DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

Tasks of an Operations Control Center for Automated Buses and its Impact on the Economic Efficiency of a Public Transport Service

Aufgaben einer Betriebsleitstelle für automatisierte Busse und ihre Auswirkungen auf die Wirtschaftlichkeit eines öffentlichen Verkehrsunternehmens

M.Sc. Olga Biletska
M.Sc. Sönke Beckmann
Prof. Dr.-Ing. Hartmut Zadek

Department of Logistics,
Institute of Logistics and Material Handling Systems,
Otto-von-Guericke-University Magdeburg

Automated vehicles are expected to change future mobility. However, until the vehicles are on the road autonomously, they must be monitored with the help of an operation control center, which has a significant impact on the costs. Based on a cost-effectiveness analysis, the impact of the Operation Control Center on the economic efficiency of automated buses is evaluated. Data is derived from pilot operations with automated buses in public spaces. For this purpose, different scenarios of automated buses from automation level 0 to automation level 4 are calculated and compared.

[Keywords: Automated Bus; Operation Control Center; Cost-Effectiveness analysis, Automated Freight Transport]

Es wird erwartet, dass automatisierte Fahrzeuge die zukünftige Mobilität verändern werden. Bis die Fahrzeuge jedoch autonom auf der Straße unterwegs sind, müssen sie mit Hilfe einer Betriebsleitzentrale überwacht werden, was einen erheblichen Einfluss auf die Kosten hat. Anhand einer Kosten-Wirksamkeits-Analyse wird der Einfluss der Betriebsleitstelle auf die Wirtschaftlichkeit von automatisierten Bussen bewertet. Die Daten werden aus Pilotbetrieben mit automatisierten Bussen im öffentlichen Raum abgeleitet. Zu diesem Zweck werden verschiedene Szenarien für automatisierte Busse von Automatisierungsstufe 0 bis Automatisierungsstufe 4 berechnet und verglichen.

[Schlüsselwörter: Automatisierter Bus; Operation Control Center; Kosten-Wirksamkeits-Analyse, Automatisierter Güterverkehr]

1 INTRODUCTION

Climate change, demographic change, globalization, migration, urbanization and technological development are some of the biggest challenges for mobility and logistics in the future [1–5]. For this reason, future mobility concepts are needed that are climate-friendly, efficient, electrically operated, automated, networked, universally usable and safe [6–10]. Automated buses are a mobility concept that meets a number of these requirements [9, 11, 12]. Currently, the level of development of the automated buses is between level 2 and level 4 of the automation levels according to SAE ("partially automated" and "highly automated"), so that an operator is present on board during pilot operations of the buses [11, 13–16]. But in order for the advantages of the automated bus (flexibility and low costs due to high utilization) to be fulfilled and the deployment to be economical, the vehicles must be operated without a driver and automation level 4 must be achieved [9, 12, 13, 17]. Some companies, such as EasyMile in Toulouse, are already testing buses without drivers on board, and Level 4 automated buses are also planned for use in Berlin and Munich in the future [18–20]. According to forecasts, however, highly automated driving (level 4) will not be ready for the market until between 2025 and 2030, and autonomous driving (level 5) will be reached later [17, 21]. In order to nevertheless offer passengers a high level of reliability in local public transport, a driver is essential for taking over the driving functions in emergency situations [22, 23]. In addition, communication with passengers is also an important task that should continue to provide [24]. For this reason, it makes sense to use the existing operation control centres (OCC) of transport companies and deploy human operators who monitor the bus remotely and intervene if necessary [22, 25, 26].

This requires the integration of new tasks into the existing control centres of potential operators such as transport companies [25]. To enable regular operation with highly automated vehicles on predefined routes even without a safety person on board (SAE level 4), the German government passed the Autonomous Driving Act and a subsequent ordinance [27, 28]. In addition to the requirements for the manufacturer and the owner, it also defines the duties of a "technical supervisor". The Technical Supervision (hereinafter also referred to as Operation Control Centre) thus plays an essential role for the use of automated vehicles in public transport [27, 28].

The objective of this paper is to shed light on the tasks of an OCC in the context of the requirements for the operation of automated buses and to investigate the impact on economic efficiency from the perspective of public transport companies. Chapter 2 explains the potentials and tasks of the OCC for automated buses and summarizes previous studies investigating the cost aspects or economic viability of automated buses in public transport. The third chapter describes the methodology used in this paper to evaluate the cost effectiveness of automated buses. Chapter 4 presents the results, which are subsequently discussed in Chapter 5. Finally, chapter 6 summarizes the findings of the economic feasibility study and identifies the need for further research.

2 LITERATURE REVIEW

In the following, tasks of an OCC for remote monitoring and control of automated buses for different automation levels are shown. These serve as the basis for the subsequent economic evaluation.

Furthermore, the current research regarding the cost calculation or profitability analysis of automated vehicles in public transport is presented.

2.1 TASKS OF AN OPERATION CONTROL CENTER

In order to implement the operation of automated vehicles in public road transport, not only the technical requirements for the bus or bus fleet must be met, but also the framework conditions such as an OCC, intelligent and networked infrastructure, telecommunications and legal framework must be established [29].

The main tasks of an OCC depend on the automation level of the bus fleet. The automation level is classified between level 0 and 5 according to SAE J3016, which is shown in Table 1 [13].

Levels 0 through 2 make up the regular bus fleet of most transit agencies. As shown in Table 1, the main driving tasks and responsibility for passenger safety lie with the driver. [13]

Table 1: Levels of automation following [13]

Automation level	*Vehicle driving task*	*Driver task*	*Safety Fallback*
Level 0: No Driving Automation	Warnings and momentary assistance	Driving all of the time; Constantly supervise the support features;	Driver
Level 1: Driver Assistance	Steering **OR** acceleration; brake support	Driving all of the time; Constantly supervise the support features;	Driver
Level 2: Partial Driving Automation	Steering **AND** acceleration; brake support	Driving all of the time; Constantly supervise the support features;	Driver
Level 3: Conditional Driving Automation	All driving tasks under limited conditions	Not driving when automated driving features are engaged; **BUT** when the feature requests, taking over control	Driver / Safety operator on board
Level 4: High Driving Automation	All driving tasks under limited conditions	Not driving when automated driving features are engaged; No request to take over the control under limited conditions	System has to perform a minimum risk condition / OCC
Level 5: Full Driving Automation (Autonomous Driving)	All driving tasks under all conditions	Not driving when automated driving features are engaged; No request to take over the control	System has to perform a minimum risk condition / OCC

The OCC performs conventional tasks such as:

1. Monitoring regular operations (traffic situation, schedule delays
2. Vehicle dispatch and dynamic rescheduling (on-demand, plannable deviations)
3. Fault and emergency management
4. Dynamic passenger information [30, 31]

The Operational Design Domain (ODD) is a key concept for the design process and validation of the safety of an automated driving system and specifies the operational conditions under which the system should operate, e.g., including possible road types, road types, weather conditions and road users [13, 32]. At Level 3, although the vehicle takes over the entire driving task for a defined area (ODD), the system can still make requests for human assistance, which requires the presence and intervention of an onboard operator, even if the operator no longer has a conventional driver's seat and takes control using a joystick [13]. Most pilot operations in Europe in recent years have been conducted at level 3 [33, 34]. The providers of automated buses such as EasyMile or Navya also develop and offer corresponding fleet management systems, which enable the monitoring of the vehicles by transmitting the current position, various sensor data on the technical condition, speed, driving mode, temperature, battery level, etc. to the control centre via an API or web application [35]. This means that the conventional tasks of the operations control centre at level 3 are expanded to include monitoring of the vehicle sensors, but the scope of the tasks remains largely unchanged.

The operation of automated buses without a safety operator (level 4) places special demands on the vehicle and the OCC as an additional fallback level. For automated buses to be used in public transport, a high level of operational safety is required [22]. On the one hand, the vehicle must be able to independently put itself into a risk-minimizing state by safely leaving the lane and parking at the side of the road when the ODD is left, i.e., when the general conditions for automated driving no longer exist. In this case, the OCC must be able to access and control the bus remotely [25, 26, 28]. On the other hand, the current legal situation in Germany does not permit the remote execution of driving manoeuvres (teleoperation) in public areas. However, it should be possible to release the vehicle or trigger an emergency stop (tele-assist).

Furthermore, V2X technologies can provide valuable information not only to the automated driving system, but also to the OCC [36–38].

The types of connectivity included in V2X are: V2I - vehicle-to-infrastructure, V2V - vehicle-to-vehicle, V2N - vehicle-to-network, and V2P - vehicle-to-pedestrian [39]. All of these types of connectivity can improve safety, the user experience, or the amount of data from which an automated vehicle or OCC operator can make decisions.

The scope of the tasks of an OCC is greatly expanded from level 4 and includes, in addition to the activities mentioned so far, further tasks, such as:

1. Classification and prioritization of various request
2. Remote control / tele-assist;
3. If applicable, teleoperation, but only on the private domain, e.g., at a depot)
4. Infrastructure and vehicle-to-everything communication monitoring;
5. If applicable, infrastructure control
6. Passenger communication;
7. Passenger safety
8. Charging management [40–42]

Since there is no longer a contact person on board in Level 4, passenger communication represents a new important area of responsibility for the OCC. Ensuring safety in emergency situations by communicating with safety authorities and passengers is also outsourced to the OCC in this case.

2.2 ECONOMIC ASPECTS OF AUTOMATED BUSES

One expectation of automated vehicles is to reduce mobility costs [6]. In the following, approaches from the literature are presented that shed light on this aspect. Burns et al. calculate total fleet costs, vehicle reductions, and cost savings when using automated shared vehicles in three scenarios (small to medium town, suburban and urban) [43]. In the first approach by Fagnant & Kockelman in 2015, the annual economic benefits (crash cost savings, congestion costs, and other impacts such as parking savings) of automated vehicles for the U.S. are estimated [44]. In another paper by the two authors, a total fleet for automated shared vehicles and waiting times are determined based on a simulation model in Austin, Texas, and user fees are derived from this [45]. In addition to the cost of the equipment in the automated vehicle (e.g., navigation, sensors, computers, software, and servers), Litman cites additional costs that occur with automated shared vehicles [46]. These include empty runs, cleaning and vandalism, reduced service for limited people, and reduced comfort and privacy [46]. Friedrich & Hartl calculate the demand for automated vehicles in various scenarios [47]. Based on the required vehicles and investment costs, the cost of automated vehicles is calculated at 0.15€ per passenger kilometer [47]. Stephens et al. research potential impact of automated shared vehicles on consumer costs [48]. Components of the total costs are connected automated vehicle (CAV) technology cost, maintenance and repair costs connectivity service fee,

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

insurance premiums, costs of crashes not covered by insurance, fuel cost and cost of travel time [48]. Merlin compares the cost of a conventional bus to that of automated cabs, with the latter showing a cost advantage in shared use [49].

In 2018, Bösch et al. completed the cost structures of individual operating models, through a bottom-up calculation of fully autonomous vehicles. Additionally, overhead costs are included in the calculation. Costs for four scenarios (private conventional vehicle, private automated vehicle, conventional cab, and automated cab) are calculated. The costs per passenger kilometer of buses are also determined on this basis. The results show that automated vehicles have a cost advantage over conventional vehicles. [50]

Based on the cost calculation of Bösch et al., Abe calculates the costs for the use of automated cabs with consideration of OCC monitoring [51]. In various scenarios, an operator remotely monitors one to ten vehicles, which has a significant impact on costs [51]. A similarly detailed calculation as Bösch et al. has been made by Ongel et al. for electric vehicles, automated electric vehicles and buses [52]. As a result, the automated vehicle incurs $0.10 per passenger mile [52]. In addition, a sensitivity analysis is performed according to which energy costs have a major impact on the cost structure of automated electric vehicles [52].

Furthermore, PTV and Richter et al. describe in general terms the cost changes related to operational and economic approaches [53, 54]. In their 2020 study, Quarles et al. calculate and compare the cost development of electric and automated buses over a 20-year period [55]. Grote and Röntgen calculate the costs of using automated buses for a period of three years [56]. Thereby, a large part of the costs is based on actual values from a real operation [56]. Sadrani et al. are devoted to the cost evolution of automated buses when frequency and vehicle size are changed [57]. Furthermore, a sensitivity analysis is carried out with regard to travel time, demand fluctuation and extra waiting times, among others [57]. Based on the Berlin use case, Carreyre et al. analyse the costs and benefits of automated vehicles [58]. Here, the vehicles are used on-demand and the results of different stop strategies (door-to-door or stop-based) are calculated with MATSim [58]. Finally, Litman compares the costs of different studies of conventional and automated vehicles (e.g., cab or bus) [59]. The development of future costs is further described in qualitative terms [59].

The literature analysis clearly shows that only a few studies consider the costs of an operation control centre. Bösch et al. consider the costs in general [50]. Abe calculates these costs in detail for different ratios between operator and cab [51]. For an automated bus that has already been deployed in public spaces, no cost calculation has yet been carried out that includes the costs of the OCC and the support relationship between operator and bus. This research gap will be closed in the following.

3 METHODOLOGY

For the economic feasibility study, a three-step procedure was applied, as shown in Figure 1. First, the scenarios to be considered were selected on the basis of automation levels and the state of the art. In order to cover as many of the currently relevant operational scenarios as possible, the following six operational scenarios are selected: two non-automated operational scenarios - with a conventional diesel minibus (level 0-2) and an electric minibus (level 0-2), two semi-automated operational scenarios with a safety operator on board - with a bus (level 3) in a rural area and a bus (level 3) an urban area - and two highly automated operational scenarios without a safety operator on board - with a bus (level 4) before market readiness (BMR) and a bus (level 4) after market readiness (AMR).

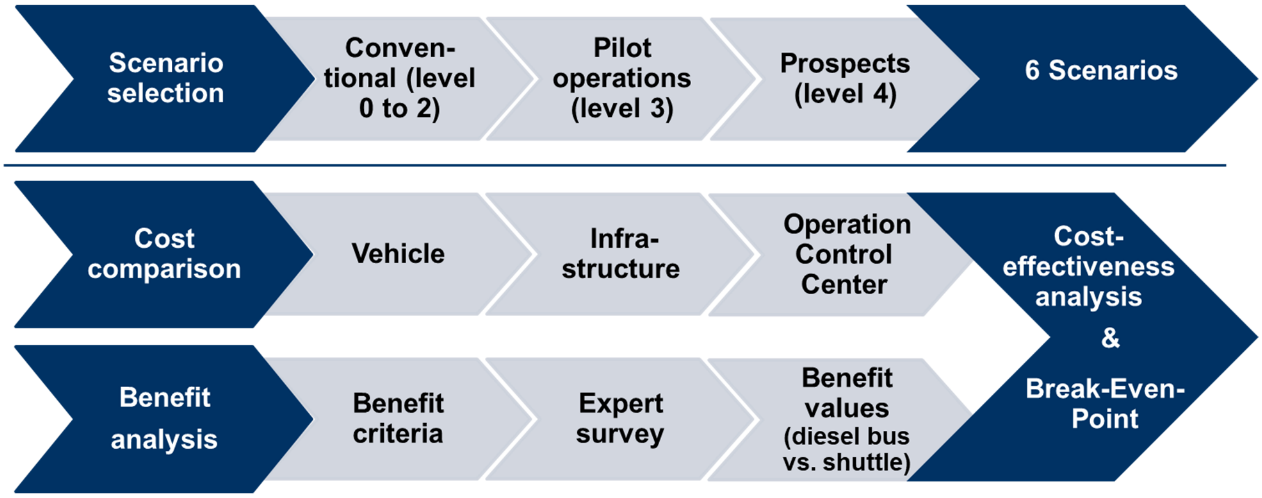

Figure 1. Methodology of the cost-effectiveness analysis

	Diesel bus	E-bus	Pilot operation in rural area	Pilot operation in urban area	SAE Level 4 (BMR)	SAE Level 4 (AMR)
Mileage	40 000 km		18 688 km	26 864 km	26 864 km	40 000 km
Vehicle model	Mini bus Vito Tourer PRO (Mercedes)	Mini bus eVito Tourer PRO (Mercedes)	EZ10 Gen2 from EasyMile		EZ10 Gen3 from EasyMile	EZ10 GenX from EasyMile or other
Infrastructure	No adjustments		Traffic infrastructure measures	Traffic infrastructure measures + additional sensors for V2X	Traffic infrastructure measures + additional sensors for V2X	
Operation Control Center	Fleet management (conventional tasks of an OCC)		Fleet management + (Monitoring)		Fleet management + Monitoring + Control	
Operation hours and duration	7 days per week; in 2 shifts (16 hours); over 5 years					

Figure 2. Scenarios for the profitability calculation

Market readiness in this context means that the bus is mass-produced and thus the expected purchase price is significantly low. An overview of the scenarios is summarized in Figure 2. For a detailed account of the OCC's areas of responsibility, please refer to chapter 2.1.

For the diesel bus and electric bus, vehicles are selected that are similar to the EasyMile EZ10 Gen2 in terms of space capacity. The EasyMile vehicle is selected for the Level 3 scenarios because it is used very frequently in pilot operations in Europe, and also in two research projects of the Department of Logistics at the University of Magdeburg. The data collected in these projects is incorporated into the cost comparison analysis. Furthermore, for the cost comparison and benefit analysis, a local transport company is assumed as operator and an operating period of seven days a week with two eight-hour shifts each. The mileage of 40,000km per year is recommended from the literature [Ver07].

Level 4 operation is expected to increase the economic efficiency of automated buses in the future by having one operator supervise multiple vehicles [42]. Therefore, the OCC costs for each of the two Level 4 scenarios are additionally determined as a function of the supervision ratio. Calculations are performed for the supervision ratios of 1:1 (one operator for one vehicle), 1:2, 1:3, 1:4, 1:5 and 1:10.

To determine the costs in the second stage, a static cost comparison calculation is applied [60]. Linear depreciation with a residual value is used [60]. The cost types of the infrastructure, the vehicle, the control centre and for the project management are taken into account.

For the individual costs compare table 2.

Table 2: Overview of the cost items used

	Vehicle	**Infrastructure**	**OCC**
Investment costs	Depreciation per year Imputed interest Approval Programming of the route Safety operator training Preparation for pilot operation	Depreciation per year Road Site Units Road markings Signage Localization Shelter (near the route)	Workplace Software Employee training
Operating costs	Personnel costs Vehicle usage: – Insurance – Maintenance / servicing – Energy costs – Overhead	Use of infrastructure: – Maintenance / repair – Energy – Insurance	Personnel costs Software license fees Maintenance / servicing Insurance

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

The costs are determined by project experience, expert interviews and literature research. In the benefit analysis (third stage), benefit criteria are first determined from the literature, which are then evaluated in an expert survey on a 10-point scale for a conventional diesel bus and an electric bus. To determine the overall benefit per vehicle variant, the criteria ratings are multiplied by the weighting per criterion and added together. The prioritization of the criteria is also done by asking experts and using a pairwise comparison [61]. The results of the cost analysis and benefit analysis are ultimately summarized in a cost-impact analysis and the break-even point is calculated.

4 RESULTS

First, the results of the cost calculation are presented in chapter 4.1 for different scenarios. This is followed in chapter 4.2 by the results for the benefits, which are then compared with the costs.

4.1 RESULTS COST CALCULATION

As already explained in chapter 3, the costs are collected in an Excel spreadsheet and calculated for a total of 16 different scenarios, which are summarized below:

1. Diesel Bus (Level 0 – 2)
2. Electric Bus (Level 0 – 2)
3. Automated (Aut.) Bus Stolberg (Level 3)
4. Aut. Bus Magdeburg (Level 3
5. SAE Level 4 before market readiness (BMR) with ratio 1:1 (one operator is responsible for one vehicle)
6. SAE Level 4 BMR (1:2)
7. SAE Level 4 BMR (1:3)
8. SAE Level 4 BMR (1:4)
9. SAE Level 4 BMR (1:5)
10. SAE Level 4 BMR (1:10)
11. SAE Level 4 after market readiness (AMR) with ratio 1:1
12. SAE Level 4 AMR (1:2)
13. SAE Level 4 AMR (1:3)
14. SAE Level 4 AMR (1:4)
15. SAE Level 4 AMR (1:5)
16. SAE Level 4 AMR (1:10)

In the following, the results for selected scenarios are shown and briefly explained. Figure 3 shows the costs for the first year of operation. A distinction is made between one-time costs, annual investment costs and annual operating costs. It is clear that annual operating costs account for the largest share of costs in the first year. Furthermore, it can be seen that the diesel and electric buses are the cheapest alternatives in the first year with costs of approximately 240,000 euros. In comparison, the automated buses have costs up to 441,000 euros (SAE Level 4 BMR 1:1). However, if the supervision ratio of control centre staff to vehicles increases, the difference decreases significantly. In the SAE Level 4 AMR scenario (1:3), costs are reduced to 245,00 euros in the first year of operation. At this point, the break-even point is reached. At a higher support ratio, the costs of automated buses would be below those of conventional vehicles. From these results, it can be seen that the personnel costs for drivers and control centre personnel have the largest share and, consequently, the greatest leverage.

The results for the annual costs are similar (see Figure 4). Diesel and electric buses (costs amounting to approximately 215,000 euros per year) are significantly cheaper than the current automated buses that have been deployed in Stolberg and Magdeburg. With the onset of market maturity and increasing support ratios, this will change. The break-even point is already reached in the SAE Level 4 AMR (1:2) scenario (costs of 203,544.55 euros), which is not listed in the figure.

The total costs for a five-year service life show that automated buses with SAE Level 4 AMR with a support ratio of 1:3 are already cheaper overall than diesel and electric buses (Figure 5). The costs for automated buses with SAE Level 4 BMR also approach the costs of conventional vehicles as the support ratio increases.

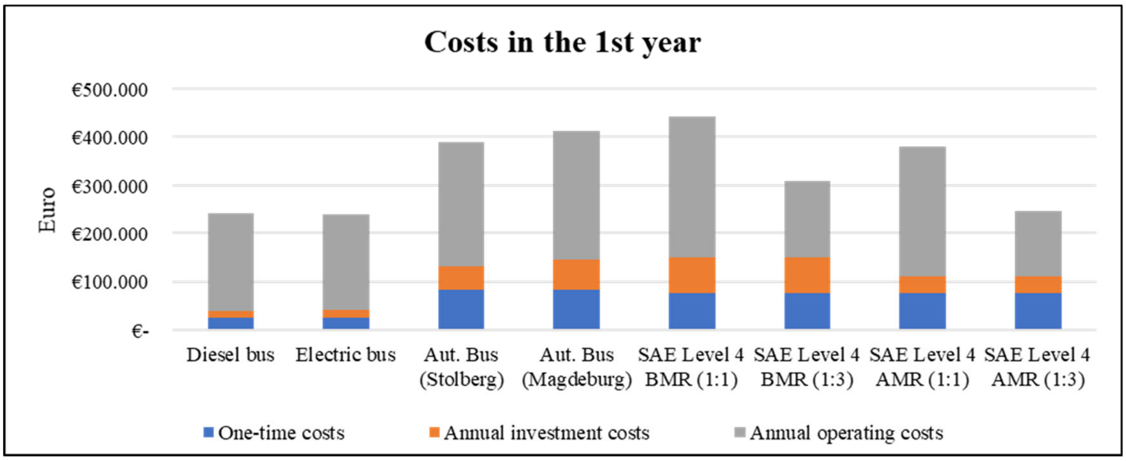

Figure 3. *Costs in the first year*

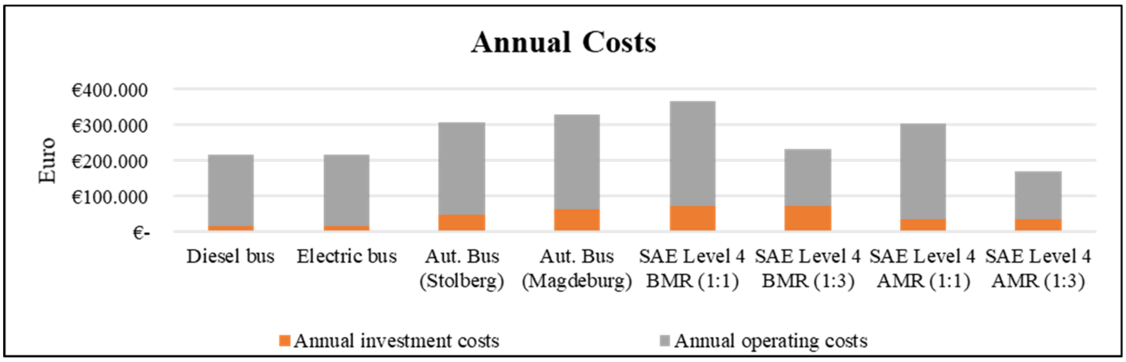

Figure 4. *Annual costs*

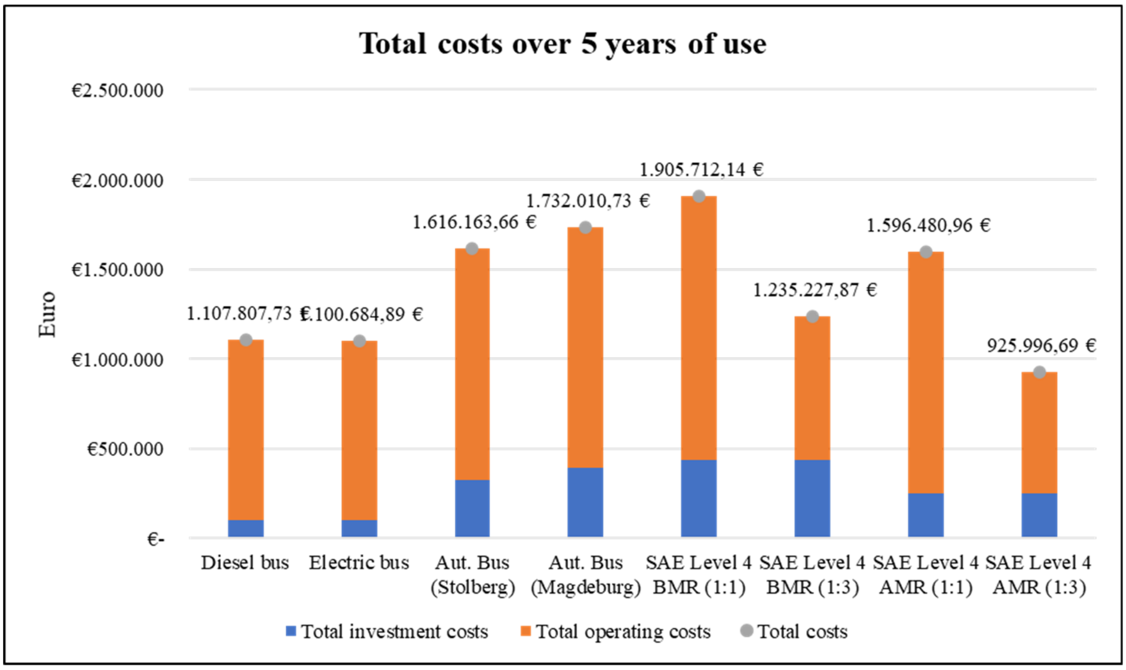

Figure 5. *Total Costs over five years of use*

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

Broken down into the five cost categories (project management, vehicle operating costs, infrastructure + operation control centre operating costs, vehicle investment costs and infrastructure + operation control centre investment costs), it can be seen that vehicle costs decrease and infrastructure and OCC operating costs increase as automation increases (Figure 6). In addition, the investment costs of the vehicle decrease due to market maturity and the then possible series production.

Figure 7 shows the total costs of the 16 scenarios in relation to the total mileage over a period of five years. In this calculation, the infrastructure costs incurred to operate the buses are fully applied to the total cost of the buses. In this approach, it should be noted that the SAE Level 4 BMR scenarios not only have higher costs, but also assume low mileage per year for these vehicles. While a mileage of 40,000 km per year is assumed for the diesel bus, the electric bus, and all SAE Level 4 AMR scenarios, the mileage for the SAE Level 4 BMR scenarios is only 28,864 km per year. Therefore, automated buses SAE Level 4 BMR (blue line) do not reach the cost of conventional buses of about 5.50 euros per vehicle-kilometer. Automated buses SAE Level 4 AMR are already more cost-effective from a support ratio of one control centre employee to two vehicles (5.47 euros per vehicle kilometer).

Since the infrastructure measures (including roadside units) can also be used by other road users, Figure 8 shows the costs per vehicle kilometer without infrastructure costs. Thus, especially the cost values for automated buses are significantly reduced and perform better.

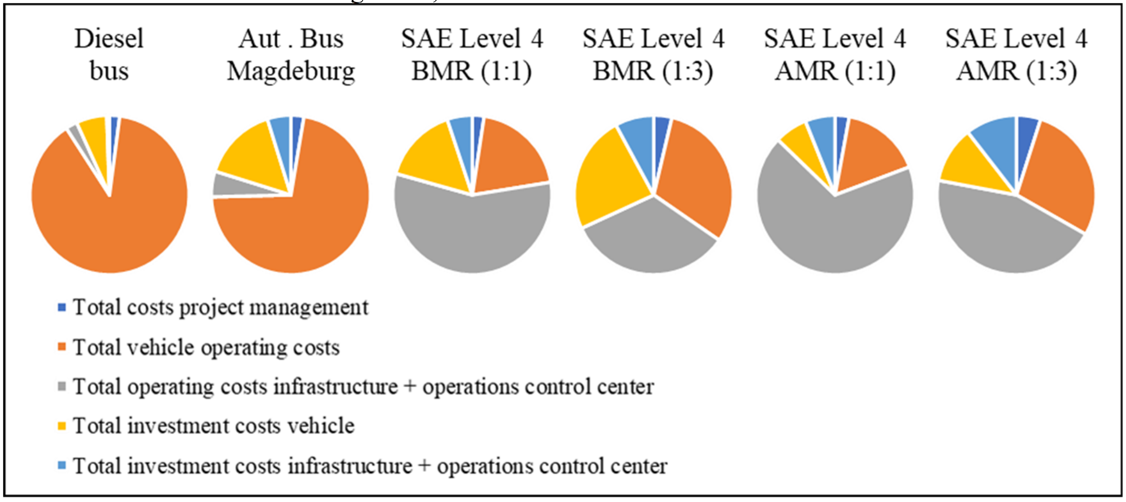

Figure 6. Comparison of five cost categories

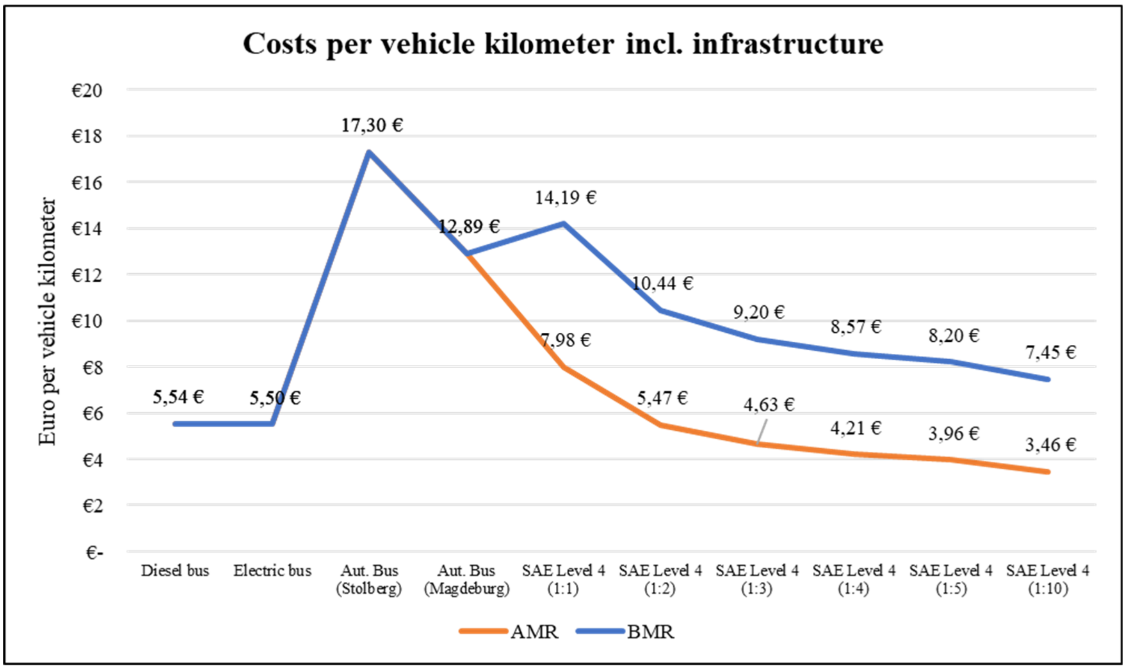

Figure 7. Cost per vehicle kilometer incl. infrastructure

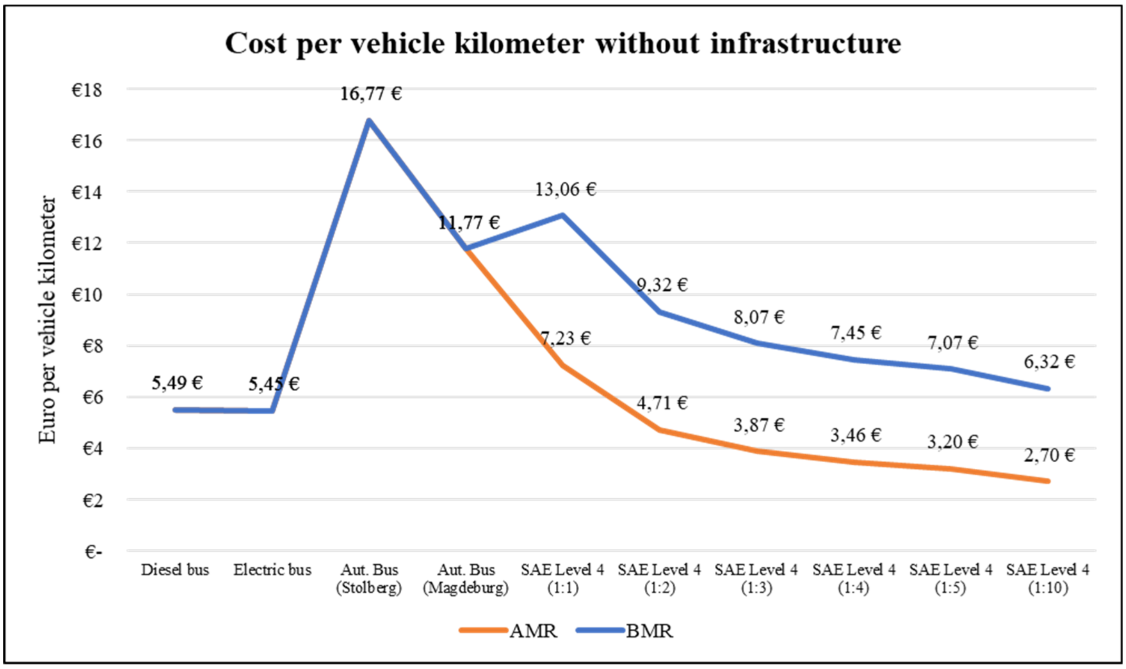

Figure 8. Cost per vehicle kilometer without infrastructure

4.2 RESULTS COST-EFFECTIVENESS ANALYSIS

In the expert survey, the criteria selected are climate protection, time flexibility, safety, opening up new spaces, and opening up new user groups. The results of the survey are compared in pairs and the partial benefit is formed. Figure 9 shows the result of the expert survey by visualizing the part worth for each criterion.

The automated bus is rated significantly better than the conventional diesel bus in terms of climate protection, opening up new areas and new user groups. In terms of time availability, both systems are rated identically, and only in terms of safety is the diesel bus rated better. The latter is again in contrast to the opinions in the literature [6]. Overall, according to the experts, the automated bus has a higher overall benefit.

In summary, the total costs of the alternatives per benefit point are calculated (Figure 10). The same benefit value is determined for the electric bus based on the expert survey as for the automated bus, which is why it has an advantage over the diesel bus. Automated bus BMRs have a better cost-effectiveness ratio than diesel bus from a ratio of 1:3 and a better cost-benefit ratio than electric bus from a ratio of 1:6. The scenarios with SAE Level 4 AMR have a better cost-effectiveness ratio than the diesel and electric bus starting at a care ratio of 1:2.

The same representation without considering infrastructure is shown in Figure 11. Similar to Figure 8, the automated bus becomes more attractive compared to the diesel bus due to the elimination of infrastructure costs. Even at a service ratio of 1:2, the BMR automated bus is rated better than the conventional diesel bus.

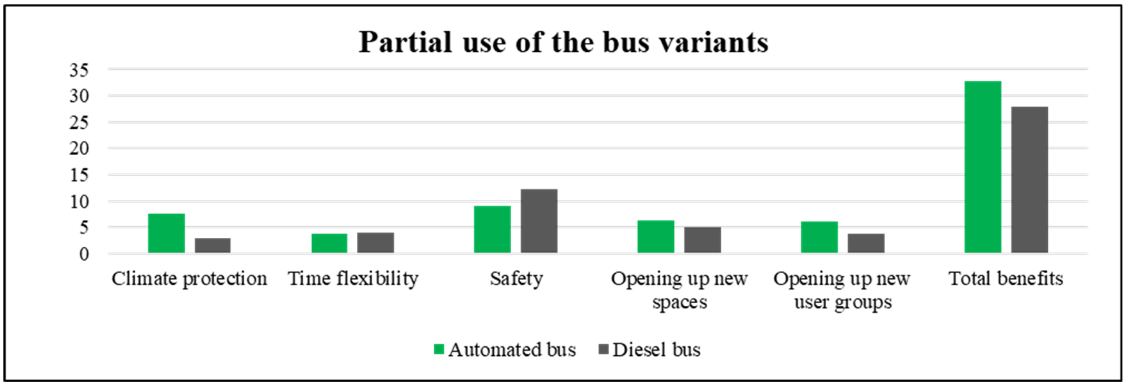

Figure 9. Benefit points per benefit criterion and bus variant

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

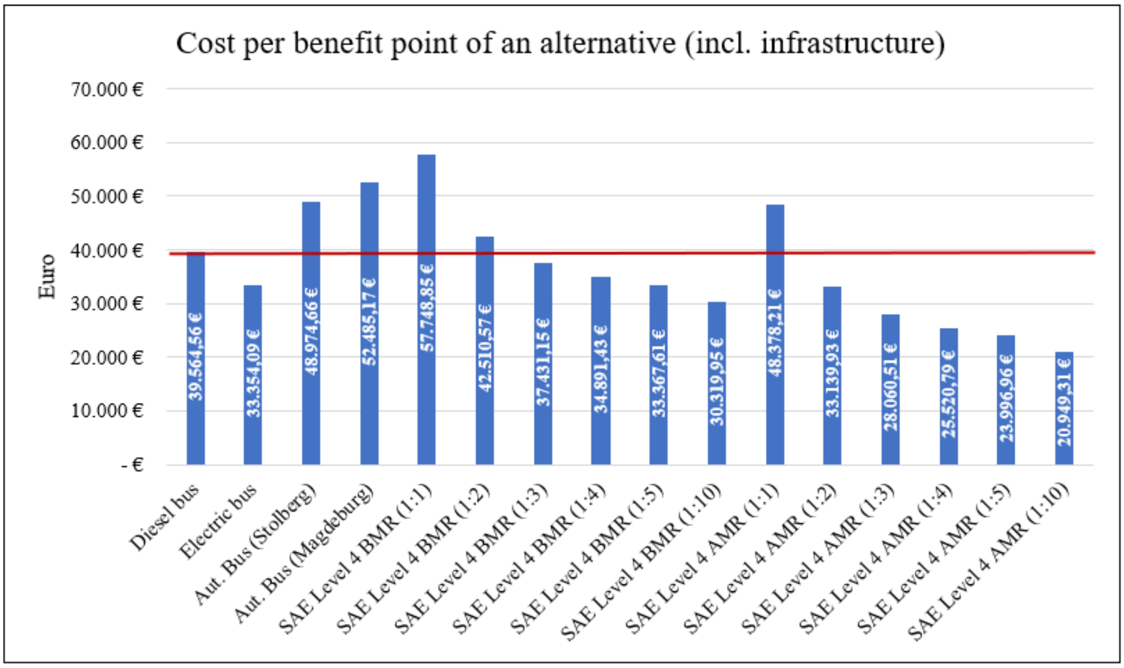

Figure 10. *Cost per benefit point of an alternative (incl. infrastructure)*

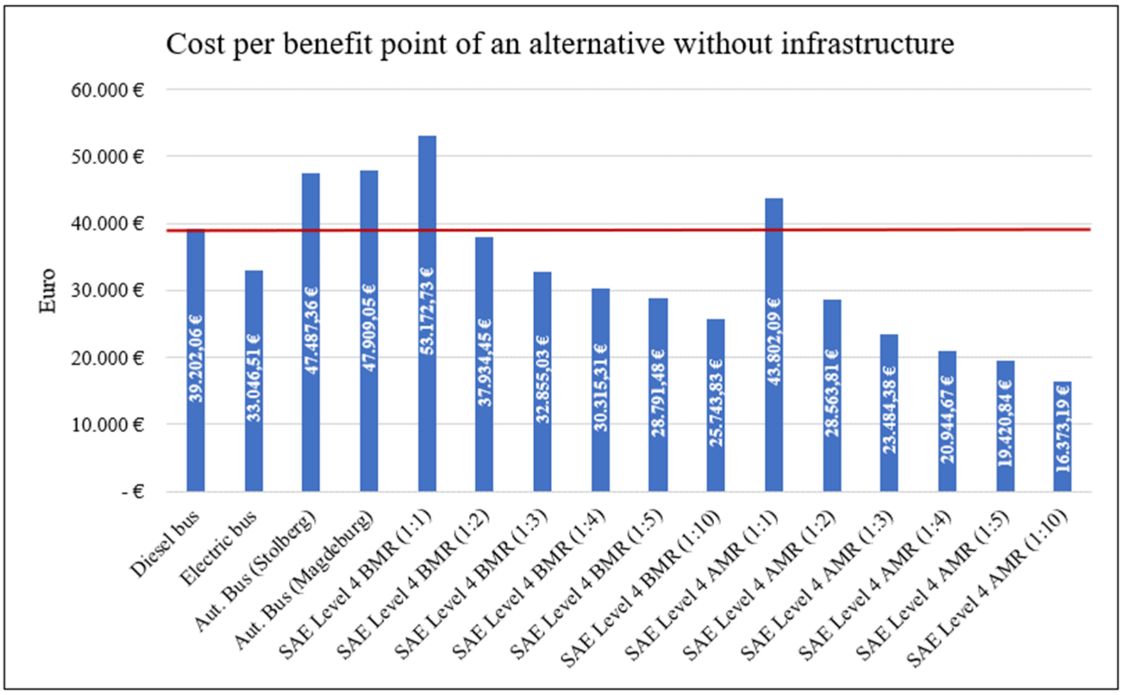

Figure 11. *Cost per benefit point of an alternative without. infrastructure*

5 DISCUSSION

In the following, the question of the economic viability of automated buses is answered in summary from today's perspective and in a short- to medium-term perspective. The limitations of the selected method and the data situation are examined and the need for further investigation is derived. Furthermore, the transferability of the economic feasibility studies in this paper to freight transport is discussed and the need for future research is defined.

5.1 KEY THESES ON THE ECONOMIC EFFICIENCY OF AUTOMATED BUSES

According to the current state of the art, the use of an automated bus is significantly more expensive than conventional alternatives. This is true even up to an operator ratio of one operator for ten vehicles. Once they are ready for the market, however, automated buses (level 4) will become more cost-effective than conventional vehicles with a service ratio of one operator for three vehicles. Considering qualitative benefit criteria, though, a more favourable cost-effectiveness index of automated buses compared to diesel buses already results from an operator ratio of 1:2 (AMR) or 1:3 (BMR). Moreover, in this paper, the costs for upgrading the infrastructure are attributed entirely to the bus operator, which is the rule for the pilot operations with automated buses to date [15]. In principle, however, the expenses for upgrading the infrastructure do not always lie with the operator. It is also possible that the state or local authorities will assume these expenses, because with the increase of automated vehicles in traffic, other road users will also share this infrastructure. Without taking infrastructure costs into account, the cost-effectiveness index of automated buses is more favourable than that of diesel buses at a ratio of 1:2 (AMR and BMR).

Instead of a cost-benefit analysis, a cost-effectiveness index is calculated, since the benefits of the alternative scenarios, with the exception of the conventional variants (diesel bus and electric bus), are difficult or impossible to quantify according to current technology readiness levels. The pilot operations with automated buses (Level 3) to date have generally been conducted as part of research projects and without ticketing requirements. From these results, it cannot be concluded whether the demand will be comparable in a regular operation. For this reason, it was decided in this analysis to look at the benefit criteria qualitatively, which is possible with the help of a cost-effectiveness analysis [60].

In Europe, for the first time in 2022, an operation was approved without a safety operator on board and with supervision by an OCC [18]. The Level 4 pilot operations in Germany were in the planning phase at the time of the economic feasibility studies. Therefore, the costs could only be estimated on the basis of the requirements for Level 4 operation described in Chapter 2 and on the basis of the experience gained from Level 3 operation. For the Level 4 scenarios, too, the benefits can currently only be assessed qualitatively, as there is a lack of data on usage and demand from practice. Furthermore, the required infrastructure adjustments depend strongly on the chosen route [62]. Although user acceptance of an automated bus without a safety person appears to be high, it still needs to be validated in real operation [63, 64].

With regard to the Level 4 operations currently in the start-up phase, many questions and economic aspects remain unanswered. For example, the availability of highly automated buses (Level 4) needs to be investigated and included in the evaluation. Also, the cost of additional security, including cybersecurity, or nationwide network coverage (at least 4G) should be investigated and factored in. In the context of the operator role, there is hardly any practical knowledge about how many automated buses can be supervised by one operator and what the optimal fleet composition might then be, if necessary. These are important questions that must also be answered for future economic feasibility studies.

5.2 AUTOMATED VEHICLES IN FREIGHT TRANSPORT

The methodology used in this paper to evaluate cost-effectiveness can also be applied to the transport of goods with automated vehicles on public or private roads by adapting the scenarios. However, each section of the supply chain has different requirements and cost drivers. These should be analysed separately to accurately understand the impact of deploying automated transportation in each use case. For example, long-haul, short-haul, and in-plant transportation (including handling process) all have different vehicle and infrastructure requirements, as well as different regulatory requirements. The use of highly automated, driverless vehicles on factory premises is already possible and is being actively tested [65-67]. For this reason, the use of automated vehicles for freight transport on factory premises will be of great importance [68]. Some requirements for autonomous driving are not in the foreground for freight transport, e.g. driving speed. While speed is a critical factor in passenger acceptance, automated freight transportation can operate reliably at lower speeds. Reliability and predictability are more important in freight transportation. This opens up a wide range of applications for trips on company premises and in the immediate vicinity (shuttle services). This opens up new potential for logistics, comparable to the developments in the indoor sector since the 1990s.

Teleoperation, i.e. the complete takeover of vehicle control by a human operator at a distance (from an OCC) by means of telecommunication technology, can also be of great relevance for freight transport, since drivers often have to bridge long waiting times during the loading and unloading of trucks along the transport process [42]. A teleoperator can use the waiting time to control another truck [68]. Another function that can be performed by the OCC is fine positioning, which is essential for goods handling. With the help of the OCC, the development phase can be bridged up to full automation according to level 5. For this reason, a highly automated outdoor goods handling system, in which it is estimated that 80% of the tasks can be performed without human assistance and 20% of the processes are performed by a teleoperator from the OCC, leads to major efficiency gains in plant logistics [68]. Instead of deploying, dispatching, and scheduling multiple drivers for material handling equipment, such as forklifts, on a shift basis, all that is needed is to schedule personnel in the OCC who are called from the vehicles as needed, perform the necessary processes via teleoperation, and are available for the next need (request).

In summary, in addition to monitoring vehicle data and providing tele-assistance, an OCC in freight transportation can perform the following additional tasks, similar to those in passenger transportation:

1. Monitoring of:
    a. vehicle sensor data
    b. delivery schedules and deviations
    c. vehicle capacity
    d. freight, cold-chain monitoring
    e. goods handling
    f. site and infrastructure for delivery (parking space, etc.)
2. Order management (e.g., current transport / delivery costs, delivery times, delivery quality (using interface to the ERP system of the logistics service providers, if applicable)
3. Vehicle module management, if hybrid transport (automated or remote-controlled module switch, maintenance, resource overview)
4. Teleoperation (e.g. goods handling, driving on specific sections of the route)
5. Customer communication (answering requests from logistic service customer) [41]

To perform a cost-effectiveness analysis in freight transportation, it is recommended to first specify the use case and the levels of automation to be compared. Depending on the availability of data, a cost-benefit analysis or a cost-effectiveness analysis can then be performed. To ensure availability, security and high quality of service for the customer, an OCC should be included in the calculation from automation level 4, regardless of the use case. Similar to passenger transportation, instead of the personnel costs for the drivers, the personnel, investment and operating costs of the OCC would have a greater or lesser impact, depending on the use case and the support ratio.

6 CONCLUSION

This paper first presented the role and influence of OCC on the use of automated buses in public transport depending on the automation level according to SAE. Subsequently, a total of 16 scenarios were formed, on the basis of which the economic viability of conventional buses, partially automated buses in the context of pilot operations and highly automated buses without a safety driver for public transport companies was examined. For this purpose, the respective total costs were calculated and the costs per benefit point of the alternatives were compared, taking into account the benefit criteria such as climate protection, time flexibility, safety, and the opening up of new areas and user groups.

State-of-the-art automated buses are significantly more expensive than conventional alternatives. The total costs over 5 years of use are about 46% higher for an automated bus operated according to SAE level 3 in a rural area and about 56% higher in an urban area compared to a diesel bus. The total cost for a Level 4 operation, with 1:1 monitoring of the vehicle by the control centre according to today's market maturity is even 72% higher. This difference in cost, however, will decrease with the increase in vehicles monitored per control centre operator. However, until the capital cost of the automated vehicle decreases as a result of volume production, the SAE Level 4 BMR scenarios will remain more expensive than conventional buses. After market readiness, the costs for the SAE Level 4 AMR (1:2) scenario roughly equal the costs of the diesel and electric bus and continue to decrease as the number of automated vehicles increases. The SAE Level 4 AMR (1:3) scenario is approximately 16% less expensive than the diesel bus.

Considering the potential benefits, the operation of SAE Level 4 automated buses can already be beneficial today despite the high investment costs. The results of the cost-effectiveness analysis have shown that the cost per benefit point is already lower for the SAE Level 4 BMR (1:3) scenario than for the diesel bus. However, the actual monetary benefits must be explored in future regular operations and the expected net benefit or net present value calculated in a cost-benefit analysis.

While some companies are already experimenting with driverless buses, it is important that these vehicles can be operated without a driver in order to achieve their full economic efficiency. This requires the further development of existing control centres of the transport companies and the implementation of new work processes, interfaces and standards. The results of this study provide transit agencies and decision makers considering the implementation of automated bus systems with an overview of the selected potential automation scenarios and their impact on total cost and estimated cost-effectiveness.

7 FUNDING INFORMATION

This publication was funded as part of the research projects “Automated Shuttle Buses – Urban Public Transport” with support from the State of Saxony-Anhalt from the European Regional Development Fund (ERDF), "Automated Shuttle Buses - Benefit Analysis Saxony-Anhalt" with support from the state of Saxony-Anhalt from the European Regional Development Fund (ERDF) and "Be_automateD" with support from the Federal ministry for Digital and Transport (BMDV) from the mFUND program.

LITERATURE

[1] C. Krys und K. Fuest. „Roland Berger Trend Compendium 2030: Trend 3 Scarcity of resources.” https://www.rolandberger.com/publications/publication_pdf/roland_berger_trend_compendium_2030___trend_3_scarcity_of_resources_1.pdf (Zugriff am: 31. Juli 2023).

[2] C. Krys, D. Born und S. Geering. „Trend Compendium 2050: Six megatrends that will shape the world.” https://www.rolandberger.com/publications/publication_pdf/roland_berger_trend_compendium_2050_compact_version.pdf (Zugriff am: 31. Juli 2023).

[3] J. Linthorst und A. de Waal, „Megatrends and Disruptors and Their Postulated Impact on Organizations,“ *Sustainability*, Jg. 12, Nr. 20, S. 8740, 2020, doi: 10.3390/su12208740.

[4] V. Maraš, M. Bugarinović, E. Anoyrkati und A. Avarello, „Megatrends, a Way to Identify the Future Transport Challenges,“ in *Data Analytics Paving the Way to Sustainable Urban Mobility: Proceedings of 4th Conference on Sustainable Urban Mobility (CSUM2018), 24 - 25 May, Skiathos Island, Greece* (Advances in Intelligent Systems and Computing 879), E. G. Nathanail und I. D. Karakikes, Hg., 1. Aufl. Cham: Springer International Publishing; Imprint: Springer, 2019, S. 223–232.

[5] J. S. Dangschat, „Automatisierter Verkehr – was kommt da auf uns zu?,“ *Z Politikwiss*, Jg. 27, Nr. 4, S. 493–507, 2017. doi: 10.1007/s41358-017-0118-8. [Online]. Verfügbar unter: https://link.springer.com/interrupt/article/10.1007/s41358-017-0118-8?format=pdf&gtmEventCategory=Article

[6] Agora Verkehrswende. „Transforming Transport to Ensure Tomorrow’s Mobility.” https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/12_Thesen/Agora-Verkehrswende-12-Insights_EN_WEB.pdf (Zugriff am: 31. Juli 2023).

[7] A. Kirimtat, O. Krejcar, A. Kertesz und M. F. Tasgetiren, „Future Trends and Current State of Smart City Concepts: A Survey,“ *IEEE Access*, Jg. 8, S. 86448–86467, 2020, doi: 10.1109/ACCESS.2020.2992441.

[8] Sustainable Mobility for All. „Global Roadmap of Action: Toward Sustainable Mobility.” https://sum4all.org/data/files/gra-globalroadmapofaction-press.pdf (Zugriff am: 8. Juli 2020).

[9] A. Prof. Dr. Knie, W. Dr. habil. Canzler und L. Dr. Ruhrort. „Autonomes Fahren im Öffentlichen Verkehr – Chancen, Risiken und politischer Handlungsbedarf.” https://www.gruene-hamburg.de/wp-content/uploads/2019/04/Autonomes_Fahren_Gutachten_030419.pdf (Zugriff am: 31. März 2022).

[10] H. Kagermann, „Die Mobilitätswende: Die Zukunft der Mobilität ist elektrisch, vernetzt und automatisiert,“ in *CSR und Digitalisierung*, A. Hildebrandt und W. Landhäußer, Hg., Berlin, Heidelberg: Springer-Verlag GmbH, 2017, S. 357–371.

[11] N. Kostorz, T. Hilgert und M. Kagerbauer, „Automatisierte Kleinbusse im Öffentlichen Personennahverkehr – Akzeptanz und Nutzungsintentonen in Deutschland,“ *Journal für Mobilität und Verkehr*, Nr. 2, S. 23–32, 2019.

[12] M. Barrillère-Scholz, C. Büttner und A. Becker, „Mobilität 4.0: Deutschlands erste autonome Buslinie in Bad Birnbach als Pionierleistung für neue Verkehrskonzepte,“ in *Autonome Shuttlebusse im ÖPNV*, A. Riener, A. Appel, W. Dorner, T. Huber, J. C. Kolb und H. Wagner, Hg., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, S. 15–22.

[13] SAE International, *SAE J3016: Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*, 2018.

[14] J. C. Kolb, L. Wech, M. Schwabe, C. Ruzok und C. Trost, „Technische Aspekte des automatisierten Fahrens am Projekt des autonomen Shuttlebusses in Bad Birnbach,“ in *Autonome Shuttlebusse im ÖPNV*, A. Riener, A. Appel, W. Dorner, T. Huber, J. C. Kolb und H. Wagner, Hg., Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, 57–94.

[15] J. Ainsalu *et al.*, „State of the Art of Automated Buses,“ *Sustainability*, Jg. 10, Nr. 3118, S. 1–34, 2018. [Online]. Verfügbar unter: https://www.mdpi.com/2071-1050/10/9/3118/htm

[16] K. Kolodge, S. Cicotte und H. Peng. „Mcity Driverless Shuttle: What We Learned About Consumer Acceptance of Automated Vehicles.” https://mcity.umich.edu/wp-content/uploads/2020/10/mcity-driverless-shuttle-whitepaper.pdf (Zugriff am: 25. März 2022).

[17] M. Lalli, *Autonomes Fahren und die Zukunft der Mobilität,* 2. Aufl. Heidelberg: sociotrend, 2019.

[18] EasyMile. „Fully Driverless Shuttle Service on Medical Campus.” https://easymile.com/success-stories/oncopole (Zugriff am: 31. Juli 2023).

[19] K. Nordenbeck. „Selbstfahrende Kleinbusse in Berlin: Die BVG macht den Test.” https://t3n.de/news/

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

bvg-test-selbstfahrende-bus-berlin-1556509/ (Zugriff am: 31. Juli 2023).

[20] Bundesministerium für Digitales und Verkehr (BMDV). „BMDV fördert selbstfahrende Fahrzeuge in München.” https://bmdv.bund.de/SharedDocs/DE/Pressemitteilungen/2023/035-wissing-selbstfahrende-fahrzeuge-muenchen.html (Zugriff am: 31. Juli 2023).

[21] ERTRAC. „Connected, Cooperative and Automated Mobility Roadmap.” https://www.ertrac.org/wp-content/uploads/2022/07/ERTRAC-CCAM-Roadmap-V10.pdf (Zugriff am: 31. Juli 2023).

[22] M. Bout, A. P. Brenden, M. Klingegård, A. Habibovic und M.-P. Böckle, „A Head-Mounted Display to Support Teleoperations of Shared Automated Vehicles,“ in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, Oldenburg Germany, S. Boll et al., Hg., 2017, S. 62–66, doi: 10.1145/3131726.3131758.

[23] S. Nordhoff, J. de Winter, M. Kyriakidis, B. van Arem und R. Happee, „Acceptance of Driverless Vehicles: Results from a Large Cross-National Questionnaire Study,“ *Journal of Advanced Transportation*, Jg. 2018, S. 1–22, 2018, doi: 10.1155/2018/5382192.

[24] I. S. Franke, S. Beckmann, O. Biletska und H. Zadek, „Mockup einer Betriebsleitstelle für automatisierte Shuttlebusse – Konzeption und Design eines universellen, visuellen und auditiven Interfaces,“ in *Entwerfen Entwickeln Erleben in Produktentwicklung und Design 2021*, R. H. Stelzer und J. Krzywinski, Hg., 2021, S. 601–612.

[25] C. Kettwich und A. Dreßler, „Requirements of Future Control Centers in Public Transport,“ in *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Virtual Event DC USA, AutomotiveUI ‘20, Hg., 2020, S. 69–73, doi: 10.1145/3409251.3411726.

[26] T. Zhang, „Toward Automated Vehicle Teleoperation: Vision, Opportunities, and Challenges,“ *IEEE Internet Things J.*, Jg. 7, Nr. 12, S. 11347–11354, 2020, doi: 10.1109/JIOT.2020.3028766.

[27] Bundesministerium für Digitales und Verkehr (BMDV). „Entwurf eines Gesetzes zur Änderung des Straßenverkehrsgesetzes und des Pflichtversicherungsgesetzes – Gesetz zum autonomen Fahren.” https://bmdv.bund.de/SharedDocs/DE/Anlage/Gesetze/Gesetze-19/gesetz-aenderung-strassenverkehrsgesetz-pflichtversicherungsgesetz-autonomes-fahren.pdf?__blob=publicationFile (Zugriff am: 24. August 2023).

[28] Bundesministerium für Digitales und Verkehr (BMDV). „Verordnung des Bundesministeriums für Digitales und Verkehr. Verordnung zur Regelung des Betriebs von Kraftfahr-zeugen mit automatisierter und autonomer Fahrfunktion und zur Änderung straßenverkehrsrechtlicher Vorschriften.” https://bmdv.bund.de/SharedDocs/DE/Anlage/K/presse/008-verordnung-automatisierte-autonome-fahrfunktion.pdf?__blob=publicationFile (Zugriff am: 24. August 2023).

[29] N. Brenner, A. Lauber, C. Meier, W. Reitmeier und E. Sax, „Requirements of Automated Vehicles and Depots for the Initial Step of Automated Public Transport,“ in *Commercial Vehicle Technology 2020/2021: Proceedings of the 6th Commercial Vehicle Technology Symposium* (Proceedings), K. Berns, K. Dressler, R. Kalmar, N. Stephan, R. Teutsch und M. Thul, Hg., 1. Aufl. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint Springer Vieweg, 2021, S. 15–26.

[30] *VDV-Schrift 731 - Betriebliche Anforderungen an ÖPNV-Leitstellen,* Verband Deutscher Verkehrsunternehmen, Köln, Nov. 2015.

[31] J. Janecke, A. Dobe, A. Pilz und A. Jaeschke, „Wirkung und Bewertung eines RBL in der Region (Teil 2),“ *V+T*, Nr. 5, S. 167–174, 2005, doi: 10.37307/j.1868-7911.2005.05.02.

[32] R. Schubert, M. Nolte, A. de La Fortelle und M. Maurer, „ODD-Centric Contextual Sensitivity Analysis Applied To A Non-Linear Vehicle Dynamics Model,“ in *2023 IEEE Intelligent Vehicles Symposium (IV)*, Anchorage, AK, USA, IEEE, Hg., Jun. 2023 - Jun. 2023, S. 1–8, doi: 10.1109/IV55152.2023.10186729.

[33] Verband Deutscher Verkehrsunternehmen. „Autonome Shutte-Bus-Projekte in Deutschland.” https://www.vdv.de/liste-autonome-shuttle-bus-projekte.aspx (Zugriff am: 22. September 2022).

[34] A. Soteropoulos *et al.*, „Automatisierung, öffentlicher Verkehr und Mobility as a Service: Erfahrungen aus Tests mit automatisierten Shuttlebussen,“ in *AVENUE21. Politische und planerische Aspekte der automatisierten Mobilität*, Erscheinungsort nicht ermittelbar: Springer Nature, 2021, S. 75–106.

[35] EasyMile. „Fleet Management.” https://easymile.com/de/technology/ezfleet (Zugriff am: 24. August 2023).

[36] M. Wood *et al.* „Safety First for Automated Driving.” https://www.daimler.com/dokumente/innovation/sonstiges/safety-first-for-automated-driving.pdf (Zugriff am: 2. März 2020).

[37] P. Lin, „Why Ethics Matters for Autonomous Cars,“ in *Autonomes Fahren: Technische, rechtliche und gesellschaftliche Aspekte*, M. Maurer, J. C. Gerdes, B. Lenz und H. Winner, Hg., Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, S. 69–86.

[38] B. Färber, „Kommunikationsprobleme zwischen autonomen Fahrzeugen und menschlichen Fahrern,“ in *Autonomes Fahren: Technische, rechtliche und gesellschaftliche Aspekte*, M. Maurer, J. C. Gerdes, B. Lenz und H. Winner, Hg., Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, S. 127–150.

[39] R. Coppola und M. Morisio, „Connected Car,“ *ACM Comput. Surv.*, Jg. 49, Nr. 3, S. 1–36, 2016, doi: 10.1145/2971482.

[40] O. Biletska, S. Beckmann, T. Glimm und H. Zadek, „Key Requirements and Concept For the Future Operations Control Center,“ in *2021 International Scientific Symposium on Logistics: Conference Volume*, T. Schmidt, K. Furmans, M. Freitag, B. Hellingrath, R. de Koster und A. Lange, Hg., 2021, S. 57–68.

[41] O. Biletska, G. L. Kurtz und H. Zadek, „Operation control center for automated vehicles : conceptual design,“ in *Proceedings of the Hamburg International Conference of Logistics (HICL) 2022*, W. Kersten, C. Jahn, T. Blecker und C. M. Ringle, Hg., 2022, S. 731–752.

[42] N. Herzberger, J. Wasser und F. Flemisch, „Control Centers for Maneuver-based Teleoperation of Highly Automated and Autonomous Vehicles: System Model and Requirements,“ in *Human Factors in Transportation*, K. Plant und G. Praetorius, Hg., 2022, S. 501–507, doi: 10.54941/ahfe1002483.

[43] L. D. Burns, W. Jordan und B. Scarborough, „Transforming Personal Mobility, Technical Report,“ *The Earth Institute, Columbia University*, 2013.

[44] D. J. Fagnant und K. Kockelman, „Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations,“ *Paper Presented at the 93rd Annual Meeting of the Transportation Research Board*, Jg. Washington DC, 2014, doi: 10.1016/j.tra.2015.04.003.

[45] D. Fagnant und K. Kockelman, „Dynamic ride-sharing and optimal fleet sizing for a system of shared autonomous vehicles,“ *Paper Presented at the 94th Annual Meeting of the Transportation Research Board*, Jg. Washington DC, 2015.

[46] T. Litman. „Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.” https://mayorsinnovation.org/wp-content/uploads/sites/868/2019/11/Winter-2017-Autonomous-Vehicle-Implementation-Predictions.pdf (Zugriff am: 17. August 2023).

[47] M. Friedrich und M. Hartl. „MEGAFON - Modellergebnisse geteilter autonomer Fahrzeugflotten des oeffentlichen Nahverkehrs.” https://www.isv.uni-stuttgart.de/vuv/publikationen/downloads/MEGAFON_Abschlussbericht_V028_20161212.pdf (Zugriff am: 17. August 2023).

[48] T.S. Stephens, J. Gonder, Y. Chen, Z. Lin, C. Liu und D. Gohlke. „Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles.” https://www.nrel.gov/docs/fy17osti/67216.pdf (Zugriff am: 17. August 2023).

[49] L. Merlin, „Comparing Automated Shared Taxis and Conventional Bus Transit for a Small City,“ *JPT*, Jg. 20, Nr. 2, S. 19–39, 2017, doi: 10.5038/2375-0901.20.2.2.

[50] P. M. Bösch, F. Becker, H. Becker und K. W. Axhausen, „Cost-based analysis of autonomous mobility services,“ *Transport Policy*, Jg. 64, S. 76–91, 2018, doi: 10.1016/j.tranpol.2017.09.005.

[51] R. Abe, „Introducing autonomous buses and taxis: Quantifying the potential benefits in Japanese transportation systems,“ *Transportation Research Part A: Policy and Practice*, Jg. 126, Nr. 2, S. 94–113, 2019, doi: 10.1016/j.tra.2019.06.003.

[52] A. Ongel, E. Loewer, F. Roemer, G. Sethuraman, F. Chang und M. Lienkamp, „Economic Assessment of Autonomous Electric Microtransit Vehicles,“ *Sustainability*, Jg. 11, Nr. 3, S. 648, 2019, doi: 10.3390/su11030648.

[53] PTV Group, Karlsruher Institut für Technologie und Rödl & Partner. „Voraussetzungen & Einsatzmöglichkeiten von automatisiert und elektrisch fahrenden (Klein-) Bussen im ÖPNV: Ergebnisse aus dem Forschungsvorhaben LEA (Klein-) Bus.” https://fops.de/wp-content/uploads/2020/07/70.941_Schlussbericht.pdf (Zugriff am: 31. Juli 2023).

[54] T. Richter, A. Brenck, L. Böckler und A. Egoldt. „AutoNV_OPR - Autonomer Öffentlicher Nahverkehr im ländlichen Raum (Landkreis Ostprignitz-Ruppin).” https://www.tib.eu/de/suchen?tx_tibse-

DOI: 10.2195/lj_proc_biletska_en_202310_01
URN: urn:nbn:de:0009-14-58105

arch_search%5Baction%5D=download&tx_tibsearch_search%5Bcontroller%5D=Download&tx_tibsearch_search%5Bdocid%5D=TIBKAT%3A1795015837&cHash=d961d1c54066b94a1d72069ffde9090e (Zugriff am: 17. August 2023).

[55] N. Quarles, K. M. Kockelman und M. Mohamed, „Costs and Benefits of Electrifying and Automating Bus Transit Fleets,“ *Sustainability*, Jg. 12, Nr. 10, S. 3977, 2020, doi: 10.3390/su12103977.

[56] M. Grote und O. Röntgen, *Kosten autonom fahrender Minibusse: Literaturanalyse ergänzt um Erfahrungen aus dem Betrieb eines Testprojektes und den Ergebnissen einer Expert:innenbefragung*. TUHH Universitätsbibliothek, 2021.

[57] M. Sadrani, A. Tirachini und C. Antoniou, „Optimization of service frequency and vehicle size for automated bus systems with crowding externalities and travel time stochasticity,“ *Transportation Research Part C: Emerging Technologies*, Jg. 143, S. 103793, 2022, doi: 10.1016/j.trc.2022.103793.

[58] F. Carreyre, T. Chouaki, N. Coulombel, J. Berrada, L. Bouillaut und S. Hörl, „On-Demand Autonomous Vehicles in Berlin: A Cost–Benefit Analysis,“ *Transportation Research Record: Journal of the Transportation Research Board*, Jg. 6, S. 1, 2023, doi: 10.1177/03611981231186988.

[59] T. Litman. „Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.” https://www.vtpi.org/avip.pdf (Zugriff am: 17. August 2023).

[60] G. Wöhe, U. Döring und G. Brösel, *Einführung in die allgemeine Betriebswirtschaftslehre,* 27. Aufl. Vahlen, 2020.

[61] G. Westermann, *Kosten-Nutzen-Analyse: Einführung und Fallstudien*. Berlin: Erich Schmidt Verlag GmbH & Co., 2012.

[62] S. Beckmann, O. Biletska und H. Zadek, „Requirements for Pilot Routes and Infrastructure for the Introduction of Automated Shuttle Buses in Public Areas,“ *Logistics Journal: Proceedings*, 2020, doi: 10.2195/LJ_PROC_BECKMANN_EN_202012_01.

[63] S. Beckmann und H. Zadek, „User Acceptance of Automated Shuttle Buses - Results of a Passenger Survey in Stolberg,“ in *Smart Energy for Smart Transport*, E. G. Nathanail, N. Gavanas und G. Adamos, Hg., Cham: Springer Nature Switzerland, 2023, S. 1095–1107.

[64] S. Beckmann und H. Zadek, „Empirical investigation of the acceptance of the automated shuttle bus in Stolberg,“ in *15th International Doctoral Students Workshop on Logistics, June 23, 2022 Magdeburg*, E. Glistau und S. Trojahn, Hg., 2022, S. 7–14.

[65] M. Kopp. „Revolution im Hafen: Container werden automatisch gestapelt.” https://www.abendblatt.de/wirtschaft/article238759473/Revolution-im-Hafen-Container-werden-automatisch-gestapelt.html (Zugriff am: 24. August 2023).

[66] BMW Group. „Smarte Werkslogistik: Automatisierte Transportsysteme im Outdoor Einsatz.” https://www.press.bmwgroup.com/deutschland/article/detail/T0345312DE/smarte-werkslogistik:-automatisierte-transportsysteme-im-outdoor-einsatz?language=de (Zugriff am: 24. August 2023).

[67] Fernride GmbH. „Fernride.” https://www.fernride.com/ (Zugriff am: 24. August 2023).

[68] T. Ghandriz, B. Jacobson, L. Laine und J. Hellgren, „Impact of automated driving systems on road freight transport and electrified propulsion of heavy vehicles,“ *Transportation Research Part C: Emerging Technologies*, Jg. 115, Nr. 3, S. 102610, 2020, doi: 10.1016/j.trc.2020.102610.

Olga Biletska, M.Sc., Research Assistant, Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”.
E-Mail: olga.biletska@ovgu.de

Address: Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”,
Universitätsplatz 2, 39106 Magdeburg

Sönke Beckmann, M.Sc., Research Assistant, Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”.
E-Mail: soenke.beckmann@ovgu.de

Address: Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”,
Universitätsplatz 2, 39106 Magdeburg

Univ-Prof. Dr.-Ing. Hartmut Zadek, Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”.
E-Mail: zadek@ovgu.de

Address: Institute of Logistics and Material Handling Systems (ILM), University Magdeburg “Otto-von-Guericke”,
Universitätsplatz 2, 39106 Magdeburg