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Requirements for Pilot Routes and Infrastructure for the Introduction of Automated Shuttle Buses in Public Areas

Anforderungen an Pilotstrecke und Infrastruktur bei der Einführung automatisierter Shuttlebusse im öffentlichen Raum

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Automated shuttle buses are part of future mobility concepts due to their flexibility and cost efficiency. In order to enlarge the expansion of pilot operations with automated shuttle buses, local authorities and transport companies in particular need information on the possible uses of the vehicles in public areas. On the basis of a best-practice analysis and a market analysis, this paper presents requirements for pilot routes and infrastructure for the introduction of automated shuttle buses in public areas. Furthermore, the results of the analysis are evaluated in relation to the time horizon.

[Keywords: Automated Shuttle Buses; Pilot Routes, Infrastructure; Requirements; Possible Applications]

Automatisierte Shuttlebusse sind durch Flexibilität und Kosteneffizienz Teil der zukünftigen Mobilitätskonzepte. Um den Ausbau von Pilotbetrieben mit automatisierten Shuttlebussen zu erweitern, benötigen vor allem Kommunen und Verkehrsgesellschaften Informationen zu den Einsatzmöglichkeiten der Fahrzeuge im öffentlichen Raum. Anhand einer Best-Practice-Analyse und einer Marktanalyse werden in diesem Beitrag Anforderungen an Pilotstrecken und Infrastruktur bei der Einführung automatisierter Shuttlebusse im öffentlichen Raum vorgestellt. Darüber hinaus werden die Ergebnisse der Analyse in Abhängigkeit des zeitlichen Horizonts bewertet.

[Schlüsselwörter: Automatisierte Shuttlebusse; Pilotstrecken; Infrastruktur; Anforderungen; Einsatzmöglichkeiten]

1 INTRODUCTION

The future development of mobility is primarily driven by megatrends. These include demographic change, increasing urbanization, individualization, scarcity of resources, climate change, the increasing focus on sustainability and technological developments focussing on digitization [Ber17a; Dan19b, pp. 495ff; Rin12, p. 4; Heg18, pp. 4-7; Rit18 pp. 208ff]. The current situation in urban areas reveals that, as the number of inhabitants and the age of users increases, so does transport performance [Bun18b, pp. 218f]. This consequently leads to traffic jams, high level of pollution and an increased demand for space for designated traffic in cities [Kni19, pp. 6f]. In rural areas, public transport with its rigid line management, is declining. The reduction in population and the increased demand for individualization require flexible solutions in rural areas [Kni19, p. 7; Heg18, p. 4]. As a result, the population in rural areas increasingly favours motorised private transport [Kni19, p. 7]. In order to counteract these megatrends and ease the current symptoms of mobility, literature describes the future mobility as efficient, organized, electric, automated, networked and safe [Ago17, pp. 22- 60; Kni19, pp. 11-20; Kag17, pp. 359-366; Sus19, pp. 19ff]. In addition, it should be possible to use mobility systems collectively and universally [Ago17, pp. 44ff; Kni19, p. 12]. Efficiency means offering as much mobility as possible while simultaneously using as few resources as possible [Ago17, pp. 22ff]. This also contains implementing of new mobility services which are more flexible and demand oriented [Kni19, pp. 12f]. Infrastructures such as roads and parking spaces, pollution (e.g. CO2 emissions) and money are the resources that must be reduced [Kni19, pp. 11f; Ago17, p. 22ff]. In order to realize better use of space resources, traffic must be organized [Kni19, p. 12]. Electric mobility is a key to both energy system transformation within the transport sector and the reduction of CO2 emissions [Ago17, pp. 52ff; Sus19, pp. 19ff; Kag17, pp.359ff]. The automation of vehicles has positive and negative effects [Ago17, p. 45]. If the automated vehicles are used jointly, the number of vehicles, traffic accidents, mobility cost and emissions can be reduced [Ago17, p. 42]. However, if automated vehicles are only used in private ownership, the above-mentioned indicators increase, apart from road safety [Ago17, p. 45]. Automated vehicles can be used in urban areas but are especially used in rural areas [Kni19, pp. 14ff]. There are two facets concerning networking. On the one hand, there is the concept of networking vehicles to better control of the traffic flow and increase safety [Ago17, pp. 45ff]. On the other hand, there is the idea of linking all mobility systems on a digital mobility platform (Mobility as a Service), to which

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every user has universal access [Kag17, pp. 363ff; Kni19, pp. 12f]. The amount of land consumed by mobility can be reduced, among other things, by reducing the number of vehicles [Ago17, pp. 44f]. This requires a shift in the population´s attitude of mobility, moving them more towards a culture of sharing vehicles instead of owning them [Kni19, p.12]. In summary, future mobility is characterized by a demand-oriented and flexible supply of all population groups with mobility offers while at the same time being cost-efficient and meeting increased ecological requirements.

One new mobility concept that meets a majority of mobility requirements is individual public transport [Bar20, p. 16]. It combines the flexibility of individual transport with the capacity utilisation and economy of public transport [Bar20, pp. 16f; Lal19, pp. 40ff]. An example for individual public transport is the automated shuttle bus which can be supplemented by on-demand services [Kni19, pp. 22f]. The automated shuttle bus is a minibus used for public transport [Kol20, p. 68]. Depending on the type, the vehicles offer space for up to 15 people and are electrically operated [Kol20, p. 68; Kos19, p. 24]. In active pilot operations, the routes are programmed into the shuttle buses via differential GPS [Kol20, p. 62]. The vehicle thus moves on virtual tracks, can detect obstacles, but most of the time cannot avoid them independently [Kol20, pp. 62f]. In that case, the vehicle is handled by an operator via joystick, who must be present at all times in accordance with the approval requirements [Kol20, pp. 62f; Mic17, p. 12]. According to the automation stages defined by [SAE18] the automated shuttle buses are classified between "partially automated and "fully automated" [Kol20, p. 63; Kos19, p. 64]. That is why the term "automated" is used in this paper. It is anticipated that automation will offer more cost-effective operation [Kol20, p. 59]. Furthermore, the automated shuttle bus is predestined for rural areas and low-capacity routes in the city, where it should reduce motorized individual traffic [Kol20, p. 59; Jür20, p. 39; Kos19, p. 23]. The electric drive is also expected to reduce pollution such as CO_2 emissions [Lab18, p. 11].

Although autonomous driving will not be achieved before 2030, the number of pilot projects with automated shuttle buses increases [Lal19, p. 19; Kni19, pp. 17f; Ver20a]. The potentials of automated vehicles can already be used and experiences in public space can be gathered [Ver20a; Kni19, pp. 22f]. The introduction of automated shuttle buses places a number of demands on the infrastructure of the region it is entering [Mic17, pp. 29f; Mit20, pp. 67ff]. That is why it is important in pilot projects, to plan the route for the automated shuttlebus at an early stage. Since automated transport has not yet matured on a technological level, the requirements for the route and infrastructure must be considered in addition to legal, economic and administrative demands before an automated shuttle bus line can be introduced [Bra18; Bar20, p. 21; PTV19b; PTV19a]. Therefore, the aim of this publication is to present the requirements for the pilot route and infrastructure necessary to introduce automated shuttle buses in public areas. For this purpose, a best practice analysis of automated shuttle bus projects in Germany, as well as a market analysis of manufacturers of these vehicles will be used.

At the beginning of this publication, the existing literature pertaining to this topic is discussed. Afterwards, the procedure of best practice analysis and market analysis will be explained. The results of the analysis together with the requirements for pilot route and infrastructure will then finally presented in the fourth chapter. In the fifth chapter the benefit of the requirements is discussed. Finally, a summary and further research regarding this topic are given.

2 RELATED LITERATURE (STATE OF THE ART)

Automated shuttle buses have gained in importance in recent years and the number of pilot operations has increased not only in Germany but also worldwide [Ver20a; Bak18]. The beforementioned trends in Chapter 1 promote this development. Due to their innovative value, most pilot operations are conducted within the framework of research projects or in cooperation with research institutions [Ver20a]. They range from the investigation of potential applications of automated shuttle buses and user acceptance (social and economic aspects) to the testing of technology development and safety as well as the analysis of the legal basis for autonomous driving [Aza19, pp. 2ff].

The pilot projects are usually evaluated and documented in the literature in two ways. On the one hand, the individual pilot operation with automated buses is analysed and described in detail in the form of a report or a case study. On the other hand, the projects on automated shuttle buses are summarised in the form of general overviews or literature reviews, which usually contain the key data and the most important goals/ findings of the projects. The comparisons of the projects serve to generalise the results and to derive specific recommendations for the planning and implementation of pilot operations.

Most pilot operations and research projects are currently being implemented in Europe [Aza19, pp. 2ff; Pes16, pp. 1ff]. A prominent example of the cooperation of European shuttle bus manufacturers, co-funded by the European Union's Seventh Framework Programme, is the CityMobil2 project [Pes16, pp. 1ff]. The pilot operations took place in seven European cities between 2012 and 2016 [Pes16, pp. 1ff]. The aim of this big project was to advance the vision where automated vehicles become a part of an Automated Road Transport System (ARTS) and to evaluate the legal and technical frameworks necessary to implement ARTS on the roads [Ale14]. The project provided important insights into the development and integration of ARTS in urban areas [COR16]. Data was collected on how other road users interact with automated vehicles and a legal framework for the certification of ARTS was designed [Pes16, pp. 1ff; COR16].

One of the larger studies conducted in Germany on the use of automated shuttle buses as an extension of public transport services is based on the pilot operation in Bad Birnbach. The study focuses on the analysis and evaluation of the use of automated shuttles from a technical, social and planning perspective. The investigations of the connectivity in the public transport service structure have shown, for example, that the use of automated shuttle buses can make a significant contribution to better connecting rural areas. The subjects of the user acceptance study were generally positive about the shuttle bus. The automated shuttle bus also scored well in terms of safety. [Kol20; Bar20; Win20b; Win20a; Jür20; Rau20]

The case study commissioned by the Federal Ministry of Economics and Energy to the VDI Technology Center also reflects the pilot operation in Bad Birnbach with regard to the requirements of the legal, economic and administrative framework for the introduction of automated shuttle buses. The case study provides valuable information for the approval procedure of automated shuttle buses. In addition, the example of Bad Birnbach shows that the financing of such a project can be guaranteed by the industrial partners on the one hand and by the communities and state governments on the other hand. [Bra18]

The Association of German Transport Companies (VDV) maintains a general overview of current and planned pilot operations in Germany. At the time of publication, the overview includes 44 autonomous shuttle bus projects. For each project, the overview lists the formal framework conditions such as the location, provider, cooperation partners, the vehicle, the goals as well as the current status of the project. More detailed information can be found on the respective project homepage. Whereby no or only a few results of pilot operations for most active projects are available yet. [Ver20a]

The results of the "LEA (Klein-) Bus" research project, funded by the Federal Ministry of Transport and Digital Infrastructure, are based on a comparison of 34 pilot operations in Germany and around 70 pilot operations abroad, most of which are localised in Europe. The final report of the study illustrates important prerequisites and possible applications for automated shuttle buses. A total of eight categories were defined and analysed, such as vehicle technology, IT and transport infrastructure, operational effects, cost effectiveness, fields of application and forms of operation, system acceptance, legal framework, market development and possible business models. As an important aspect in the implementation of the pilot operations, questions of approval and liability were identified. The IT infrastructure plays a central role in the feasibility analyses and the planning of the pilot operations. For example, network coverage for data communication and updating of digital maps is paramount. With regard to the transport infrastructure, the "LEA (Klein-) Bus" project concludes that most road infrastructures are currently not suitable for fully automated, connected driving. The main point here is the importance of regular care and maintenance of the infrastructure, signage and road markings. [PTV19a]

Similarly, [McK19b; McK19a] concludes that stops, signage, lane markings and charging infrastructure should be more developed. This is confirmed by the latest McKinsey studies for the USA. In order to fully exploit the potential of automated vehicles, key tasks such as integration of autonomous vehicles with existing transit, capital planning for an uncertain future, optimizing and redefining curb, redeveloping off-street parking, rethinking road construction and maintenance should be addressed. [McK19b; McK19a]

Furthermore, there are standalone approaches in the literature, which deal with the evaluation of existing infrastructure regarding the usability for automated shuttle buses. The approach of [Sch19b] is based on the analysis of the essential traffic and information technology requirements for the infrastructure and the identification of the weak points using selected model regions in Germany (Leonberg and Böblingen). The results of the analysis were presented in the form of a flowchart (decision tree) for each of the categories "charging infrastructure", "road equipment", "road space and road infrastructure", "data collection", "data transmission" and "platform and functionality". The questions of the flowchart can be answered with "yes" or "no" and are intended to provide assistance in evaluating the suitability of a region for automated shuttle buses. For example, the flowchart "Road space and road infrastructure" takes into account such aspects as the presence of separate bus lanes, road condition, road markings, intelligent equipment, parking spaces and bridges. [Sch19b]

Information on the requirements for the pilot route and the infrastructure are essential for potential stakeholders [Kni19, p. 23]. Counties and municipalities as well as mobility providers need them for a fast and optimal decision making for the realisation of autonomous shuttle bus lines [Kni19, p. 23]. However, so far there are hardly any comprehensive studies that analyse the infrastructural requirements for the use of automated shuttle buses in public transport. While the study "LEA (Klein-) Bus" [PTV19a] carried out under the direction of the PTV Group and the work of [Sch19b] provide some approaches for the analysis of potential infrastructure requirements, this aspect has not yet been sufficiently investigated in the literature. The before mentioned studies offer important indications as to which infrastructural aspects need to be considered when planning a pilot operation. But they do not go into more detail about the feasibility of concrete route characteristics such as route length, carriageway width, stops, vehicle velocities or special features such as intersections, roundabouts and traffic lights. The actual infrastructure required for the implementation of a pilot operation is also not specified.

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Therefore, this publication aims to answer the question of the current structural and technical requirements for a pilot route. The objective is to give the stakeholders an overview over the currently feasible routes and traffic situations as well as the infrastructure adjustments that may be necessary for the pilot operation. It should be noted that the requirements should always be considered in the context of the current technological development of automated shuttle buses.

3 METHODICAL APPROACH

To determine the requirements for the pilot route and infrastructure required for the introduction of automated shuttle buses, the methods of benchmarking and market analysis are used.

Benchmarking is a targeted way of searching for new ideas and approaches to improve products, processes and methods [Mer09, pp. 19ff; Töp97, p. 4]. A distinction is made between the benchmarking of companies, of sectors and of framework conditions [Mer09, p. 31]. The external benchmarking of companies is then divided again into market-related benchmarking (with regard to competitors), sector-related benchmarking and sector-independent benchmarking [Mer09, p. 32]. Municipalities and transport providers, which are responsible for the implementation of pilot operations with automated shuttle buses, are equated with companies or competitors in this methodology. The pilot operations are products/ services of the municipalities and transport providers. In the context of the aforementioned definition, market-related benchmarking analyses the pilot operations of automated shuttle buses for which municipalities and transport providers are responsible. Benchmarking is characterised through the examination of best practices [Sys06, p. 29]. Therefore, a best practice analysis of pilot operations with automated shuttle buses was carried out to determine the requirements for the pilot route and infrastructure. This analysis is presented in Chapter 3.1.

A market analysis serves to identify the producers/ owners and examine the performance characteristics of the products/ services offered [Pil16, pp. 85ff; Alb16, pp. 1358f]. The implementation of the pilot operations or the selection of the pilot routes depends on the vehicles used [REG20b]. Accordingly, the market analysis serves to identify the manufacturers/ providers and their vehicles as well as examine the performance characteristics of the automated shuttle buses (Chapter 3.2).

In Chapter 3.3 the methodical approach is critically evaluated.

3.1 BEST PRACTICE ANALYSIS PILOT PROJECTS

A best practice analysis is divided into the following steps: Identifying, analysing and implementing [Hei99, p. 39]. In this analysis, the focus is on recording the pilot projects. These results are used to derive the requirements. Therefore, the implementation is not considered. The first step is identifying the pilot projects. The analysis is then further divided into three steps: Developing a catalogue of criteria, conducting the analysis and evaluating the results. An iterative procedure is used for the analysis. The criteria catalogue is adapted from the basis of the analysis findings.

Identifying Pilot Projects

The approval of an automated shuttle bus, which is thus the approval of a pilot operation, depends on the vehicle approval ordinance, the road traffic law, the road traffic regulations and the road traffic approval regulations [Bra18, p. 4]. The registration law is also regulated beyond Germany in accordance with ECE regulation 79 [Lut17, p. 214]. However, the road traffic regulations are regulated nationally [Lut17. pp. 217f]. In order to ensure comparability between the pilot projects, only pilot projects in Germany are analysed. In addition, only pilot operations with an automated shuttle bus in which passengers are transported are considered. [Ver20a] and [PTV19b] provide a detailed overview of pilot projects centred around automated shuttle buses in Germany. This is supplemented by an own internet research.

Developing a Catalogue of Criteria

To evaluate the pilot projects, the criteria are determined using the brainstorming method and are divided into six categories:

1. Vehicle-related criteria
2. Route-related criteria
3. Communication technology-related criteria
4. Legal criteria
5. User/provider-specific criteria
6. Organisational criteria

Vehicle-related criteria include the designation of the vehicle, passengers to be carried and speeds of pilot operation. The route length, number of stops and special features of the route (e.g. roundabouts and intersections) are determined under the route-related criteria. The communication criteria include the communication of the vehicle with a control centre or traffic lights. As already explained, the approval of the vehicle is necessary for the pilot operation. Criteria concerning the type of approval, the competent authorities and the duration of the approval process are part of the legal criteria. In order to be able to evaluate the implementation of the pilot operation with regard to the user and provider, for example, it will be determined whether the use is free of charge, whether a user survey will be carried out and whether there have been accidents in the operation. With the help of the organisational criteria, the

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processing steps, the time schedule and the infrastructural adjustments are identified.

Execution of the Analysis

The analysis of the pilot projects of automated shuttle buses is largely based on internet and literature research. This is supplemented by telephone interviews and personal visit to selected pilot operations. Due the lack of contact persons for the pilot projects and the higher expenditure of time and personnel, this is the chosen approach. For each pilot project the criteria catalogue was filled in as much as possible. Each piece of information is provided with a reference to the source. The analysis was carried out between October 2019 and June 2020 (deadline on 09.06.2020).

Evaluating Results

A total of 63 projects with automated shuttle buses were identified in the analysis. In the first step of the evaluation, the degree in which the respective criteria catalogues were filled out, was observed. In order to be included in evaluation, information on either the vehicle or route or on the pilot operation had to be available. This filter reduced the number of projects to 49. The results from the individual criteria catalogues were summarised within the categories in order to evaluate and compare the individual criteria (see Chapter 4).

3.2 Market Analysis Automated Shuttle Buses

Similar to [Pil16, pp. 85f] and [Alb16, p. 1358f], the market analysis procedure is divided into four steps. First, the providers of automated shuttle buses are identified. Before the survey is conducted in the third step, the questionnaire is designed in the second step. The results are then evaluated.

Identifying Providers

As with the best practice analysis, the market analysis focuses on providers of automated shuttle buses used for passenger transport. For the market analysis, it is irrelevant whether a provider´s automated shuttle bus is already in pilot operation or whether the provider's vehicle has not yet been used in public. Based on the internet and literature research on pilot projects in Germany, Europe and worldwide, the providers of automated shuttle buses could be identified. The providers are differentiated between manufacturers (e.g. EasyMile, Navya, Local Motors) and operators (e.g. Transdev Group S.A., Keolis S.A, ioki GmbH). A total of 13 providers were identified, of which three act as operators.

Designing the Questionnaire

The questionnaire is divided into four categories, "Vehicle/ Performance Data", "Steering", "Communication/ Infrastructure" and "Organisation (time estimation/ pilot route)". The individual questions are largely taken over from the criteria catalogue for the pilot operations and partly supplemented.

For the implementation of a pilot operation, it is important to know how fast the vehicles are driving, how many passengers can be transported, whether the vehicles are barrier-free and which road widths and gradients they can be driven on. These criteria were, among others, queried in the category "Vehicle/ Performance Data". Questions pertaining to the automation level of the vehicle, weather-related restrictions and control in the intersections are part of the category "Steering". In order to test communication with the infrastructure, possible interfaces, V2X technologies of the vehicle and infrastructure requirements were queried in the third category. Finally, the providers were asked about the preparation time of a pilot operation, an approval of the vehicle, requirements for the pilot route and their experiences with the implementation of a pilot operation.

Conducting of the Survey

As part of a "Request for Information" (RFI) in preparation for a public tender for an automated shuttle bus, the questionnaire was sent by e-mail to all 13 identified providers. The providers were given 14 days to answer the questions. The survey was conducted in October 2019.

Evaluation of the Questionnaire

A total of three completed questionnaires were returned (EasyMile, Navya, Local Motors). Furthermore, there was a personal interview with e.GO MOOVE GmbH. The answers provided from individual manufacturers were then evaluated separately for each category and compared with one another. The results are presented in Chapter 4.

3.3 Critical Evaluation of the Methodology

The key figures of sample size and usage rate are suitable for evaluating data quality [Die04, p. 25]. In this chapter, the population and the survey methodology of the best practice analysis and the market analysis are thus critically evaluated. The creation of the criteria catalogue, the questionnaire and the data evaluation are not included in this evaluation.

Best Practice Analysis

The data quality of the survey can be improved by increasing the population of the analysis [Die04, p. 25]. This would be possible if further pilot projects from Europe (or worldwide) were considered. However, this would result in an increase of the survey effort. In addition to the higher number of data sets, communication with international project teams may also be more complex. The comparability of the pilot projects due to the different legal regulations

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must be checked first. For these reasons, the authors have decided against increasing the sample size in the best practice analysis (see Chapter 3.1). The data collection is mainly based on internet and literature research. A disadvantage of this survey form is that not all information on the projects are available in the media. In addition, a large part of the information is based on newspaper articles and project homepages, some of which provide inconsistent information on the projects. To obtain a better response rate (49 of 63 projects), a personal survey of the individual pilot projects would be suitable. However, this would have been much more time-consuming, since the contact people have to be identified first.

Market Analysis

In order to determine the providers of automated shuttle buses, the pilot projects in Germany, as well as worldwide, were examined with regard to the vehicles used. As a result, a sample size of 13 providers was derived. According to the authors, this sample size includes the most important providers of automated shuttle buses and does not need to be increased.

The low utilisation rate of four answers shows that the survey methodology can be improved. As with best practice analysis, a personal survey could have been carried out and would probably have generated a larger data set. More specific questions could also have been asked in a personal dialogue on the feasibility analysis of the pilot routes carried out by the shuttle bus manufacturers. This would have made it possible to obtain a more detailed overview of the manufacturers' requirements for the pilot routes. But this approach requires more time and human resources.

In principle, both analyses could have generated better data with more effort. This should be considered in future research regarding this topic.

4 EMPIRICAL FINDINGS

The results in this chapter are based on the literature presented in Table 1. In the text in Chapter 4 the literature is therefore no longer mentioned, unless explicit examples are given.

Table 1: Literature overview Chapter 4

Topic	Literature
Cities with pilot operations (Chapter 4.1)	*[Ver20a; Dan19a; Sch18; Reu17a; I-A19; Ing17; Bön20b]*
Active pilot operations/ Duration of Pilot operations (Chapter 4.1)	*[Ver20a; Sch18; Dan19a; Reu17a; I-A19; Ing17; Bön20a; Sta20c; Ber20b; Süd20b; Ham20; FZI20; Lan20; Jan20; Eur20b; Ant20; Sta20f; ESW19; Reu18a; Süd20c; Eur20a; Rhe20; Sta18a; Red19; Süd18b; Lei20; Sta20e; Bec20c; Tec20c; Cha20; EUR20; Reu18b]*
Manufacturers and Number of vehicles (Chapter 4.1)	*[Ver20a; Kin19; App20; EUR20; Ing17; Lan20; Lud18; Ver18; Reu17a; Bön20a; Bec20c; Reh20; Reu18b; Aac19; Dig20; I-A20; Hey19; Sta20e; Fra19; Süd20b; Eur20b; Rhe20; Tra18; Pan19; Kli20; Süd18b; Tec20e; Beu19; Bil20b; Reu18a; Ver17; Sta19e; Mül19; Adl16; Sta20d; Str20; ESW19; REG20c; Nav19; Bec20a]*
Market analysis (Chapter 4.2)	*[Eas20; Nav20; e.G20b; Loc20; Eas19; Nav19; Loc19; e.G20c; Ste19; Tec20e; Sta20b; Fro19; Rai18; HEA19; REG16; Ber20a; Wie17; Nöb18; Wes19; Mär19b]*
General Requirements regarding route (Chapter 4.3)	*[Sta19a; e.G20a; I-A20; Lat18; Bra18; Sta20h; Tec20a; Ber17b; EUR20; Kug19; Joa17; Kah19; Sch19a; Reu17b; Rhe19; Tra18; HEA19; Bun20; FZI20; Ver20a; Ver20b; Ver20e; Syl19a; Süd18b; Süd20b; Bie18; Eur19; Bil20a; Ber19; Rhe18; Ver20d; Reu17a; Sta19c; Mün20; Kin16; Sta20e; Woc20; Bön20b; Str20; Bec20b; ESW20; Sch18; REG20a; Cha20; Sta20g, Ver20c]*
Route length (Chapter 4.3)	*[Sta19a; e.G20a; Lat18; Bra18; Sta20h; Tec20a; Ber17b; Kug19; Nut20; Sch19a; Reu17b; Rhe19; Tra18; HEA19; Bun20; FZI20; Ver20b; Ver20d; Ver20e; Ver20c; Syl19a; Süd18b; Beu19; Süd20b; Bie18; Eur19; Ber19; Rhe18; Reu17a; Sta19c; Mün20; Sta20g; Sta20a; Str20; ESW20; Sch18; REG20a; REG19; Eas19; Nav19]*
Number of stops (Chapter 4.3)	*[Sta19a; e.G20a; Lat18; Bra18; Sta20h; Ber17b; Kug19; Nut20; Sch19a; Rhe19; Reu17b; Tra18; HEA19; FZI20; Ver20b; Ver20d; Ver20e; Ver20c; Syl19a; Süd18b; Beu19; Süd20b; Eur19; Ber19; Rhe18; Reu17a; Sta19c; Mün20; Kin16; Sta20g; Sta20a; ESW20; Sch18; REG16]*
Special features (Chapter 4.3)	[Sta19a; Sta19d; e.G20a; Bön20b; Lat18; DB 20; Sta20h; Ber17b; Cha20; Sta18b; Flu19; Cha18; Nut20; Kah19; Reu17b; Rhe19; Rie19; Tra18; HEA19; Ham20; FZI20; Ver20b; Ver20d; Ver20e; Ehr19; Syl19a; Süd18b; E-M18; Tec20d; Jul18; Süd20b; Bie18; Eur19; Ber19; Rhe18; Reu17a; Mün20; Mül19; Sta20g; Str20; Bec20b; REG16; Ric18; Eas19]
Infrastructure (Chapter 4.4)	*[Lat18; DB 20; Sta18b; Flu19; Kug19; Süd20a; Eur20b; Wil17; Rhe19; Rie19; HEA19; FZI20; Syl19b; E-M18; Süd18a; Tec20b; Lüb19; Lei19; Jul18; Köh19; R+V18; Sta19b; Nel19; Kin16; Sta20g; Poh19; Sta20d; 3sa19; Mär19a; Eur20a]*

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4.1 GENERAL RESULTS OF THE BEST PRACTICE ANALYSIS

The 49 pilot operations with automated shuttle buses to transport passengers are realised in 35 different cities in Germany (see Table 2).

Table 2: Pilot operations with automated shuttle buses in German cities [Ver20a; Dan19a; Sch18; Reu17a; I-A19; Ing17; Bön20b]

Pilot operations with automated shuttle buses in German cities			
Aachen (4 projects)	Bad Birnbach	Bad Essen	Berlin (6 projects)
Darmstadt	Drolshagen	Enge-Sande (Sylt)	Frankfurt a. M. (3 projects)
Hamburg	Hof	Karlsruhe	Kelheim (3 projects)
Keitum (Sylt)	Kronach	Lahr	Lauenburg an der Elbe
Leipzig	Lennestadt-Mengen	Ludwigsburg	Lunden / Lehe
Magdeburg	Mainz	Mannheim (2 projects)	Marburg
Monheim am Rhein	München	Oberhausen	Osnabrück
Regensburg	Rehau	Eberbach	Soest
Stolberg (Südharz)	Wiesbaden (2 projects)	Wusterhausen	

According to the definition of rural and urban areas by [Bun18c], 36 pilot operations are located in urban areas, including the largest cities in Germany, such as Berlin, Munich, Hamburg and Frankfurt am Main [Bun18a]. The fact that 13 operations are also being carried out in rural areas (e.g. Bad Birnbach, Wusterhausen and Sylt) shows the wide range of possible applications for automated shuttle buses [Bun18a]. Currently eleven pilot projects are in operation (e.g. Wusterhausen, Lauenburg and Kelheim) and 23 pilot projects are planned (e.g. Hamburg, Aachen and Stolberg) [Ver20a; Lan20; Ham20]. The remaining 15 pilot projects have already been completed. Two projects in Berlin and the pilot operations in Lahr and Mainz are examples of completed pilot operations [Ver20a]. The first pilot operation was carried out in 2016 [Ver20a]. Thereafter, the number of approved pilot operations increased up to 24 pilot operations planned for 2020. Only two additional pilot operations are planned for 2021.

Due to the Covid-19 pandemic, however, it is likely that many projects will be postponed. The duration of the operation of automated shuttle buses is very diverse. For 15 projects a period of less than half a year is planned. In Oberhausen, for example, it lasted four days [Ver20a]. In contrast, another 15 projects are planned to run for more than a year. In Bad Birnbach, for example, the pilot operation has already lasted for almost three years [Ver20a]. The remaining pilot projects are either between the two categories or no information could be researched.

There have already been 35 vehicles used in pilot operations and further 43 automated shuttle buses are scheduled for the planned pilot operations. These statistics do not consider that vehicles have been used more often, as for example by the R+V insurance company or the project in Eberbach Castle [Bön20a; Reu17a]. The two French manufacturers EasyMile and Navya provide the majority of shuttle buses. The two German manufacturers e.GO MOOVE GmbH and IAV GmbH are the third and fourth biggest manufacturers. In almost all pilot projects with automated shuttle buses, the transport companies, as future operators predestined, are involved as leaders. They get usually support by the respective municipalities and topic related research institutes.

4.2 GENERAL RESULTS OF THE MARKET ANALYSIS

Table 3 shows the technical data of the four automated shuttles collected in the market analysis. All four vehicles are electric buses, which is why their performance in terms of maximum speed and operating time is below that of conventional diesel buses. Due to their smaller dimensions, they can also carry fewer passengers than conventional regular buses. Besides the automated driving mode, the shuttle buses can also be controlled manually by an operator. In the case of three providers, the manual control is possible with a remote control or a joystick. In this case the operator can stand. On the contrary to this, the e.GO People Mover has a driver's seat with a steering wheel. All four buses are designed to be barrier-free with an extendable ramp. According to the manufacturers' specifications, the vehicles can only drive on roads with a driving width of at least three metres. Otherwise the sensors will force the vehicle to stop. The same applies to underpasses, which should also be at least three meters high.

Table 3: Vehicle data/ performance data of automated shuttle buses [Eas20; Nav20; e.G20b; Loc20; Eas19; Nav19; Loc19; e.G20c]

	Dimensions (w x l x h)	Maximum Speed	Operating time / battery capacity	Slope	Max. Number of passengers	Manual steering	Barrier-free
EasyMile	1,89 x 4,05 x 2,87	25 km/h	14 – 16 hours	max. 15 %	6 seated 6 standing	remote control / joystick	yes
Navya Technology	2,11 x 4,75 x 2,65	25 km/h	9 hours	max. 12 – 15 %	11 seated 4 standing	remote control / joystick	yes
e.GO MOOVE GmbH	2,01 x 4,94 x 2,55	60 km/h	10 hours	no information	10 seated 5 standing	steering wheel	yes
Local Motors	2,04 x 3,94 x 2,63	40 km/h	2019: 50 km, in 2020: 115 km	max. 15 %	8 seated	remote control / joystick	yes

The technical data from the manufacturers of automated shuttle buses were compared with the results of the best practice analysis. Currently, the highest speed realised of an automated shuttle bus in public areas is 18 km/h. This is due to the approval of the bus. The vehicle and the route get a special permission by the respective state authorities on the basis of a report from a technical service [Bra18]. This speed is achieved in projects in Kelheim, Keitum and Lauenburg [Tec20e; Sta20b; Fro19]. Here the maximum speed deviates from the technical performance of the vehicles (25 km/h). However, an increase of speed can be observed over the time. In one of the first pilot operations by "R+V-Versicherung" in 2017, only 11 km/h were reached [Rai18]. The project "HEAT" in Hamburg has the goal to drive 50 km/h on public roads in 2021 [HEA19]. The data on battery capacity (see Table 3) deviates only slightly from the values of the best practice analysis. In Wusterhausen, the EZ10 from EasyMile is estimated to last nine hours [REG16]. This is sufficient for daily operation there [Ste19]. There are also deviations regarding the number of passengers. In some pilot operations, e.g. in Lauenburg, only seats are offered, as standing during transport is too dangerous due to the abrupt braking of the bus [Ste19; Tec20e].

In pilot operations, the route to be driven is programmed into the vehicle [Tec20e; Ber20a]. The vehicle orientates itself while driving on the basis of virtual lines. In motion it detects obstacles such as other vehicles and people and brakes automatically [Nav19]. When the shuttle bus is being overtaken, in most cases it will also brake [Ste19]. If the vehicle has to leave the route, for example to bypass an obstacle, the shuttle bus is usually controlled manually by an operator [Tec20e; Ber20a]. In complex traffic situations such as intersections and roundabouts, the steering depends from the use case. In some situations, the control is performed by the vehicle and in other situations it is performed by the operator [Nav19; Tec20e]. The operator is always in the vehicle while driving, which is currently required by law [Kol20]. Since the shuttle buses need an operator when driving, they cannot be described as autonomous, but highly or partially automated (according to the level of automated driving) [Wie17]. In addition to the stored route, the shuttle bus orients itself using sensor technologies such as camera systems, radar and LiDAR sensors [e.G20b]. The current capabilities in the field of sensor technologies complicate operation during heavy rain, heavy snow and fog [Tec20e]. For this reason, the operation in Wusterhausen was interrupted on two days [Ste19]. So far there have been three accidents in the pilot operations with automated shuttle buses, however, as for example in Bad Birnbach, the other party was always responsible [Nöb18; Wes19; Mär19b].

4.3 Requirements of Pilot Routes

The requirements for the pilot routes are divided into four sub-aspects in the following. At first the general requirements and afterwards specific requirements regarding route length, number of stops and special features along the routes.

General Requirements

As already explained in Chapter 4.1, automated shuttle buses can be used on pilot routes in urban areas as well as in rural areas. With regard to the spatial constellation, 13 pilot operations are carried out on private land but also 36 projects are carried out in public areas. In public area the automated shuttle buses have already contact, with all kind of traffic (pedestrians, cyclists, cars, buses, trucks and special vehicles such as ambulances). It is noticeable that, with one exception, that future pilot operations will all take place in public areas. This development shows, that there are no requirements regarding the spatial constellation for the use of automated shuttle buses. Driving in public areas is already possible with the current state of technology.

Due to the dimensions and performance data of the vehicles (see Chapter 4.2), there are general requirements regarding the route. The road width should be at least three metres, i.e. six metres in oncoming traffic. Underpasses (e.g. tunnels or gates) which are located on the pilot route, need a height of at least three meters. If the distance is less in both cases, the shuttle bus will reduce its speed or must be controlled manually [Nav19]. In underpasses the control can be done by GPS or LiDAR sensors if necessary. The gradient on the route should not exceed 15 percent and should be as short as possible. During the pilot operation in Marburg, the automated shuttle bus stopped as the engine became too hot both during ascent and descent [Reu17a]. As conclusion, larger gradients can only be travelled at reduced speed [Eas19]. Regarding the road surface, e.g. cobblestones, no restrictions exist [Eas19]. A 4G network in the area of application is recommended for the transmission of data and is a requirement for the route [Eas19; Loc19].

Route Length

The length of the route travelled, as shown in Figure 1, varies between 0.3 km in Wiesbaden and 7.5 km in Wusterhausen, with an average of 1.97 km [Sch18; REG20a]. An extension of the pilot routes can be observed, as the average of the planned routes is 2.51 km. Since these pilot routes are not yet approved, there is a residual risk of shortening the planned routes. The length of the routes (maximum 7.5 km) is not directly specified by the automated driving function or by the performance data of the vehicles. Rather, the reason is that automated shuttle buses currently only travel at a low speed of 18 km/h and usually only one shuttle bus is used in a pilot operation. In order to enable continuous operation for passengers, it is recommended to select a shorter route. It should also be emphasized that pilot operations usually start on a short route and are gradually expanded. In Bad Birnbach the route was extended from 0.67 km to 2.1 km and in Wusterhausen from 3.5 km to 7.5 km [Bra18; REG20a].

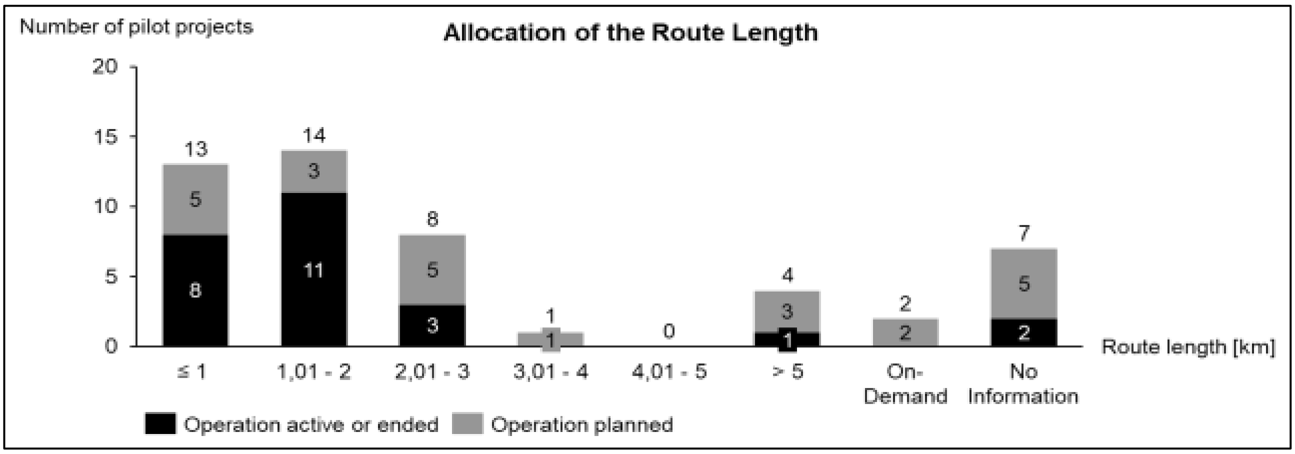

Figure 1: Allocation of the route length [Sta19a; e.G20a; Lat18; Bra18; Sta20h; Tec20a; Ber17b; Kug19; Nut20; Sch19a; Reu17b; Rhe19; Tra18; HEA19; Bun20; FZI20; Ver20b; Ver20d; Ver20e; Ver20c; Syl19a; Süd18b; Beu19; Süd20b; Bie18; Eur19; Ber19; Rhe18; Reu17a; Sta19c; Mün20; Sta20g; Sta20a; Str20; ESW20; Sch18; REG20a; REG19; Eas19; Nav19]

This is also being pursued in Hamburg, where the route is to be extended from 0.7 km to 1.84 km [HEA19]. The city of Monheim am Rhein provides a contrary example. Due to the completion of a construction site, which had to be driven around, the route was shortened from 2.7 km to 1.8 km [Sta19c]. For each of the two planned projects with on-demand traffic, a defined area is being prepared for operation. In these cases, the shuttle buses will operate flexibly on this area, depending on the passengers' wishes. Since the stops are also flexible, there is no standardized route for these projects.

On basis of these results the requirements regarding the route length can be summarized as followed: From the technical point of view there is no restriction regarding the route length, but from the operation it is. The pilot operation should start with a shorter route. Thus, the technology can be tested first. In addition, experience can be gathered as to how far the bus is accepted by the users. A shorter route is also useful to integrate a continuous operation for passengers, when only on bus is used. But in terms of the results shown in Figure 1, new routes should preferably exceed the average of two km. If more buses are in operation and the users accept the shuttlebus, an extension of the route can be done afterwards. An increasing route length should be the goal of new pilot operations, in order to get the shuttle buses to their technological limits.

Number of Stops

Due to the short pilot routes, the number of stops is also low (see Figure 2). On average there are about 5 stops on a pilot route. The number of stops on the currently planned pilot routes is 6 stops on average. With the extension of the routes in Bad Birnbach and Wusterhausen, the number of stops also increased. In Bad Birnbach from 2 to 5 stops and in Wusterhausen from 10 to 17 stops [Bra18, pp. 2ff; REG16]. Due to the shortening of the route in Monheim, the number of stops was reduced from 9 to 7 stops [Sta19c]. In the on-demand pilot operations, there is no information about the stops, as there are theoretically infinite possibilities for boarding the automated shuttle bus.

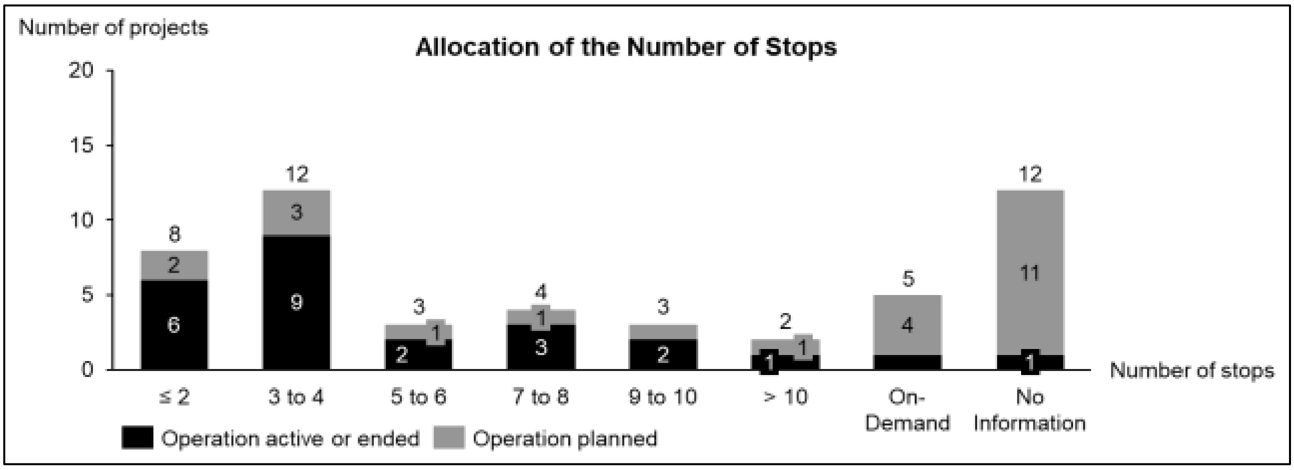

Figure 2: Allocation of the number of stops [Sta19a; e.G20a; Lat18; Bra18; Sta20h; Ber17b; Kug19; Nut20; Sch19a; Rhe19; Reu17b; Tra18; HEA19; FZI20; Ver20b; Ver20d; Ver20e; Ver20c; Syl19a; Süd18b; Beu19; Süd20b; Eur19; Ber19; Rhe18; Reu17a; Sta19c; Mün20; Kin16; Sta20g; Sta20a; ESW20; Sch18; REG16]

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The requirements for the number of stops are identical to those for the route length. The number of stops is not limited due to technical reasons. But a lower number of stops should be preferred, because of short routes and operational advantages. Too many stops on a short route prevent continuous operation. Analogue to the extension of the route, the number of stops should be increased. This should also be the goal for new pilot operations

Special Features along the Routes

The route length and the number of stops are not directly dictated by technology, but are reasonable from the operator's point of view. This is different for the special features along the route. A too complex pilot route can become an exclusion criterion for the route itself. However, it is important to gain experience with the automated shuttle buses in complex situations. Therefore, Figure 3 visualizes the special features of the pilot routes and how often they are investigated in pilot operations. As several special features can be tested in a pilot operation, the number of special features exceeds the number of pilot projects. Because not all projects list the special features of their used routes, further research is required and hence there is no claim to completeness. Figure 3 only contains special features, which are tested in more than one project.

Due to the fact, that the majority of pilot operations take place in urban cities, the allocation of special features can be explained. Especially the intersecting traffic is a big challenge for the automated shuttle buses as the other road users, signs and light signal systems must be correctly recognized. Because of the complexity in these situations, the pilot operations are testing the vehicles at signposted intersections, right-to-left situations, light signal systems and roundabouts. Depending on the visibility and complexity of the traffic point, there is a case-by-case decision concerning manual or automated control at these intersections [Eas19; Nav19].

It is worth mentioning, that the pilot operations in Lauenburg and Drolshagen are already testing intersections with federal roads [Tec20d; Nut20]. However, in most of these situations the operator has to drive manually, as is the case in Wusterhausen [Ste19]. Automated driving on these traffic points is possible, as the example in Lauenburg shows. Here, the vehicle of Navya Arma communicates with a light signal system, brakes and starts automatically [Tec20e].

As the automated shuttle buses move in public road traffic, they are also confronted with parked vehicles. The detection of the parked vehicles works well and the bus brakes automatically. However, driving around the obstacles is mainly done manually [Nav19]. Zebra crossings are simpler for the automated shuttle bus to handle, because in this case no obstacle has to be bypassed. This is being tested in Frankfurt and Hamburg for example [Reu17b; Ham20]. Due to the current capabilities in the field of sensor technology, narrow roads and driving on cobblestones are being tested in pilot operations [Tec20d]. In order to bring the electric motor to its limits, gradients are also tested [Tec20d].

Although most projects concentrate on urban traffic, country roads have particular challenges as well. The challenges are the speed difference to other road users and the orientation of the vehicle. In the city, the automated shuttle bus can orient itself on buildings, but this is only possible to a limited extent on country roads. The behaviour on country roads is currently being investigated in Bad Birnbach and Wusterhausen [DB 20; 3sa19].

In addition to the aforementioned special features, there are some other situations, which are being tested in different projects. In Aachen the pilot route partly leads through a pedestrian zone [Sta19d]. A more complex situation, due to the reaction to other road users, is the lane change on roads with multiple lanes in one direction, which is planned to be tested in Hamburg [Ham20].

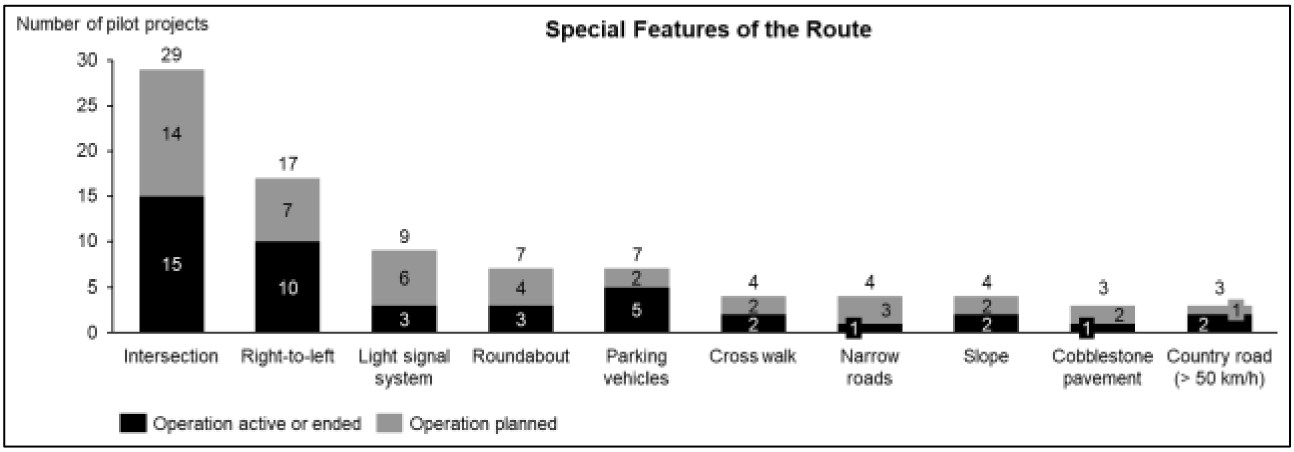

Figure 3: Special features of the route [Lat18; DB 20; Sta18b; Flu19; Kug19; Süd20a; Eur20b; Wil17; Rhe19; Rie19; HEA19; FZI20; Syl19b; E-M18; Süd18a; Tec20b; Lüb19; Lei19; Jul18; Köh19; R+V18; Sta19b; Nel19; Kin16; Sta20g; Poh19; Sta20d; 3sa19; Mär19a; Eur20a]

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In Berlin the automated shuttle bus is gaining experience with the handling at a construction site, whereas in Weltenburg near Kelheim the automated shuttle bus drives on a road without pavement [Ehr19; von17].

With regard to the requirements for the pilot route, it can be said, that most of the complex traffic situations can be part of the pilot route. It is even necessary to test complex traffic situations in pilot operations so that the technology of automated shuttle buses can be further developed. Nevertheless, besides the complexity, the benefits for passengers should also be considered. As aforementioned the shuttle bus is mostly being driven manually at complex situations. This extends the travel time. Furthermore, the route is always approved by a technical service. Too much complexity can therefore lead to a rejection of the pilot route. Therefore, the requirement for the pilot route is that it is complex enough to gain experience, but not too complex for the project to fail. Moreover, the complexity of the pilot routes has an effect on the infrastructure requirements. This is shown in the next chapter.

4.4 INFRASTRUCTURE REQUIREMENTS

To enable the shuttle bus to operate on the pilot routes, an adaption of the infrastructure along the route is partially necessary (see Figure 4). Analogous to Chapter 4.3, one pilot operation can have several infrastructural measures. Most of the infrastructural elements, which are shown in Figure 4, are measures in active or ended pilot projects. The infrastructural measures of the planned pilot projects are not yet known, since the pilot route may not yet be fixed. Therefore, Figure 4 does not claim to be complete.

Regardless of the route, a garage and a charging station for the shuttle bus will be provided [Sta18b]. Depending on the expansion of the public transport system, new stops may have to be built for the pilot operation [Ham20]. These adjustments are not included in Figure 4, but all other identified measures are.

In most pilot projects, signs are put up to make all road users aware of the automated shuttle bus [Süd20a]. Due to the speed difference between the shuttle bus and other road users, as mentioned in Chapter 4.2, the maximum speed limit is often reduced to 30 km/h along the route, e.g. in Aachen and Bad Birnbach [Lat18; DB 20]. Since the speed difference between the automated shuttle bus and other road users is the first challenge on the country roads, the maximum speed is also adjusted there. For example, dynamic signs have been set up along the route in Bad Birnbach, which reduce the speed limit to 30 km/h for all road users as long as the shuttle bus is on the country road [DB 20]. To ensure this, cameras were installed along the route.

If communication with traffic lights, e.g. in Lauenburg, is to be tested, road-side units are installed at the traffic lights [Tec20b; Tec20e].

According to the explanations in Chapter 4.2, the sensors react sensitively to narrow driving positions and oncoming traffic or when the shuttle bus is overtaken. In order to simplify the smooth running of the automated shuttle bus in pilot operation, an attempt is made to avoid obstacles as far as possible. For this reason, route changes are implemented in the respective cities. These includes closing a street to motorized traffic or rededicating a street as a one-way street [Sta19b; Rhe19]. To prevent the automated shuttle bus from being stopped in front of parked vehicles, parking areas are moved or stopping bans are issued [Rie19; Sta19b]

Too meet the second challenge on country roads, landmarkers are installed along the route, as the automated shuttle buses cannot orient themselves on the buildings as in the city. In Bad Birnbach and Wusterhausen, landmarkers were used for driving on country roads [DB 20; 3sa19]. The landmarkers are also used on Sylt so that the automated shuttle bus can drive through a roundabout [Eur20a].

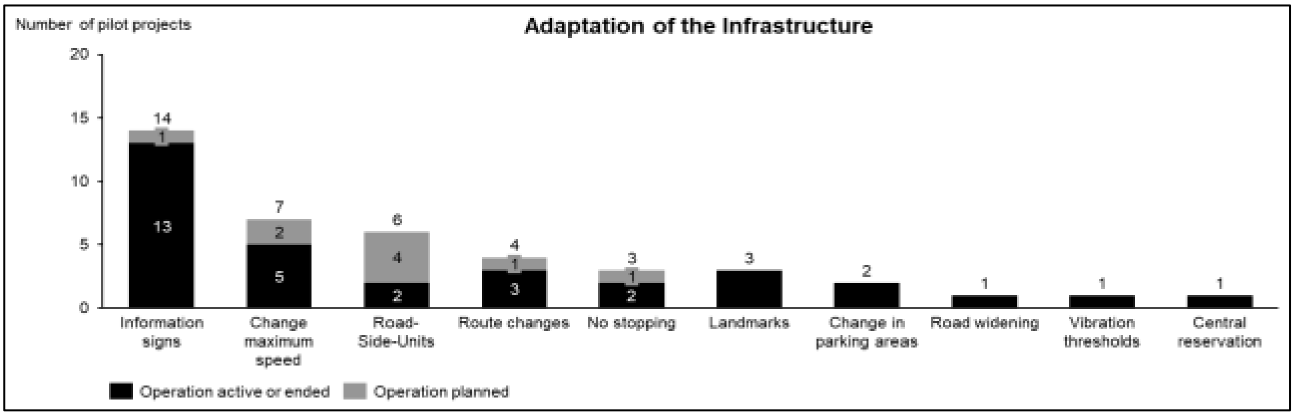

Figure 4: Adaption of infrastructure [Lat18; DB 20; Sta18b; Flu19; Kug19; Süd20a; Eur20b; Wil17; Rhe19; Rie19; HEA19; FZI20; Syl19b; E-M18; Süd18a; Tec20b; Lüb19; Lei19; Jul18; Köh19; R+V18; Sta19b; Nel19; Kin16; Sta20g; Poh19; Sta20d; 3sa19; Mär19a]

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Further infrastructural measures are the widening of the carriageway, the addition of a central reservation and the installation of a vibration threshold. The first two measures support the shuttle bus in its orientation, while the third measure aims to ensure that other road users comply with the speed limit. These measures were carried out in Bad Birnbach [DB 20]

The aforementioned infrastructural measures are the requirements for the infrastructure in pilot operation. Definitely a requirement is the installation of information signs, so that user road users are informed. A further requirement is to ensure that traffic is as fluid as possible. Therefore, route changes and no stopping as well as change in parking areas can be implemented. Depending on the special features of the routes and the research question, further requirements such as the change of maximum speed, installation of road-side-units and landmarks can be implemented.

5 Benefits of the Results

In summary, the results can be used in three different ways: To determine possible applications for future projects, to optimize the development process of the pilot route and to derive forecasts for the future development of automated shuttle buses.

The scope of services of the shuttle buses as well as the requirements for pilot routes and infrastructure as described above can be used to determine possible applications for automated shuttle buses in future projects. With these information decision-makers of project proposals thus already have an overview at the beginning of the project. As a result, it is easier to assess whether the speeds are sufficient, whether suitable pilot routes are available and whether infrastructural measures could be implemented.

The selection process of the pilot route is divided into four steps. First, the respective project team develops potential pilot routes. After selecting a shuttle bus, the shuttle bus manufacturer evaluates the feasibility of the pilot route. A pilot route is then jointly defined. That must, however, be approved by a technical service [Eas19; Nav19; e.G20c; Loc20; Bra18, pp. 4ff]. The requirements identified in this paper allow the complexity of the pilot routes for the automated shuttle bus to be assessed already during the development of potential pilot routes. Thus, the project team can develop better route proposals in advance and shorten the process.

Finally, the results can be used to derive forecasts for the future development of automated shuttle buses. As described in Chapter 4.1, the number of pilot operations in Germany is increasing. This means that this promising technology is becoming increasingly important for local authorities and transport companies. Although fewer pilot operations are planned in 2021 than in 2020 (see Chapter 4.1). Moreover, the projects so far have almost exclusively been pilot operations and not permanent offerings [Ver20a; Cha20; Bel19]. The performance of the automated shuttle buses is significantly lower than that of the conventional diesel buses, which are currently mainly used in public transport. This applies to the speed and to the automated driving functions of the vehicles. The current state of the art is far from autonomous driving without a driver. However, the best practice analysis shows that the performance of the vehicles is evolving as maximum speed is increasing due to improving automated driving functions. The growing number of shuttle bus manufacturers will also increase the competition in this market and the progress of technology. This technical development has also an influence on the pilot routes. Planned pilot operations will test longer and more complex pilot routes (see Chapter 4.3). Nevertheless, numerous infrastructural adaptation measures are currently being carried out for the pilot operations. The restrictions that the measures will impose on the local population are of importance here. Signs are not a direct restriction for the population in contrast to route changes, route closures or stopping bans. However, the authors also see some of these measures as an opportunity to reduce the number of vehicles in cities and to improve the overall traffic flow.

The authors conclude from these results that the number of pilot operations can have a positive effect on experiences with automated driving and the development of automated shuttle buses. Whether the automated shuttle bus can be implemented in the short term (in the next few years) as a new mobility solution in public transport and can represent a real alternative to conventional buses cannot be predicted in general. This certainly depends on the respective use case and the further development of automated shuttle buses [Bel19, pp. 10ff; Bra18, pp.4ff; Bar20, p. 21].

6 Conclusion and Further Research

Automated shuttle buses are a future mobility concept in public transport due to their flexibility and cost efficiency. Since pilot operation with these buses was not launched in Germany until 2016, this is a new field of research, that is reflected in the small amount of relevant literature. There is a particular research gap in the area of requirements for pilot routes and infrastructure. However, both are especially relevant for local authorities and transport companies as initiators of projects with automated shuttle buses. The implementation of a pilot project is based on the pilot route. For this reason, the development of potential pilot routes is one of the first tasks in the project. Especially since the automated driving functions are currently not fully developed, the pilot route and infrastructure are of special importance.

In order to determine the requirements for pilot routes and infrastructure, a best-practice analysis was carried out on projects with automated shuttle buses in Germany.

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Since the requirements also depend on the technical capabilities of the vehicles, the performance of the automated shuttle buses was evaluated with the help of a market analysis. Both analyses were mainly conducted online and with little personal contact.

The results of the best practice and market analysis are summarised as follows: A total of 49 pilot projects in Germany were examined. Pilot projects are being conducted in rural and urban areas. The number of pilot companies, manufacturers and vehicles is increasing. The market analysis, in which four shuttle bus manufacturers answered the questionnaire, shows that the promised performance of automated shuttle buses has not yet been achieved in the pilot operations. The pilot operations are running at lower speeds and sometimes with fewer passengers. In general, the performance of the automated shuttle buses does not come close to that of conventional buses. Based on these results the requirements for pilot route and infrastructure are derived. With regard to the pilot route requirements, it is apparent that on average the routes are no longer than three kilometres and have up to six stops. These are the prerequisites for a continuous operation. If the route is extended, the number of vehicles should therefore also be increased. In addition, care must be taken to ensure that the width of the carriageway is sufficient and that a gradient of 15 % is not exceeded if possible. A good Internet connection with 4G is also beneficial. The complexity of the routes increases with crossings, traffic lights, roundabouts or multiple lanes. However, it is also the aim of the pilot companies to push the technical possibilities of the vehicle to their limits. Therefore, by adapting the traffic infrastructure, the journey of the automated shuttle bus can be made easier. Minor adjustments relate to signs and road markings, while major adjustments include stopping bans or road closures.

These results can be used in the future for preparation and implementation of pilot operations, especially with regard to the planning of the pilot route. Although the automated shuttle bus can only be a short-term alternative in public transport under certain conditions, the authors advocate the implementation of further pilot operations. The experience of the pilot operations can have a positive effect on the technological development and the automated shuttlebus can be an alternative in future public transport without any restrictions.

This type of survey should be repeated because of the dynamics and major technical changes in the field automated shuttle buses. To this end, the survey methodology should be reconsidered in further research with a view to enlarging the sample or making it more personal.

With regard to future pilot operations, the aim should be to gradually increase speeds and automation at complex traffic points.

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