliable and long-term planned and financed transport systems.

In rail transport, for example, existing industrial solutions from companies such as Siemens have been in use for decades, whereas in road-bound public transport the technical infrastructure is still in a development process. This also results in the possibility of knowledge transfer between local governments and transport companies. The transfer of knowledge was identified as very important for the implementation process. This transfer is largely carried out within the urban rail community, while the only form of knowledge transfer in the road-bound transport sector was found with Interviewee 5. This expert was involved in the projects studied in Berlin, Osnabrück and Bad Essen. Early problems from the Berlin case were successfully avoided in Osnabrück and Bad Essen (see the following section).

One explanatory factor for these serious differences between rail and road can be found in the technical complexity of the projects. While automation in rail transport is mainly about automating the driving process, autonomous steering is additionally required in road-bound transport. Furthermore, all the projects examined in Germany also dealt with the electrification of the vehicles, while metro systems are already electrified. Some road-bound projects also focused on the implementation of an on-demand system, which again increased the complexity of the projects (cf. Interviews 1-6).

Nevertheless, there is one important commonality: transport companies play the main role in successful implementation processes in both rail and road transport, as the following section shows.

## Formation of stakeholder cooperation

### The "First Mover" and "Pole Position" projects in Berlin: The absence of a transport company

The projects were carried out under special conditions: the technology was in an early stage of development and was tested on private property (VDV, 2021; Interview 5). A key result of the Berlin projects was the finding that a transport company was needed: "If afterwards there is no one who actually has a clue how to go on, how to integrate it, how to use it, who the users are, how to advertise it, which is all the case with a transport company, then I don't know how well it works. (...) Then you need an operator" (Interview 5). Nevertheless, the project itself was successfully implemented. The vehicle manufacturer was responsible for the development of the vehicles and the software, while the private development company was responsible for the permits and approvals (Interviews 5-6).

### The "Bad Birnbach Shuttle" and "Heal" projects in Bad Birnbach: The transport company is responsible for all tasks

In the case of the projects in Bad Birnbach, the transport company was the main actor. It took the initiative, financed and coordinated the projects. The public sector benefited greatly from the offered services without having to put in much effort (see Table 2).

***Table 2**: Distribution of roles of the actors and decision-making in the projects "Bad Birnbach Shuttle" and "Heal" in Bad Birnbach (Source: own representation based on Interview 3-4).*

| | Transport Company | Local Government |
|---|---|---|
| Shuttle | • First Initiative<br>• Funding of the project | - |
| Heal | • Obtaining expert opinions and authorisations for autonomous passenger transport<br>• Individual registration of vehicles<br>• Application for commercial transport to the district government (which is above the local government) | • Acquisition (100% funding) and special registration of the vehicles in a consortium with the other project participants<br>• Traffic adaption of the route: maximum speeds and one-way street regulation |

### Osnabrück and Bad Essen: Teamwork under the leadership of the transport company

The "Hub Chain" project was the most recent of the projects studied. In this case, the planning and implementation process was driven by teamwork led by the transport operator (Interview 5). The transport company was responsible for successful operation, while the local government provided the necessary framework conditions (see Table 3).

***Table 3:** Role distribution of stakeholders in the case of the "Hub Chain" Project in Osnabrück and Bad Essen (Source: own representation based on Interview 5).*

| | Transport Company | Local Government |
|---|---|---|
| Hub Chain | • Operation<br>• Storage and maintenance in the depot<br>• Integration into the public transport system<br>• Marketing | • Preparation and adaptation of the route (one-way streets and parking bans)<br>• Installation of bus stops<br>• Communication<br>• Involvement of citizens |

### The "Rubin" project in Nuremberg: Automation without influence on cooperation

Due to the system characteristics of fully independent metros, there are hardly any differences in planning and implementation between conventional and autonomous projects (Interviews 1-2). Therefore, the processes between the municipality and the transport company remained largely unchanged (ibid.). The transport company still mainly focused on the technical planning, while the municipality was mainly involved in the construction of the tunnel and other non-transport elements (see Table 4).

***Table 4**: Distribution of roles of actors and decision-making in the case of the "Rubin" project in Nuremberg (Source: own representation based on Interview 1-2).*

| | Transport Company | Local Government |
|---|---|---|
| Rubin | *Main focus on technology*<br>• Autonomous Operation<br>• Maintenance<br>• Safety<br>• Provision of technical know-how in metro construction and planning: support for the municipality in all technical trades: energy supply, communication systems, train protection technology, planning services for operational issues).<br>• Procurement, maintenance and ownership of the vehicles | *Main focus on construction*<br>• Political decision to build the system<br>• Construction of the infrastructure, e.g. tunnels (metro construction office)<br>• Owner of the infrastructure (in other cities also transport companies)<br>• Financing of the project |

## Transfer of knowledge and technology

In the case of the autonomous metro project in Nuremberg, knowledge transfer to the city was a main factor for successful project implementation (Interviews 1-2). Later, Nuremberg exported its know-how to other cities: "When we started the project, many things were new to us. We simply went to transport companies that have an automatic system. You could also say that Lyon and their system was in a way the godfather for Nuremberg, because it's a system of the same size, with similar passenger numbers, and they basically gave us a bit of a brainstorm or answers to questions we had, or gave each other tips on what to think about. And while we were realising this in Nuremberg, we had over 40 other transport companies as guests who came to us for information because they had similar thoughts about switching to automation in the future. Of course, Hamburg was there a couple of times, Vienna was there a couple of times, so those who now practically have automation projects running" (Interview 1).

Through the "Rubin" project, city stakeholders became part of an emerging informal network working on the implementation of autonomous metro systems, spreading across the entire European continent (see Figure 5). Moreover, the technical equipment developed in the "Rubin" project was later exported to another city: "We have this system [by Siemens, open, without platform doors] running here in Nuremberg, and a similar system with the same components is [now] running in Budapest" (Interview 2). Standardisation of frame conditions as well as technology can therefore be seen as a driver for implementing fully independent autonomous metro systems.

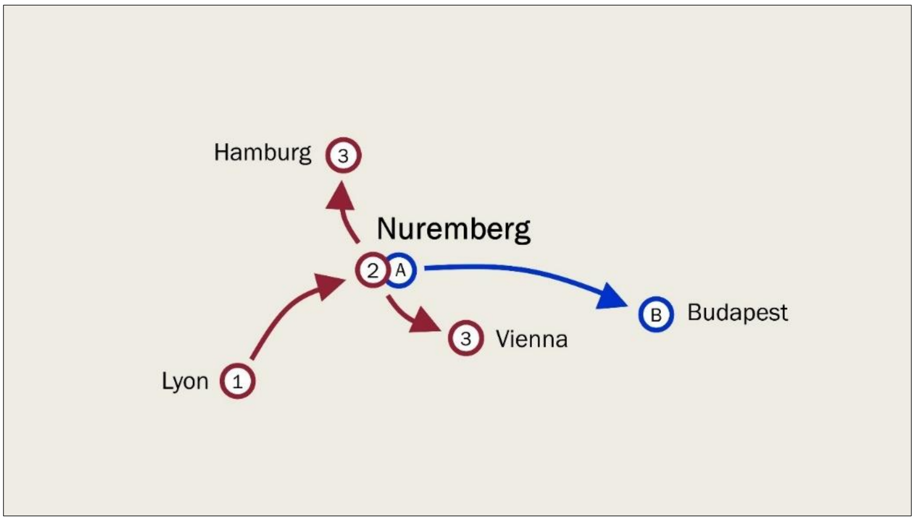


***Figure 5**: Knowledge transfer (in purple) and technical equipment (in blue) in the case of the "Rubin" project in Nuremberg (Source: own representation based on Interview 1-2).*

# Discussion

## Heterogeneous results and different research areas

This article revealed a multitude of new insights. However, a comparison of rail-bound and fully independent metro systems on the one hand and road-bound bus systems on the other hand brought hardly any new insights, apart from the important role of transport operators in implementation and operation. As the systems are very different (functionality, legal framework, operating environment, etc.), further research should be divided into two different research areas. Whereas in road-bound transport much more fundamental questions such as case-by-case approval and technical feasibility need to be answered, these aspects are fully clarified for autonomous metros. The independence of the systems from the rest of the environment leads to less complexity in automation. However, an exciting field of research here is the possible formation of informal knowledge networks – an aspect that was central to the autonomous metro in Nuremberg.

Trams represent an intermediate form of the two areas studied. Although they are more related to metros in terms of technology and legal framework, they are close to road-bound transport in terms of the diverse challenges in operation. Light rail systems are also widespread, often featuring metro-like tunnel sections in addition to historically grown tram lines on the same route. In these cases, the challenges of autonomous tunnel operation are of course much greater than with a completely independent metro system. In Germany, there are no projects with autonomous trams yet, but such vehicles are already in the industrial development stage (Siemens, 2019). Should such projects be implemented, it is worthwhile to conduct further comparative research.

Another field of research is the automation of heavy trains, which are used in particular in regional and long-distance transport. The introduction of the European Train Control

System (ETCS) enables both digital signalling and direct train control and is thus the most important basis for the introduction of autonomous trains in the future. The reason why this topic is not covered in this article are fundamental differences between heavy rail transport on the one hand and public transport with metros, trams and buses on the other hand. Different legal bases (cf. legal bases of EBO, BOStrab and BOKraft) as well as different system architectures lead to heterogeneous implementation processes. Since the EBO (heavy rail) defines the functional rules more precisely, autonomous technology can be implemented on a common technical basis. In the case of BOStrab (mainly undergrounds and trams) as well as BOKraft (buses), the transport companies are more flexible, but also more dependent on individual solutions. Cases such as the S-Bahn Hamburg, which is now introducing automatic train operation based on ETCS, are also worth investigating and comparing with metros.

### Autonomous public transport as a contribution to the provision of public services

With regard to securing services of general interest in rural areas, the current results are a setback for the many hopes that have been voiced in numerous pilot projects in Germany. It remains unclear whether and when standardised and reliable industrial solutions, analogous to self-driving subways, will be available. Overall, the results paint a rather limited picture of the current state of autonomous road transport. This is in contrast to many enthusiastic media reports about the existing and planned pilot projects.

### Changing framework conditions in the future

The advent of autonomous driving technologies has made it possible to organise public transport in a different way than before (Lenz & Fraedrich, 2015, p. 177). Mobility-on-demand in particular is becoming increasingly popular (Pavone, 2015, p. 401). The boundaries between individual transport and public transport may disappear (Beiker, 2015b, p. 204). In this case, the progressive development of private autonomous cars could also increase the possibilities for organising autonomous public transport in the future. This can be the case, for example, through a technology transfer in the direction of public transport, but also through the integration of private vehicles into public transport.

## Conclusion

Several main objectives are being pursued with the introduction of autonomous public transport. From a conceptual point of view, there are three main factors: ensuring the provision of services of general interest in rural areas, covering the first and last mile in urban public transport and compensating for the shortage of driving personnel on the German labour market. In addition, the case studies examined in this article attempted to address specific challenges, in particular the capacity expansion of the metro network in Nuremberg and a basic realisation of autonomous trial operation in the road-bound projects. The introduction of autonomous public transport also presents a number of conceptual challenges, particularly in the areas of technology, law and ethics. While technology and law are evolving, conflicts in the area of ethics remain unresolved.

The analysed case studies highlighted that the automation of public transport differs between rail- and road-bound systems. In the case of rail, only minor differences were found between different projects, as a higher degree of standardisation has already been achieved here. In the case of road transport, the processes are very different and therefore individual. Furthermore, the automation of road-bound technologies is more challenging than rail transport. While rail transport mainly requires the automation of driving for fully autonomous metro systems, road transport also requires the automation of steering. In addition, all the projects examined focus simultaneously on the electrification of vehicles, while energy supply in rail transport is already traditionally provided by electric power. Some projects additionally focus on the implementation of on-demand transport, which significantly increases the complexity.

There are also differences between road and rail in terms of the usability of existing technologies. For example, autonomous rail-bound technologies already contribute to public transport, and standardised industry solutions exist and are shared. Essential knowledge transfer is thus carried out successfully and planning processes are standardised. Moreover, differences to conventional transport in planning and implementation are relatively minor.

In contrast, autonomous road technology is still in an evolutionary development process. Industrial solutions do not yet exist. As every case is different, knowledge transfer is difficult. Autonomous road-bound technologies cannot yet contribute to public transport, especially in rural areas. Compared to conventional transport, there are huge differences. In road-bound public transport, different actors are involved in each implementation process and therefore the cooperation frameworks vary greatly. The implementation processes of autonomous bus projects also differ in urban and rural areas. As far as the research for this article shows, only successful implementation in urban areas has been possible so far. The implementation of autonomous road transport in rural areas is not yet feasible – there is not a single successful case outside settlement areas in Germany.

However, in both road and rail transport, transport companies appear as the main actors in the course of the implementation process. In conventional road transport, the authorities are the main actors. Finally, it should be emphasised that knowledge transfer was identified as a key success factor in the study. Road-bound public transport should therefore learn from the successful knowledge sharing practices in rail transport in order to be successful.

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