

Article

Optimizing Fleet Structure for Autonomous Electric Buses: A Route-Based Analysis in Aachen, Germany

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Abstract: Intelligent transportation systems enhance the potential for sustainable, user-friendly, and efficient transport. By eliminating driver costs, autonomous buses facilitate the redesign of networks, timetables, and fleet structure in a cost-effective manner. The electrification of bus fleets offers the opportunity to further improve the environmental sustainability of transportation networks, but requires adjustments to vehicle schedules due to the limited range and charging requirements. This paper examines the intricate relationship between electrification and autonomous buses. To this end, timetables for autonomous electric buses of different sizes were developed for a real bus route in Aachen, Germany. The resulting electric vehicle scheduling problem was then solved using an adaptive large neighborhood search to determine the number of vehicles needed and the total cost of ownership. By eliminating driver costs, vehicles with lower passenger capacity become much more attractive, albeit at a slightly higher cost. In comparison, the incremental costs of electrification are low if the right approach is taken. Fluctuations in typical passenger numbers can be used to modify timetables and vehicle schedules to accommodate the charging needs of autonomous electric buses. In particular, electric bus concepts with fewer charging stations and lower charging power benefit from adapting the timetable to passenger numbers. The results demonstrate that the specific requirements of electric buses should be considered when adapting networks and timetables in order to design a sustainable transport network.

Keywords: autonomous bus; electric bus; public transport; intelligent transportation systems; sustainable transportation; routing problems; electrification; network optimization; autonomous driving



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1. Introduction

Recent years have seen the launch of autonomous bus pilots, which have generally received positive public feedback [1]. Despite the lengthy preparation time for pilot projects [2,3] and ongoing challenges related to vehicle speed [1], weight, and sensor technology [4], significant technical advancements in autonomous buses are evident. Smaller vehicles with lower capacity are frequently used [5], particularly for covering the first and last mile of journeys. Autonomous buses hold promise for broader future applications in public transport [6]. The introduction of self-driving systems is transforming public mobility paradigms, offering significant benefits [7]. At the same time, public transport operators are transitioning to electric bus fleets to reduce emissions [8], driven by current policy directives [9].

1.1. Literature Review

The advent of self-driving vehicles promises to revolutionize sustainable urban transportation systems [10–12], yet it also carries the risk of undermining the efficacy and

utilization of public transit networks [11,12]. The conversion to autonomous buses is expected to result in cost savings for fixed bus routes [13–16], with higher investment costs offset by savings in operating costs for drivers [13,14,17]. A combination of buses and smaller autonomous vehicles also appears to be economically attractive [18]. In addition, the transition to autonomous buses affects network design [13,19] and makes higher service frequencies more attractive [13,14,20]. With respect to vehicle capacity, there are conflicting statements regarding the capacity of autonomous buses. Some sources indicate that the capacity of autonomous buses will decrease [14], while others assert that it will remain the same [20]. The length of the bus network increases with autonomous buses [19], so that more passengers can be transported overall. The use of autonomous buses for fixed bus routes is particularly attractive in regions where public transport is underdeveloped [19]. Overall, autonomous buses are expected to fundamentally change the network design of fixed bus routes.

The electrification of public transport and comparisons of electric bus concepts have been widely studied. Since the range of electric buses is limited, it is necessary to compare concepts at the fleet level, taking into account usability [21]. Buses must be able to complete not only single trips but the entire daily vehicle schedule [22]. In many cases, adjustments to vehicle schedules are necessary, resulting in additional costs. Only when these costs are taken into account can a serious comparison of different concepts be made [23,24]. Local conditions have a significant influence on the choice of a suitable electric bus concept [23,25]. These local conditions should take into account restrictions on crew scheduling [26]. Electric buses need to be recharged regularly for efficient operation [27,28]. The limited range and charging periods must be taken into account when planning vehicle schedules [23,24,29]. As a result, electric buses cannot be used as flexibly as conventional buses [30].

For diesel buses, extensive research has been conducted to develop models that identify the optimal fleet composition, including vehicle capacities and service frequencies, tailored to specific bus routes [14,31–35]. These studies emphasize that accommodating passenger preferences generally favors smaller vehicles with higher frequency [31], particularly during off-peak times [32]. Depending on the specific fleet design question, various methodologies have been employed, including simulation-based models [33], analytical methods [34], and evolutionary approaches [35].

However, these methodologies encounter significant challenges when applied to electric buses, primarily due to their limited range and the necessity to integrate charging schedules, which render traditional estimates of vehicle requirements obsolete. Moreover, while previous studies have examined changes in cost structures following the adoption of autonomous electric buses, they frequently neglect the diminished operational flexibility that electric buses exhibit compared to their diesel counterparts [14,36]. Prior research has indicated that adjustments to the timetable in the context of vehicle scheduling could be advantageous for electric buses [37]. As the introduction of autonomous buses has huge implications for network design and service frequency, there may be significant changes in which charging strategies are attractive for battery electric buses.

1.2. Research Gap

This paper examines the interactions between electrification and autonomous vehicle operation for route-based public transportation. The interactions between bus electrification and driverless buses have been the subject of minimal research [38,39] and have already been identified as representing a significant gap in the literature [38]. The following research questions have been identified for this work:

1. What vehicle capacities are economically attractive for operating a route with autonomous electric buses?
2. Which electric bus concepts are economically attractive for operation with autonomous vehicles of different passenger capacities?
3. How do the energy constraints of battery buses affect network adaptations for autonomous buses?

This paper aims to address the research gap described above. To this end, we will employ a case study of a real bus route to investigate the impact of autonomous bus operations on the electrical design of vehicles and charging infrastructure. Our focus will be on comparing the effects of different vehicle capacities and the adaptation to the actual passenger volume on the electrification concept.

Based on the outlined research questions, the interplay between autonomous and electric buses will be investigated in the context of a real bus route in Aachen, Germany. Timetables for autonomous electric buses with different passenger capacities will be developed. The resulting Electric Vehicle Scheduling Problem (E-VSP) is then solved using an Adaptive Large Neighborhood Search (ALNS) to determine the effort required to meet the schedule. This allows the number of vehicles required and the Total Cost of Ownership (TCO) to be determined. The focus is on how autonomous operation affects vehicle electrical design and charging infrastructure. The study fills a research gap by comparatively assessing the impact of different vehicle capacities in relation to electrical constraints and ridership patterns. By fostering a nuanced understanding of these interactions, this will lead to more efficient timetabling, energy conservation, and a responsive adaptation to ridership patterns, in line with the global push toward more sustainable and intelligent urban transportation systems.

2. Case Study

The investigation presented in this paper is based on a case study. The selected bus route, as well as the vehicle capacities, autonomous bus concepts, and assumptions regarding technology and costs, are presented below.

2.1. Bus Route 7 in Aachen, Germany

Bus route 7 runs between the terminal stops ‘Gut-Knapp-Strasse’ and ‘Siedlung Schönauf’. A trip between these two terminal stops is about 14.5 km long and takes about 50 min. The operating hours are from 06:00 to 20:00. The bus route is currently served by 12 m solo buses. Figure 1 shows the route and the bus stops that could be considered for a shortened trip: ‘Nirmer Platz’, ‘Fringsgraben’, ‘Wildbach’, and ‘Haus Linde’. The depot from which the route is served is also shown. All of the following studies are based on a typical workday on this bus route.

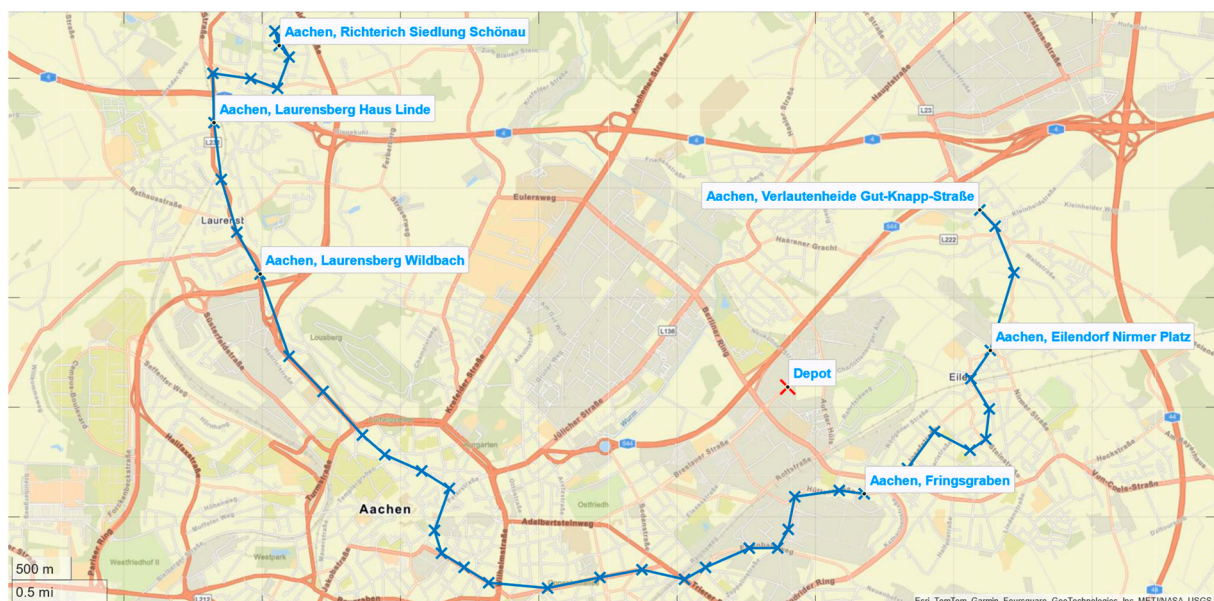


Figure 1. Bus route 7 in Aachen, Germany, created based on [40].

For bus route 7, the spatial and time-related ridership was measured on several workdays and converted to a typical ridership (Figures 2 and 3). Typical ridership varies greatly along the route and is significantly lower at the beginning and end of the route. In addition, Route 7 experiences a spike in ridership, especially in the morning and afternoon, due to the influx of students and commuters (Figure 4). This ridership pattern is emblematic of a variety of bus routes. Given that the bus route exemplifies typical lengths and ridership distribution observed in German bus systems, and that the overall ridership levels are substantial enough to render current service frequencies somewhat inadequate for a single bus, these factors collectively render the route particularly suitable for operations using smaller vehicle types. This suitability makes the route an intriguing subject for analysis in this study. Given the historical operation of the route with conventional solo buses, it is of particular interest to examine whether the elimination of driver costs would make significantly smaller vehicle capacities more economically viable.

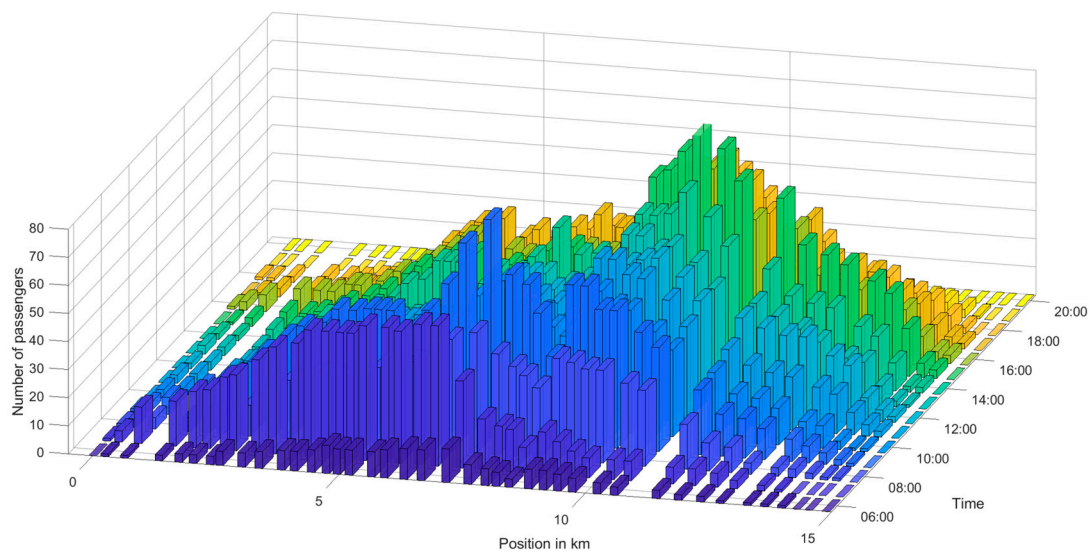


Figure 2. Ridership from 'Gut-Knapp-Strasse' to 'Siedlung Schönaue'.

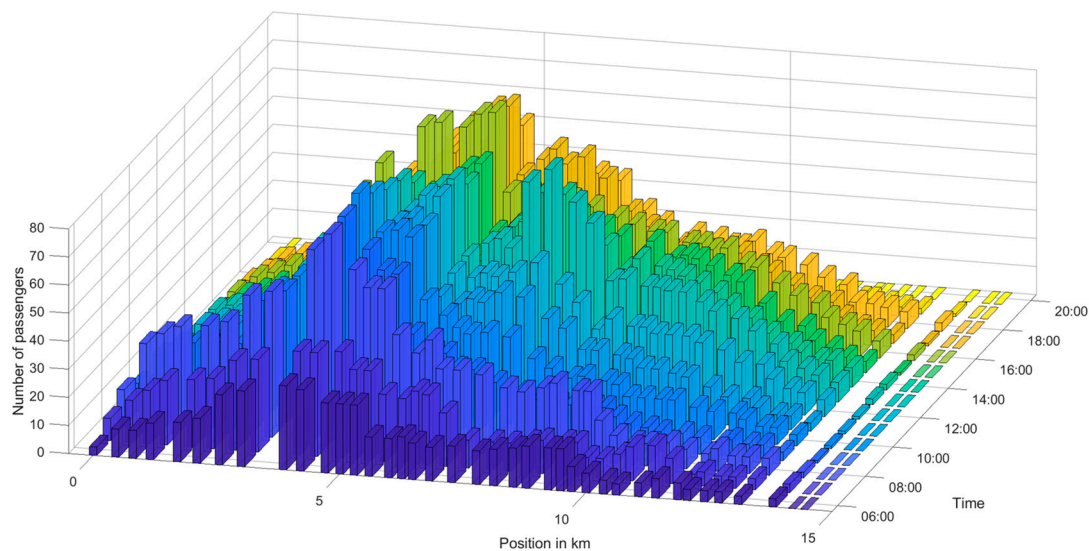


Figure 3. Ridership from 'Siedlung Schönaue' to 'Gut-Knapp-Strasse'.

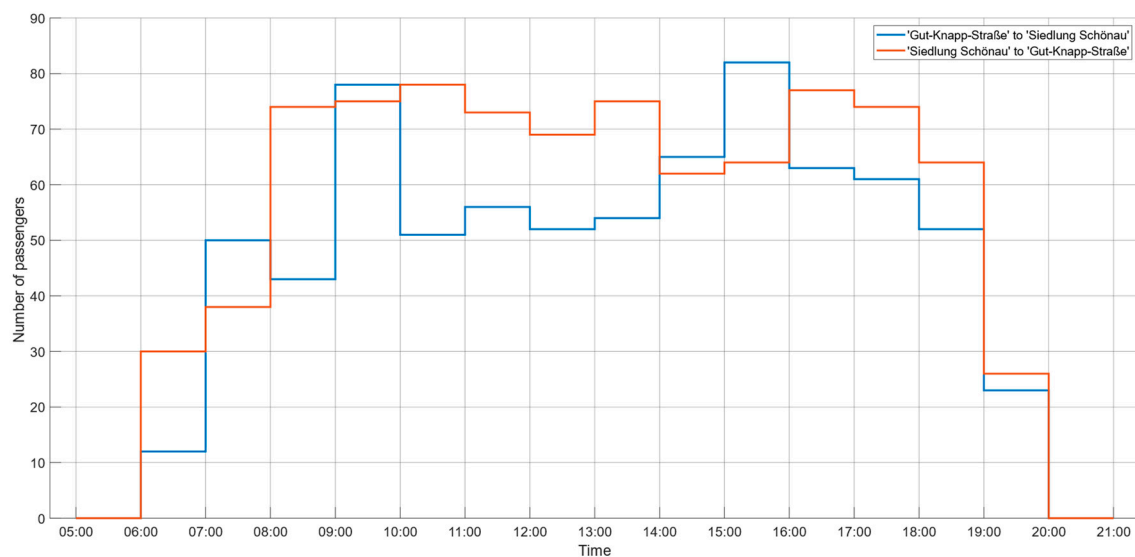


Figure 4. Maximum hourly ridership per direction over time.

2.2. Bus Types

Four different vehicle capacities are considered, namely micro, mini, midi, and solo buses, which can accommodate 9, 18, 36, and 72 passengers, respectively. The inclusion of smaller-capacity vehicles designed for 9 and 18 passengers is particularly motivated by the unique cost dynamics associated with autonomous buses, which do not include driver costs. Traditional small-capacity vehicles, on the other hand, typically have significant driver-related costs, as each vehicle requires a dedicated operator. The inclusion of smaller-capacity vehicles designed for 9 and 18 passengers is particularly motivated by the unique cost dynamics associated with autonomous buses, which do not include driver costs. Traditional small-capacity vehicles, on the other hand, typically have significant driver-related costs, as each vehicle requires a dedicated operator.

Table 1 lists the parameters of the examined bus concepts. Battery-powered electric buses are considered in both depot charging (DC) and opportunity charging (OC) at terminal stops. In terms of battery capacity, a distinction is made between installed capacity and usable capacity. Over time, battery aging results in only 80% of the nominal capacity being available by the end of the battery's service life. Additionally, the extreme margins of the state of charge—specifically below 5% and above 95%—are typically avoided to prevent accelerated aging. Consequently, this study assumes that only 72% of the installed battery capacity is effectively usable throughout the entire usage period.

Table 1. Technical parameters of the investigated bus concepts.

Name	Battery Capacity (Usable/Installed) kWh	Charging Locations	Charging Power (Usable/Installed) kW
Micro bus—diesel	-	-	-
Micro bus—DC-1	72/100	D	40/50
Micro bus—DC-2	72/100	D	60/75
Micro bus—DC-3	72/100	D	120/150
Micro bus—OC-1	72/100	D, GKS	40/50
Micro bus—OC-2	72/100	D, GKS	60/75
Micro bus—OC-3	72/100	D, GKS	120/150
Micro bus—OC-4	72/100	D, GKS, SS	40/50
Micro bus—OC-5	72/100	D, GKS, SS	60/75
Micro bus—OC-6	72/100	D, GKS, SS	120/150
Mini bus—diesel	-	-	-

Table 1. *Cont.*

Name	Battery Capacity (Usable/Installed) kWh	Charging Locations	Charging Power (Usable/Installed) kW
Mini bus—DC-1	130/180	D	80/100
Mini bus—DC-2	130/180	D	120/150
Mini bus—DC-3	130/180	D	240/300
Mini bus—OC-1	130/180	D, GKS	80/100
Mini bus—OC-2	130/180	D, GKS	120/150
Mini bus—OC-3	130/180	D, GKS	240/300
Mini bus—OC-4	130/180	D, GKS, SS	80/100
Mini bus—OC-5	130/180	D, GKS, SS	120/150
Mini bus—OC-6	130/180	D, GKS, SS	240/300
Midi bus—diesel	-	-	-
Midi bus—DC-1	202/280	D	120/150
Midi bus—DC-2	202/280	D	240/300
Midi bus—OC-1	202/280	D, GKS	120/150
Midi bus—OC-2	202/280	D, GKS	240/300
Midi bus—OC-3	202/280	D, GKS, SS	120/150
Midi bus—OC-4	202/280	D, GKS, SS	240/300
Solo bus—diesel	-	-	-
Solo bus—DC-1	324/450	D	240/300
Solo bus—DC-2	324/450	D	360/450
Solo bus—OC-1	324/450	D, GKS	240/300
Solo bus—OC-2	324/450	D, GKS	360/450
Solo bus—OC-3	324/450	D, GKS, SS	240/300
Solo bus—OC-4	324/450	D, GKS, SS	360/450

D: Depot; GKS: Gut-Knapp-Strasse; SS: Siedlung Schönaau.

Charging infrastructure can potentially be established in three locations. The installed charging power corresponds to the rated power of the charger. In practice, the power is limited by voltage and current limits of charger, coupling device, and vehicle—particularly the vehicle battery. The effective average charging power thus depends on the initial and final state of charge of the charging process. In addition, other factors such as efficiency losses, temperature, and battery aging have an impact on the charging process. Therefore, in this work an approximation factor of 80% of the nominal power is used for the effective average charging power. This average effective charging power is then used for simplified calculations in the vehicle scheduling. In addition, the coupling time must be considered. The duration depends on the coupling technology. A combined charging system with combo 2 connector (CCS2) was assumed for charging powers of up to 150 kW. For all powers above that, charging by pantograph was assumed. In this work, the coupling and uncoupling process with CCS2 plug-in is assumed to take 30 s each. For charging with the pantograph, a process time of 15 s was estimated in each case.

Table 2 shows the energy consumption assumptions for the different vehicle capacities. When it comes to bus energy consumption, a distinction is made between traction and auxiliary consumption [41,42]. Heating, air conditioning, cooling, and ventilation in particular play a role in auxiliary consumers [43,44]. In Germany, it is known that at low temperatures, the heating requirement for electric buses can account for about 50% of the energy consumption [45]. For smaller vehicle capacities, fewer empirical data are available regarding energy consumption. It must be noted that the use of passenger cars as micro buses for means of public transport is rather atypical [46], but driving cycles can have a major impact on energy consumption [47]. Therefore, for some vehicle capacities, approximations were made based on the vehicle weight and the volume of the passenger compartment. So far, there are no reliable empirical values for the procurement and maintenance costs of autonomous vehicles. The cost assumptions were therefore made based on the literature on autonomous buses [36] and feasibility and case studies of electric buses [48,49].

Table 2. Energy consumption assumptions for the different vehicle capacities.

	Traction (Deadhead/Service) kWh/km	Auxiliary Consumers (Average/Worst-Case) kW	Diesel Bus L/km
Micro bus	0.15/0.19	1.8/6	8.2
Mini bus	0.33/0.41	2.7/9	16.4
Midi bus	0.56/0.70	4.5/15	29.2
Solo bus	0.76/0.94	5.4/18	36.5

2.3. Cost Assumptions

Table 3 presents the cost assumptions for the various vehicle capacities. The cost of electric buses includes the base vehicle and a battery price of 300 EUR/kWh, with the assumption that the battery cost will decrease 5% per year [48,50–53]. Battery replacement is expected after six years due to limited battery lifetime. The projected costs for the installation of charging infrastructure are estimated at 600 EUR/kW [48,52,54]. This estimate encompasses the expenses associated with the charging station itself, as well as the upstream network infrastructure required by the transport operator and the associated construction costs. To include the costs for maintenance and repair of the charging stations, costs of 35 EUR/kW/a are assumed, which corresponds to 5.8% of the investment costs [54]. Energy costs are set at 0.25 EUR/kWh for electricity and 1.70 EUR/L for diesel, with a 5% yearly cost increase for both sources. The costs for monitoring autonomous vehicles are assumed to be 1 EUR/h. For traditional electric buses, the driver costs are assumed to be 35 EUR/h. The interest rate is 3% per year, and all operational costs are scaled to 12 years based on mileage.

Table 3. Cost assumptions for the different vehicle capacities.

	Base Vehicle			Maintenance Costs EUR/km
	EB	ADB	AEB	
	EUR	EUR	EUR	
Micro bus	5000	60,000	75,000	0.10
Mini bus	110,000	120,000	150,000	0.15
Midi bus	175,000	200,000	250,000	0.20
Solo bus	250,000	280,000	350,000	0.35

EB: conventional electric bus; ADB: autonomous diesel bus; AEB: autonomous electric bus.

3. Methods

Utilizing ridership data, a timetable was constructed featuring trips for various vehicle capacities. In the next phase, vehicle schedules are created to determine the required number of vehicles and operational parameters. These schedules and parameters form the foundational framework for calculating the TCO.

3.1. Timetabling

During the initial phase of the analysis, scheduled service trips are extrapolated from the ridership data. Three distinct scenarios are examined, with variations in the extent to which the timetable corresponds with the ridership patterns.

In Scenario 1, service trips are confined to the routes between the terminal stops. Moreover, a uniform service frequency is maintained throughout the entire operating period. The maximum daily ridership R is the basis for determining these frequencies. Utilizing the vehicle's capacity C and a maximum occupancy rate of 70% n , the necessary number of service trips per hour S is computed in a straightforward manner as per Equa-

tion (1). Subsequently, the calculated service trips are allocated as evenly as feasible within each hour.

$$S = \max\left(\frac{R}{C \cdot n}\right) \quad (1)$$

In the second scenario, trips are also only permitted between the terminal stops. In this case, however, the maximum hourly ridership per direction $R(t)$ is considered, which changes the frequency throughout the day. The number of trips is then determined according to Equation (2). The service trips derived from this are then distributed uniformly across each hour.

$$S(t) = \max\left(\frac{R(t)}{C \cdot n}\right) \quad (2)$$

In the third scenario, shortened trips are allowed. The required number of trips per hour for every route section d of a bus route is calculated using Equation (3). Subsequently, trips are organized to maximize the frequency of transit through route section. Efforts are made to distribute both long and short trips as uniformly as possible over the course of the hour.

$$S(t, d) = \max\left(\frac{R(t, d)}{C \cdot n}\right) \quad (3)$$

3.2. Vehicle Scheduling

In the second step, the trips are assigned to vehicles as part of the vehicle scheduling. The scheduling of electric vehicles is known as E-VSP and has been addressed by several works [55,56]. Given a set of timetabled service trips, the E-VSP aims to find feasible vehicle schedules for electric vehicles with the minimum total cost. The problem is a special case of the electric vehicle routing problem (E-VRP) and can be extended in a variety of ways, for example, to consider the crew scheduling of drivers [26,57,58].

A directed graph $G = (V, A)$ denotes the vehicle scheduling network. Source o and sink s are created to represent the depot. Let T be the set of timetabled service trips. Each service trip $t \in T$ has an energy consumption h_t . For each feasible combination of service trips $i, j \in T$, F_{ij} is defined as the possible charging event between these two trips. To simplify the problem, it is assumed that only the charging event is possible in each case, which allows the largest possible recharge. Each charging event $f \in F$ has a maximum rechargeable energy k_f .

To keep track of the remaining energy of the battery, E_0 is defined as the usable battery capacity and e_i^+ and e_j^- as the remaining energy at the start and end of vertex $i \in V \setminus \{o\}$ and $j \in V \setminus \{s\}$. Each arc $A(i, j)$ with $i \in T$, $j \in F \cup \{o, s\}$ $\vee$ $i \in F \cup \{o, s\}$, $j \in T$ is defined by its costs c_{ij} and an energy consumption l_{ij} . Binary decision variables x_{ij} indicate whether arc $A(i, j)$ is used.

The objective of the E-VSP is to minimize costs, encompassing both vehicle investment and operational costs (4). Constraints (5) mandate that each service trip is assigned to exactly one vehicle. Constraints (6) limit each charging event to a maximum of one visit. Constraints (7) maintain the flow conservation. Constraints (8) to (11) define the energy equations for the battery of the vehicle. Constraints (12) and guarantee that the battery's remaining energy does not drop below zero.

$$\min \left(\sum_{(i,j) \in A} c_{ij} \cdot x_{ij} \right) \quad (4)$$

s.t.

$$\sum_{j:(t,j) \in A} x_{tj} = 1 \quad \forall t \in T \quad (5)$$

$$\sum_{j:(f,j) \in A} x_{fj} \leq 1 \quad \forall f \in F \quad (6)$$

$$\sum_{j:(j,i) \in A} x_{ji} = \sum_{j:(i,j) \in A} x_{ij} \quad \forall i \in V \setminus \{o, s\} \quad (7)$$

$$e_o^- = E_0 \quad (8)$$

$$e_f^- = \min(e_f^+ + k_f, E_0) \quad \forall f \in F \quad (9)$$

$$e_t^- = \min(e_t^+ - h_t, E_0) \quad \forall t \in T \quad (10)$$

$$e_i^+ = \min\left(\sum_{j:(j,i) \in A} (e_j^- - l_{ji}) \cdot x_{ji}, E_0\right) \quad \forall i \in T \cup F \cup s \quad (11)$$

$$e_i^+ \geq 0 \quad \forall i \in T \cup F \cup s \quad (12)$$

$$e_i^- \geq 0 \quad \forall i \in T \cup F \cup o \quad (13)$$

$$x_{ij} \in \{0, 1\} \quad \forall (i, j) \in A \quad (14)$$

To tackle the E-VSP, an ALNS heuristic is used. ALNS has been successfully applied to a large variety of E-VRP [59]. In particular, the method is suitable because the E-VSP is an NP-hard problem and ALNS heuristics can find good solutions in reasonable time even for large problem instances. The principle of ALNS is to search for better solutions in neighborhoods starting from a current solution. The neighborhoods are formed by the combination of destroy methods and repair methods.

The methodology used in this work is based on the solution approach for the electric vehicle and crew scheduling problem developed in Sistig et al. [26]. Algorithm 1 illustrates the heuristic principle. Initially, a baseline solution is established, and the weights p for the destroy methods and repair methods are set. In each iteration, a destroy method and a repair method are chosen. The current solution x is first disrupted by the selected destroy method, which removes the assignments of trips to blocks. In this study, methods such as random trip removal, random block removal, worst block removal, and time-based removal have been implemented as destroy methods. The destroyed solution x_d is then mended using a repair method, reassigning trips to blocks to forge a new solution x' . Repair methods utilized include those based on the concurrent scheduler algorithm and regret insertion heuristics. The concurrent scheduler offers three sequencing strategies: random, first-to-last, and last-to-first. Additionally, various forms of regret insertion heuristics—from regret-1 to regret-4—are implemented to enhance the reassignment of trips during the repair phase. The cost of the new solution is then compared to the optimal solution x^* . An acceptance function determines whether the new solution should replace the current solution. In this study, record-to-record travel was adopted as an acceptance criterion. The new solution is accepted if the cost difference between the new and the optimal solution falls below a predefined threshold, which gradually decreases to zero as the number of iterations increases. The probability of selecting each method is adjusted based on its success, leading to the next iteration. The iterative loop concludes once any of the termination criteria are met.

Algorithm 1: ALNS heuristic for E-VSP

```

1:  $x \leftarrow \text{InitializeSolution}()$ ;
2:  $\rho \leftarrow \text{InitializeWeights}()$ ;
3: while stop criteria are not met do
4:   Select destroy and repair method based on  $\rho$ 
5:    $x_d \leftarrow \text{Destroy}(x)$ ;
6:    $x' \leftarrow \text{Repair}(x_d)$ ;
7:   if  $\text{Accept}(f(x'), f(x^*))$  then
8:      $x \leftarrow x'$ ;
9:   if  $f(x') < f(x^*)$  then
10:     $x^* \leftarrow x'$ ;
11:    $\rho \leftarrow \text{UpdateWeights}(\rho)$ ;
12: end
13: return  $x^*$ 

```

3.3. Calculation of TCO

Based on the vehicle schedules, the TCO for each bus concept is calculated. In this analysis, the net present value (NPV) is used to determine TCO for long-term infrastructure projects. The NPV is crucial for assessing the financial viability of such investments by quantifying the present value of expected future cash flows, thereby providing a clear picture of the project's potential profitability. Annual cash flows (CF) in the NPV calculation typically include operational expenses, maintenance costs, and potential revenues, capturing both the inflows and outflows over the project's lifecycle. The time horizon N corresponds to the expected operational lifespan of the infrastructure, while the discount rate i adjusts future cash flows to their present value, reflecting the time value of money and associated risks.

$$NPV = \sum_{t=0}^N \frac{CF_t}{(1+i)^t} \quad (15)$$

4. Results

For bus route 7, timetables were drawn up for the four vehicle capacities solo, midi, mini, and micro and the three scenarios regarding adaptation to ridership. Table 4 illustrates the trips and distance covered during regular service across different vehicle capacities and scenarios. A decline in passenger capacity leads to an increase in the number of trips, albeit not in a linear fashion. This is because smaller vehicles can meet the ridership more precisely, resulting in reduced passenger mileage for lower vehicle capacities.

Table 4. Number of service trips and service mileage for the scenarios under consideration.

	Number of Service Trips	Service Mileage km	Ridership Service Mileage km
Solo bus, Scenario 1	56	804	57,879
Solo bus, Scenario 2	49	703	50,650
Solo bus, Scenario 3	49	563	40,565
Midi bus, Scenario 1	112	1608	57,879
Midi bus, Scenario 2	79	1134	40,834
Midi bus, Scenario 3	79	851	30,644
Mini bus, Scenario 1	196	2814	50,644
Mini bus, Scenario 2	143	2054	36,965
Mini bus, Scenario 3	143	1479	26,624
Micro bus, Scenario 1	378	5425	48,826
Micro bus, Scenario 2	270	3878	34,898
Micro bus, Scenario 3	270	2722	24,502

These timetables were the basis for the creation of the vehicle schedules and the subsequent calculation of the TCO. In the following, the results of the vehicle scheduling and the TCO calculation per vehicle capacity are presented. The different electric bus concepts for each scenario are compared to each other and to diesel buses. The breakdown of the individual cost items is as follows:

- Base vehicle: investment costs for the base vehicle—without batteries.
- Vehicle maintenance: maintenance costs for the base vehicle.
- Battery: investment costs for the battery as well as for the replacement of the battery at the end of its service life.
- Charging infrastructure: investment costs for the battery as well as for the replacement of the battery at the end of its service life.
- Energy: operative costs for electricity and diesel respectively.
- Vehicle monitoring: operative costs for monitoring the vehicles.
- Driver: operative costs for the driving personnel.

4.1. Solo Buses

For solo buses, vehicle counts are consistent across scenario (Table 5). DC concepts need five buses for extra depot trips for charging, while diesel and OC electric options require four. The lack of differences between the scenarios is due to the fact that the vehicle requirement is determined by the peak passenger load, which is identical in all scenarios. The low number of vehicles makes a more ridership-driven deployment of vehicles less attractive.

Table 5. Number of solo buses for different scenarios.

	Diesel	DC-1	DC-2	OC-1	OC-2	OC-3	OC-4
Scenario 1	4	5	5	4	4	4	4
Scenario 2	4	5	5	4	4	4	4
Scenario 3	4	5	5	4	4	4	4

In Scenario 1 (Figure 5), diesel buses are approximately EUR 400,000 more cost-effective overall, at approximately EUR 4.8 million, than the least expensive electric bus concept, at approximately EUR 5.2 million (OC-1). The difference between the cheapest and the most expensive electric bus concept is approximately EUR 400,000. For the electric bus concepts, the investment costs for vehicles, batteries, and charging infrastructure are approximately twice as high as for diesel buses. The operating costs of electric buses, particularly those related to energy, are lower than those of diesel buses. However, these lower costs cannot offset the higher investment costs associated with electric buses.

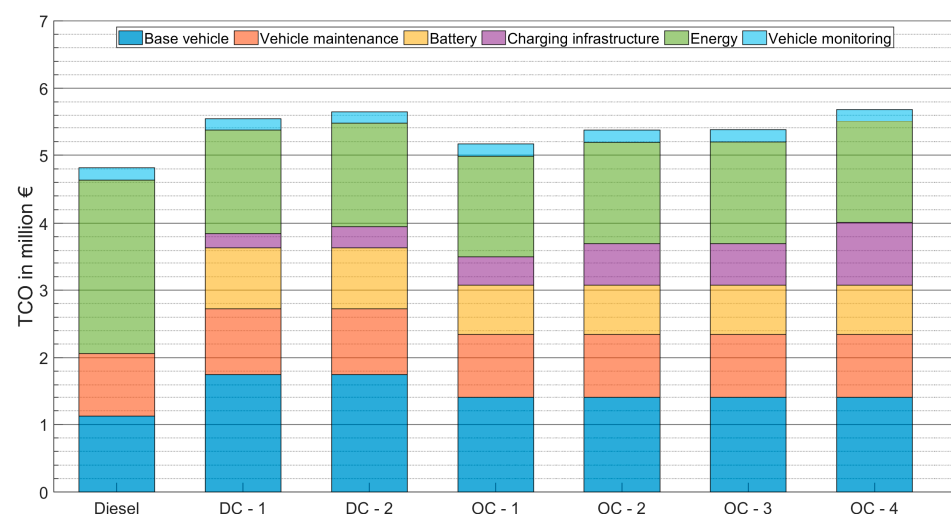


Figure 5. TCO in millions of EUR for solo buses in Scenario 1.

Scenario 2 (Figure 6) and Scenario 3 (Figure 7) show a similar picture and demonstrate a comparable pattern. The elevated investment costs of electric buses are not fully offset by the reduced operational expenses. Consequently, the discrepancy between electric buses and diesel buses widens slightly relative to Scenario 1, as the reduced mileage results in diminished energy consumption. For solo buses, the cost discrepancies between scenarios 1, 2, and 3 are relatively minor, and the operational structure remains largely unchanged.

4.2. Midi Buses

Table 6 illustrates the number of midi buses required for the various scenarios. In Scenario 1, eight diesel buses are needed to operate the route. In Scenario 1, eight diesel buses are needed to serve the route. For scenarios 2 and 3, the number of vehicles reduced to seven. The difference is more pronounced for electric buses. This applies to electric buses

in depot charging. In this instance, the number of vehicles increases to eleven or ten buses in Scenario 1. Conversely, Scenario 3 can be served by all concepts with seven buses.

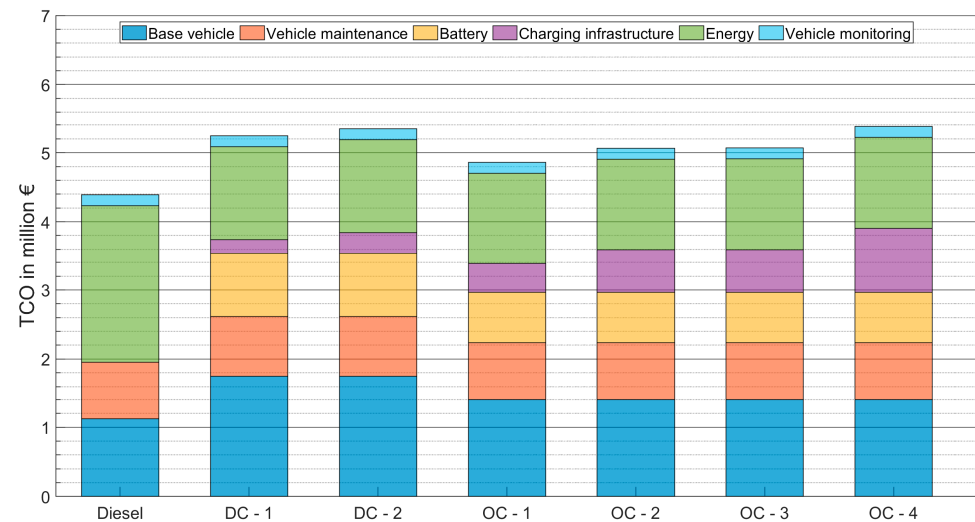


Figure 6. TCO in millions of EUR for solo buses in Scenario 2.

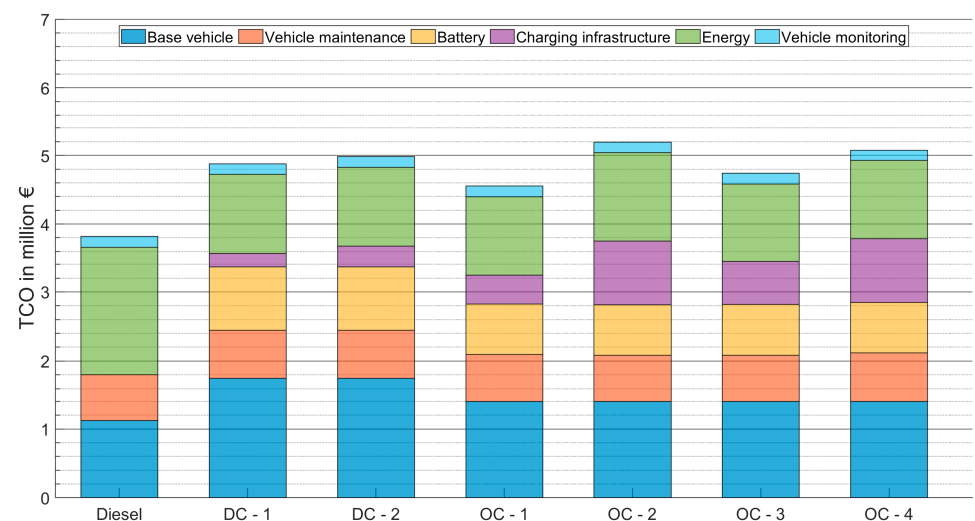


Figure 7. TCO in millions of EUR for solo buses in Scenario 3.

Table 6. Number of midi buses for different scenarios.

	Diesel	DC-1	DC-2	OC-1	OC-2	OC-3	OC-4
Scenario 1	8	11	10	9	8	9	8
Scenario 2	7	9	8	7	7	7	7
Scenario 3	7	7	7	7	7	7	7

In Scenario 1, the electric bus concept OC-2 can compete with diesel buses in terms of costs (Figure 8). Lower energy costs offset higher investments for electric buses, but depot charging is notably costlier. In Scenario 2, the cheapest electric and diesel options are similarly priced, with a narrowed gap between DC and OC (Figure 9). For OC concepts, there is generally no advantage when more charging stations are available. In Scenario 3, diesel buses are less expensive than electric buses (Figure 10). This is primarily due to the lower mileage and therefore lower energy costs. Across scenarios, energy costs account for approximately half of diesel bus expenses.

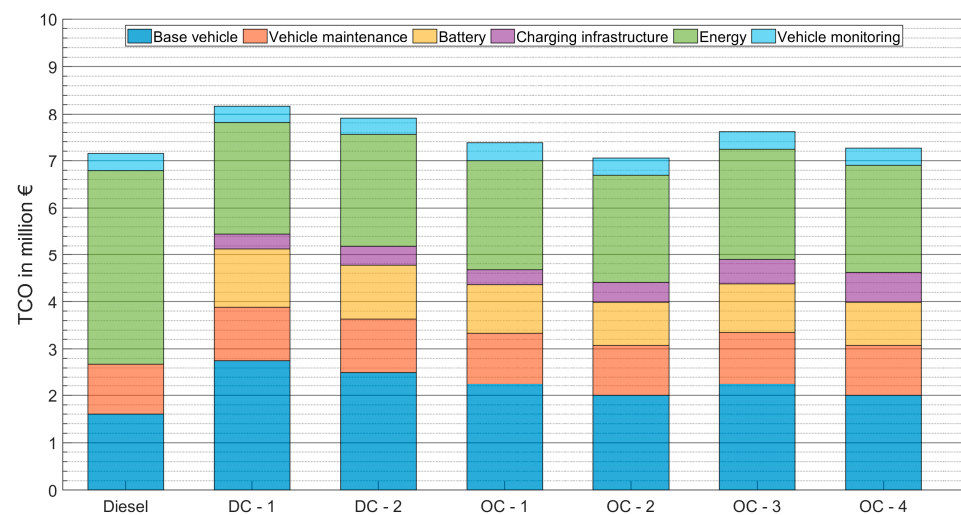


Figure 8. TCO in millions of EUR for midi buses in Scenario 1.

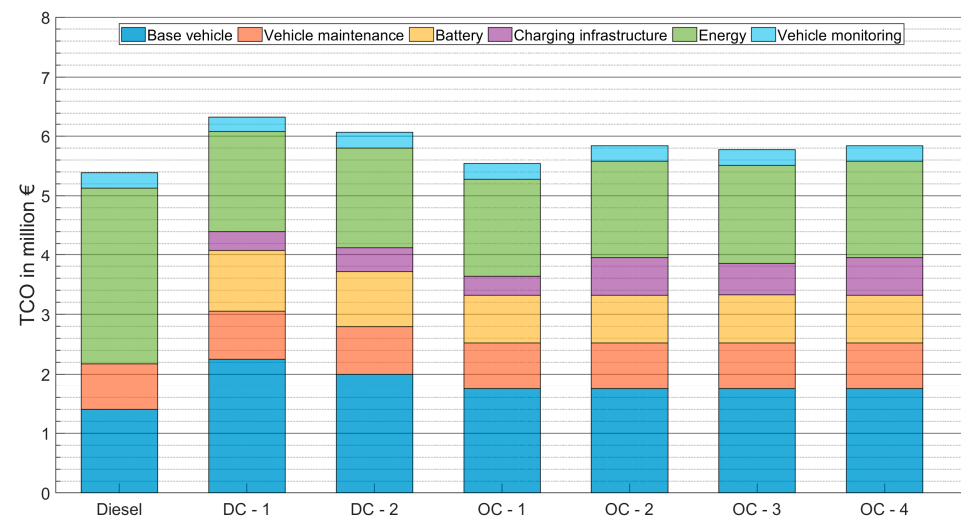


Figure 9. TCO in millions of EUR for midi buses in Scenario 2.

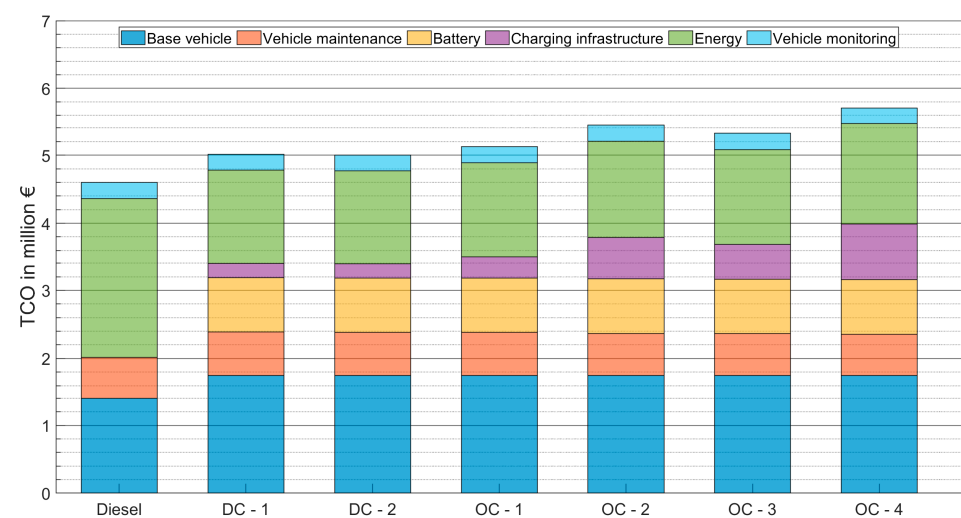


Figure 10. TCO in millions of EUR for midi buses in Scenario 3.

4.3. Mini Buses

In Scenario 1, 14 diesel buses are required to meet the service mileage (Table 7). While the same number of vehicles can be achieved with electric buses for opportunity charging, there is an additional vehicle requirement of at least three buses for depot charging concepts. Overall, the charging capacity is more relevant for the OC concept than the number of charging stations. For Scenario 2, the vehicle requirement for diesel buses is thirteen. The same number of vehicles can be achieved for electric bus concepts. This time, it is also possible to achieve the same number of vehicles with depot charging and a correspondingly high charging capacity. The reason for this is the change in service times. Full fleet deployment is only required during peak hours. This impact is particularly notable for mini buses, which can adjust their trip frequency more closely to typical ridership. This flexibility creates windows of time for charging electric buses, particularly benefiting those with lower charging capabilities. Batteries help to fill the brief periods when all buses are in operation. This effect is further emphasized in Scenario 3, where all concepts require twelve buses.

Table 7. Number of mini buses for different scenarios.

	Diesel	DC-1	DC-2	DC-3	OC-1	OC-2	OC-3	OC-4	OC-5	OC-6
Scenario 1	14	18	17	17	15	14	14	15	14	14
Scenario 2	13	15	14	13	13	13	13	13	13	13
Scenario 3	12	12	12	12	12	12	12	12	12	12

The total operating costs for diesel buses in Scenario 1 are approximately EUR 7.8 million. (Figure 11). The OC-2 electric bus concept requires almost the same costs. Increasing the charging power or the number of charging points is more expensive. The most expensive concepts in this case are DC electric buses. This is due to the higher number of vehicles. In addition to the high energy costs, vehicle maintenance costs play an increasing role. The smaller vehicle capacities result in a greater total distance covered. Consequently, all costs related to kilometers driven increase in proportion.

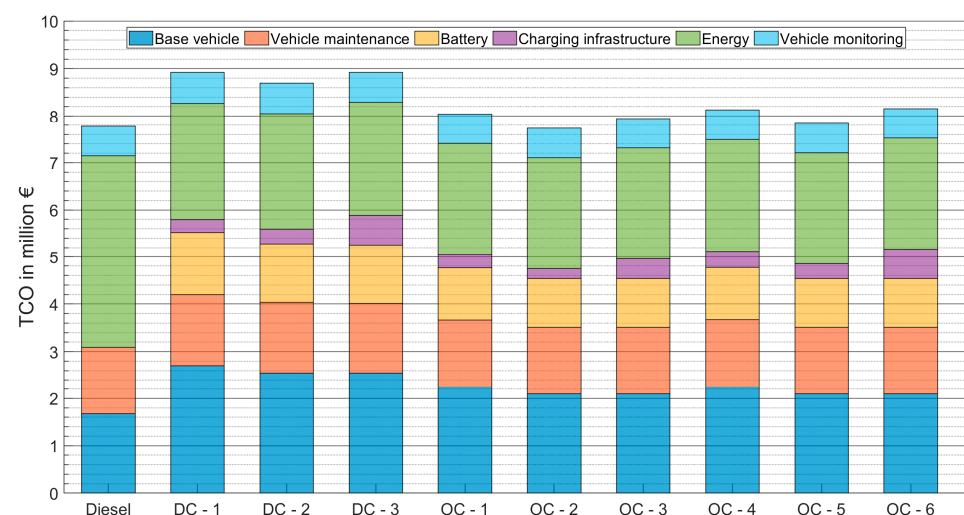


Figure 11. TCO in millions of EUR for mini buses in Scenario 1.

In Scenario 2, costs decrease significantly for all concepts compared to Scenario 1 (Figure 12). This is because vehicles can be saved. The effect is particularly noticeable for depot charging concepts and electric bus concepts with less charging infrastructure. As a result, the energy cost savings are less significant. In total, the cost of diesel buses is approximately EUR 6.2 million. The least expensive electric bus concept is the OC-1, which has an estimated cost of approximately EUR 6.5 million.

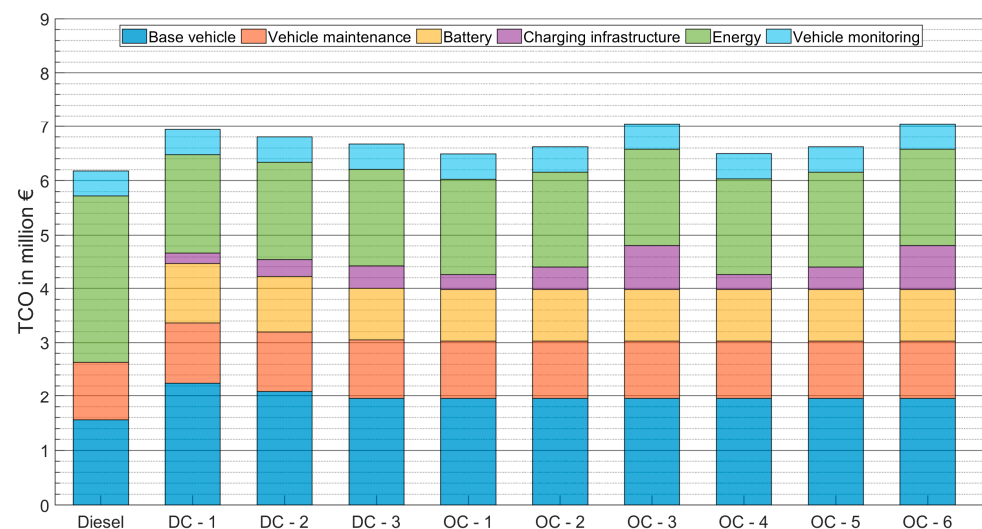


Figure 12. TCO in millions of EUR for mini buses in Scenario 2.

In Scenario 3, the costs drop again significantly to EUR 5.1 million for diesel buses and EUR 5.5 million for the lowest-cost electric bus concept (Figure 13). The least expensive electric bus concept is DC-1, which has the lowest investment costs. The operating costs of the electric bus concepts do not differ significantly.

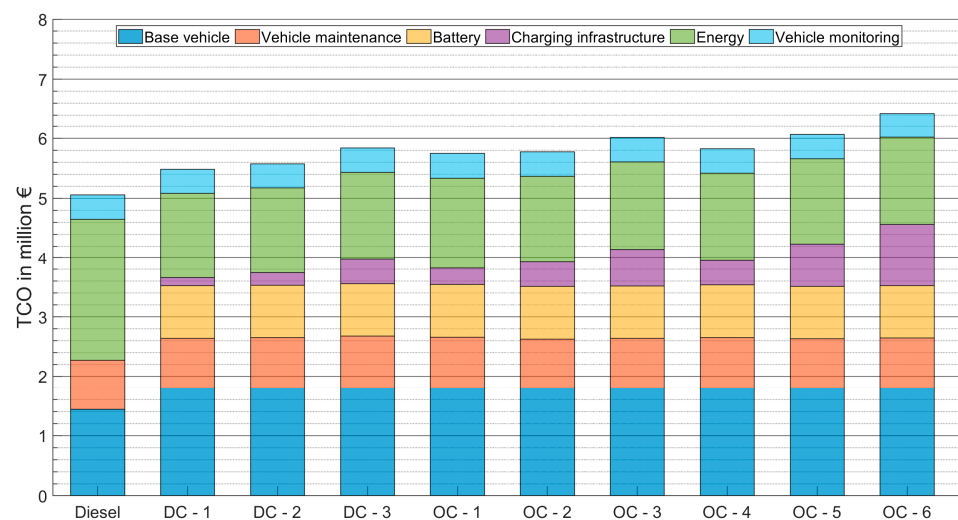


Figure 13. TCO in millions of EUR for mini buses in Scenario 3.

4.4. Micro Buses

Table 8 illustrates the number of micro buses required for the different scenarios. Scenario 1 necessitates the operation of 26 diesel vehicles for the bus route. Additional vehicles are required for all electric bus concepts due to the significantly higher energy consumption per passenger compared to the other vehicle capacities. This makes it much more challenging to balance the energy consumption on average. The charging capacity is of greater importance than the number of charging points. This is a logical consequence of the fact that vehicles can be taken out of service in much smaller increments to create charging windows. For depot charging, this results in additional deadhead trips that reduce the effective charging time and increase vehicle demand.

Table 8. Number of micro buses for different scenarios.

	Diesel	DC-1	DC-2	DC-3	OC-1	OC-2	OC-3	OC-4	OC-5	OC-6
Scenario 1	26	33	32	30	30	28	27	30	28	27
Scenario 2	23	26	25	24	25	24	23	24	23	23
Scenario 3	22	22	22	22	22	22	22	22	22	22

In Scenario 2, the demand decreases by three diesel vehicles compared to Scenario 1. The discrepancy is even more pronounced in the case of electric buses. For instance, OC-3 requires 23 vehicles, which means that there is no additional demand compared to diesel buses. In particular, DC concepts benefit from a change in the cycle time during the day. The impact of the additional possible charging times is even more pronounced in the case of micro buses than in the case of mini buses. In Scenario 3, all concepts are able to accommodate 22 vehicles. Consequently, those with lower charging power and fewer charging points are able to benefit from a stronger orientation of the trips to the passengers.

Figure 14 illustrates the total cost of ownership (TCO) for Scenario 1. The TCO for diesel buses is EUR 8.5 million, while the TCO for the least expensive electric concept (OC-3) is EUR 9 million. The higher costs associated with electric vehicles are primarily attributed to the additional costs associated with batteries. For micro buses, the costs of vehicle maintenance and monitoring play a more significant role than for mini buses. In Scenario 2, the costs decrease significantly, primarily due to the reduction in the number of vehicles required to provide the service (Figure 15). As the effective mileage declines, so too do the energy and maintenance costs. The total operating costs are EUR 6.5 million for diesel vehicles and EUR 7.1 million for the most cost-effective electric concept (OC-3). In Scenario 3, the costs decrease once more to EUR 5.3 million for diesel vehicles and EUR 5.9 million for electric vehicles (Figure 16). Consequently, the additional investment costs for vehicles, charging infrastructure, and especially batteries cannot be fully compensated by lower operating costs.

**Figure 14.** TCO in millions of EUR for micro buses in Scenario 1.

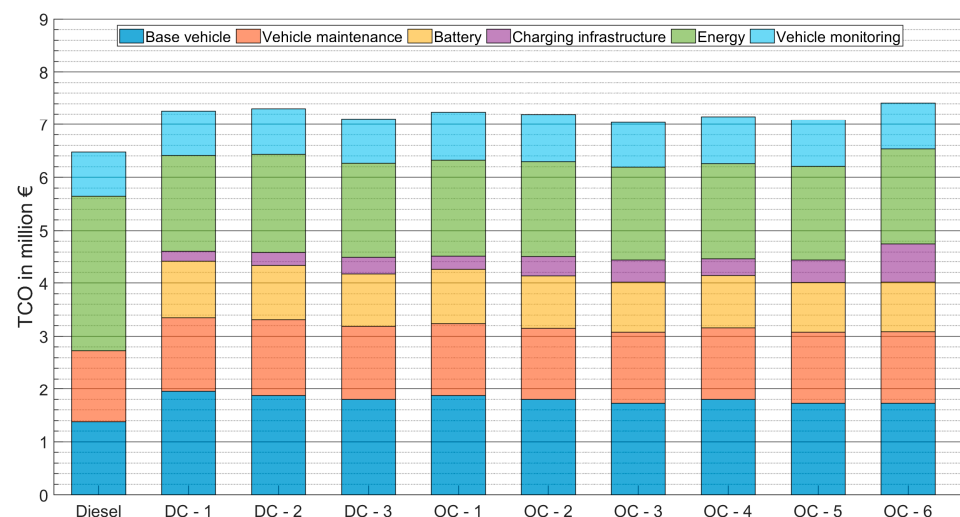


Figure 15. TCO in millions of EUR for micro buses in Scenario 2.

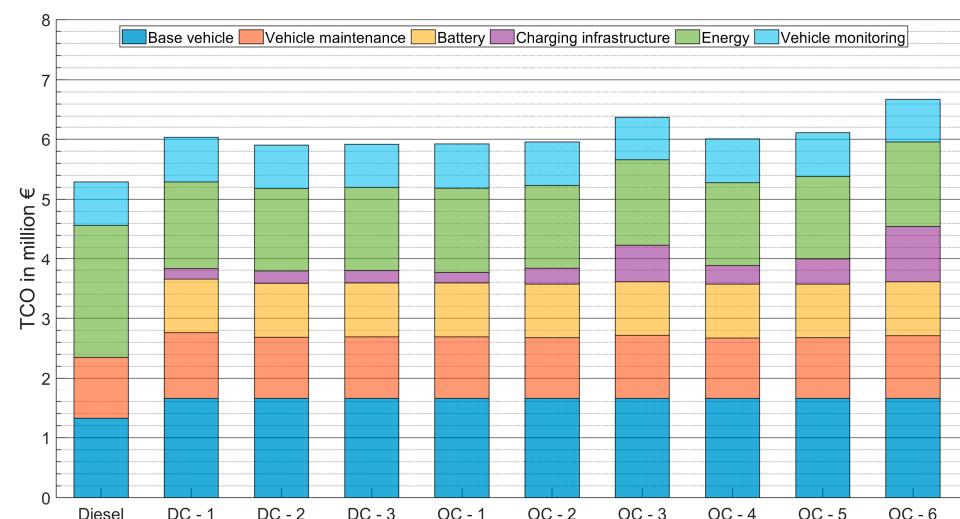


Figure 16. TCO in millions of EUR for micro buses in Scenario 3.

5. Discussion

The following is a discussion of the research questions based on the results:

1. What vehicle capacities are economically attractive for operating a route with autonomous electric buses?

Figure 17 illustrates the costs associated with the different vehicle capacities for conventional electric buses (“EB”) and autonomous electric buses (“AEB”) in Scenario 1. The graph depicts only the least expensive technical concept in each case. The comparison is based on autonomous electric bus vehicle schedules and includes only one change in cost structure.

Consequently, the cost of small-capacity electric buses is considerably higher than that of solo buses. This is attributable to driver costs, as each vehicle, irrespective of size, must be staffed by a driver. Conversely, for autonomous electric buses, the cost differences are considerably smaller, rendering small vehicles considerably more attractive. This brings other issues and criteria to the fore, and a detailed consideration is therefore warranted.

Table 9 and Figure 18 illustrate the TCO of the various scenarios and vehicle capacities for the least expensive autonomous electric bus concept (labeled “_E”) and autonomous diesel buses (labeled “_D”). It is evident that costs increase with decreasing vehicle capacities. This phenomenon is observed in both autonomous diesel and autonomous electric

operations. The cost discrepancies between scenarios 1, 2, and 3 become considerably more pronounced for smaller vehicle capacities. The cost differential between Scenario 1 and 3 for electric buses is EUR 0.6 million for solo buses and EUR 3.1 million for micro buses. These differences are considerably greater than the cost differences between vehicle capacities. In Scenario 3, the cost (electric) is EUR 4.6 million for solo buses, EUR 5.0 million for midi buses, EUR 5.5 million for mini buses, EUR 5.5 million for micro buses, and EUR 5.9 million for micro buses. From a TCO perspective, small vehicle capacities are only attractive to public transport operators if there is a strong focus on actual ridership, since in this case, the systematic advantage of smaller vehicle capacity can be exploited to a greater extent.

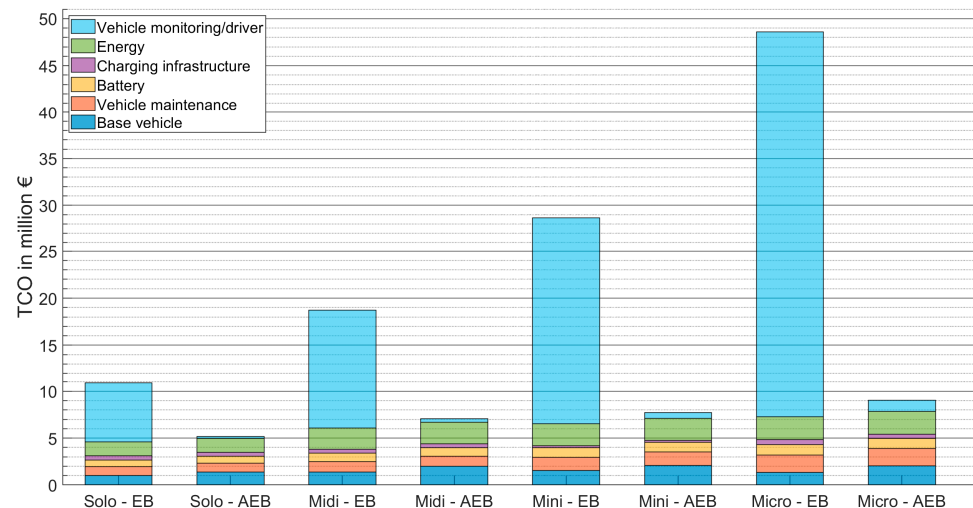


Figure 17. TCO in millions of EUR for conventional electric buses and autonomous electric buses.

Table 9. TCO in millions of EUR for different vehicle capacities and timetable scenarios. Abbreviations: [vehicle capacity]_[scenario]_D/E (D: diesel; E: electric).

TCO in Mio. EUR	Base Vehicle	Vehicle Maintenance	Battery	Charging Infrastructure	Energy	Vehicle Monitoring	Total
Solo_1_D	1.1	0.9	-	-	2.6	0.2	4.8
Solo_1_E	1.4	0.9	0.7	0.4	1.5	0.2	5.2
Solo_2_D	1.1	0.8	-	-	2.3	0.2	4.4
Solo_2_E	1.4	0.8	0.7	0.4	1.3	0.2	4.9
Solo_3_D	1.1	0.7	-	-	1.9	0.2	3.8
Solo_3_E	1.4	0.7	0.7	0.4	1.2	0.2	4.6
Midi_1_D	1.6	1.1	-	-	4.1	0.4	7.2
Midi_1_E	2.0	1.1	0.9	0.4	2.3	0.4	7.1
Midi_2_D	1.4	0.8	-	-	3.0	0.3	5.4
Midi_2_E	1.8	0.8	0.8	0.3	1.6	0.3	5.5
Midi_3_D	1.4	0.6	-	-	2.3	0.2	4.6
Midi_3_E	1.8	0.6	0.8	0.2	1.4	0.2	5.0
Mini_1_D	1.7	1.4	-	-	4.0	0.6	7.8
Mini_1_E	2.1	1.4	1.0	0.2	2.4	0.6	7.7
Mini_2_D	1.6	1.1	-	-	3.1	0.5	6.2
Mini_2_E	2.0	1.1	1.0	0.3	1.8	0.5	6.5
Mini_3_D	1.4	0.8	-	-	2.4	0.4	5.1
Mini_3_E	1.8	0.8	0.9	0.1	1.4	0.4	5.5
Micro_1_D	1.6	1.8	-	-	4.0	1.1	8.5
Micro_1_E	2.0	1.9	1.1	0.4	2.4	1.2	9.0
Micro_2_D	1.4	1.4	-	-	2.9	0.8	6.5
Micro_2_E	1.7	1.4	0.9	0.4	1.8	0.8	7.0
Micro_3_D	1.3	1.0	-	-	2.2	0.7	5.3
Micro_3_E	1.7	1.0	0.9	0.2	1.4	0.7	5.9

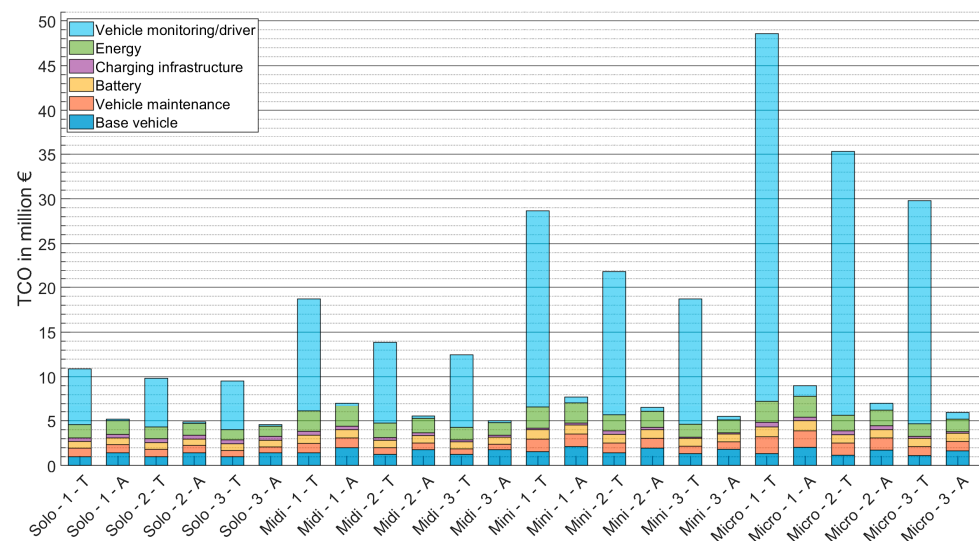


Figure 18. TCO in millions of EUR for different vehicle capacities and timetable scenarios.

The higher costs associated with smaller vehicle capacities are a consequence of the higher mileage required for operation. The cost of monitoring vehicles rises sharply with smaller vehicle capacities. However, there is no reported experience in this area, which means that expenses in this area could be significantly lower or significantly higher, which could have a significant impact on operating costs. Vehicle maintenance costs also increase significantly. Again, there is no reported experience in this area. It is theoretically possible that the number of accidents will be significantly reduced with autonomous vehicles, which would result in lower costs in this area.

2. Which electric bus concepts are economically attractive for operation with autonomous vehicles of different passenger capacities?

It is important to note that the electric bus models reviewed are based on established and verified technical concepts. However, they are not exclusive and represent a selection of plausible models. It is essential that the components are designed and coordinated thoughtfully; this has already been executed by the authors. Table 10 shows the most cost-effective concept for each scenario and vehicle capacity. In general, for vehicle capacities below that of a solo bus, a transition from OC to DC is observed when the timetable is more closely aligned with typical ridership patterns. The orientation of the ridership thus influences which system design is advantageous.

Table 10. Most cost-efficient concepts for different vehicle capacities and timetable scenarios.

Vehicle Capacity	Timetable Scenario	Most Cost-Efficient Concept
Solo bus	1	OC-1
Solo bus	2	OC-1
Solo bus	3	OC-1
Midi bus	1	OC-2
Midi bus	2	OC-1
Midi bus	3	DC-1
Mini bus	1	OC-2
Mini bus	2	OC-1
Mini bus	3	DC-1
Micro bus	1	OC-2, OC-3
Micro bus	2	OC-3
Micro bus	3	DC-2, DC-3

In contrast, solo buses have markedly lower energy requirements than other vehicle capacities. This is reflected in the energy procurement costs. In Scenario 1, diesel-powered

solo buses incur energy costs of EUR 2.6 million, while midi, mini, and micro buses incur costs of EUR 4.1 million, EUR 4.0 million, and EUR 4.0 million, respectively. In Scenario 1, the energy costs associated with battery-powered solo buses are estimated to be EUR 1.5 million, while the costs for midi, mini, and micro buses are EUR 2.3 million, EUR 2.4 million, and EUR 2.4 million, respectively. This represents an increase in energy costs of approximately 55%. The additional energy costs for midi, mini, and micro buses compared to solo buses are in the range of 22 to 38% for Scenario 2 and 15 to 22% for Scenario 3. Consequently, the difference between the two scenarios diminishes. In addition to the direct energy costs, investments in charging infrastructure and batteries must be made in advance to enable the operation of electric buses. The investment costs in this area would decrease if energy consumption were to decrease, as the electrical components could be designed smaller. In this context, the energy consumption increases for small vehicle capacities. It can be observed that the share of energy consumption for traction energy increases for small vehicle capacities. This is mainly due to the fact that the weight of the vehicles does not decrease at the same rate as the number of passengers. Thus, reducing the energy consumption of autonomous buses is of significant interest from an economic standpoint.

With respect to electric buses, there is a notable interplay between the chosen vehicle capacity and how trips are planned around ridership. When vehicle capacities are smaller, there is a relative increase in energy consumption. This expended energy needs to be replenished through charging, implying a need for larger batteries to enable longer durations between charges. During the times these buses are charging, they are out of service, diminishing the effective usability and generally leading to a need for more vehicles. This challenge becomes more pronounced as the energy consumption rises.

Consequently, the ability of the vehicle to charge swiftly was identified as crucial, particularly for buses with smaller capacities. The availability of charging locations does not hold as much weight for smaller capacities as it does for larger ones. Therefore, the charging power of the vehicle was found to be critical for smaller vehicle capacities. The number of charging locations is less vital for small vehicle capacities than for large ones. This is because charging times are more precise with smaller capacities due to the greater frequency of trips, and in larger fleets, individual buses can more easily undertake deadhead trips to charging locations.

3. How do the energy constraints of battery buses affect network adaptations for autonomous buses?

It is important to consider the energy limitations of electric buses when developing vehicle schedules. Overall, it can be said that autonomous electric buses can be used to manage all the timetables studied. However, since the cost of providing the timetable depends significantly on the vehicle schedules, it is essential to take the limitations into account. This is particularly evident when considering the differences between the different timetable scenarios. For instance, Scenario 1, which featured a uniform service frequency, consistently exhibited the highest cost. In particular, the cost differences were pronounced for smaller vehicle capacities.

The utilization of service breaks for charging in scenarios 2 and 3 has the notable effect of reducing the number of vehicles required for electric bus models, particularly those with limited charging capacities or fewer charging stations. It is noteworthy that this phenomenon challenges the prevailing hypothesis in the literature, which posits that autonomous buses would exhibit greater off-peak frequencies than conventional buses when service frequencies vary:

The elimination of driver-related expenses has the potential to significantly reduce the costs associated with existing vehicle operations. However, this approach does require a higher initial investment. In order to achieve the greatest economic benefit, it is essential to maximize the daily use of vehicles, while balancing service frequencies between peak and off-peak times. When examining the cost structure of electric buses, it becomes evident that this trend may appear to amplify, given the rising investment and decreasing operational costs compared to diesel buses. However, the energy limitations of battery buses restrict

their range and flexibility due to the necessity of recharging periods. Failing to consider these constraints while aligning peak and off-peak service frequencies increases the demand for vehicles, thereby raising costs.

For a fixed electric bus concept, it is certainly possible to formulate rules for adapting the network: Concepts with small vehicle capacities and concepts with a small number of charging locations—especially DC—benefit enormously from adapting the timetable to typical ridership. OC electric bus concepts allow for much more consistent vehicle operation and are therefore more advisable when combined with a consistent service frequency.

Outlook and Challenges

With regard to the cost assumptions, it is important to note that there is a paucity of experience with the investment and operating costs of autonomous buses. Consequently, the results of the total TCO calculation are subject to uncertainty. The findings of this study are based on data collected from bus route 7 in Aachen, Germany. This implies that the results may not be directly applicable to regions with different passenger volume dynamics and climatic conditions. Consequently, it is advisable to extend the scope of the research to encompass bus routes in diverse geographical locations, thus facilitating a more nuanced and comprehensive comprehension of the subject matter. Furthermore, the length and speed of a bus route may influence the frequency of service and the economic balance between time and non-time costs. One intriguing research question posed in this thesis is to identify the characteristics of a bus route that would facilitate the adoption of autonomous buses. It is postulated that the operation of slower routes with autonomous buses could be particularly advantageous, potentially reducing the reliance on time-dependent costs such as driver wages.

In the scenario under study, the typical ridership of a working day was assumed based on measured data. In practice, however, ridership varies for different seasons and varies per working day. In this work, this issue was addressed with a buffer. An interesting extension of the consideration would be the detailed mapping of the variance, including the uncertainties in the determination of the current ridership. In addition, when looking at different days, the effects of temperature on energy consumption could be included.

The scenarios examined in the case study are markedly distinct from a passenger perspective. Service frequencies are considerably higher for smaller vehicles. Consequently, waiting times remain an attractive proposition for passengers, even with a lower formal passenger capacity. Therefore, a switch to smaller vehicle capacities and higher service frequencies would potentially increase ridership. However, it is crucial to note that the safety of autonomous vehicles plays a central role in passenger acceptance and must also be considered. The analysis in this paper, though, focused solely on the TCO for the public transport operator, leaving these broader considerations unexplored. Further research in this area is needed to adequately address all needs.

It can be observed that larger vehicles tend to have lower costs and energy consumption, while smaller vehicles can be used more flexibly and thus allow better adaptation to actual ridership. It is also conceivable to use a mixture of different vehicle capacities to serve the timetable. Further research in this direction to optimally combine vehicle capacities is therefore of interest.

The network design of the bus route has a clear impact on the cost of different electrification concepts for autonomous buses. In the case study considered, a greater focus on ridership allowed for better integration of vehicle charging times into operations. This demonstrates that aligning the service frequencies in for peak and off-peak times without taking into account the limitations of electric buses is associated with additional costs. The optimization and expansion of the route network through the operation of electric buses is a promising avenue of research, not only for autonomous buses on fixed routes. The results of this study indicate that further research in this area is warranted.

6. Conclusions

This study examines the interplay between autonomous buses and electrification, focusing on the case study of bus route 7 in Aachen, Germany. The total cost of ownership was evaluated for different vehicle capacities and six electric bus configurations, including depot and opportunity charging. Three timetable scenarios were developed, varying in service frequency and alignment with actual ridership patterns. Energy-based vehicle schedules were then optimized for both diesel and electric buses across these scenarios. The total cost of ownership was then calculated, resulting in the following key findings:

- The elimination of driver costs renders the use of autonomous electric buses economically attractive. For instance, the total cost of ownership for solo buses is reduced from EUR 10.9 million to EUR 5.2 million for a timetable with constant service frequency. Furthermore, smaller vehicle types benefit even more from the elimination of driver costs, rendering them economically feasible.
- Even when this effect is taken into account, the economic competitiveness of smaller vehicle capacities can only be achieved when the timetable is synchronized with typical ridership. For example, the total cost of ownership for autonomous electric micro buses is EUR 9.0 million for a constant frequency schedule, while it is only EUR 5.9 million for a timetable that is predominantly based on typical ridership.
- The additional costs associated with bus electrification can be effectively managed by selecting a coherent concept. In particular, the variation in the most economically viable electric bus concept can range from cost equivalence to an additional cost of up to EUR 0.8 million, depending on the vehicle capacity and timetable scenario chosen.
- The choice of timetable scenario played a critical role in determining the success of different electric bus concepts. A focus on actual ridership patterns provides opportunities for service breaks, especially for smaller vehicles, which makes it easier to charge electric vehicles. In such scenarios, designs with fewer charging stations and lower charging power become much more attractive.
- Smaller vehicles have higher energy consumption per passenger, which contributes significantly to operating costs and requires an expanded battery and charging infrastructure. Reducing energy consumption in autonomous electric vehicles is therefore highly beneficial.
- In contrast to previous findings regarding autonomous diesel buses, aligning off-peak and peak frequencies is less advantageous for electric buses due to their energy limitations. When integrating autonomous buses, it is of paramount importance to consider the distinctive requirements of electric buses in network design modifications.

In conclusion, the findings and limitations of this study provide compelling avenues for future research. This research used the total cost of ownership as the evaluation criterion, and the inclusion of additional elements, such as passenger attractiveness, could make evaluations more comprehensive and insightful. For example, future evaluations should consider the likely increase in ridership if the solutions are more attractive to passengers. The study of ridership variability and uncertainty and the development of strategies to deal with them are fascinating topics for further research. The intelligent combination of different vehicle capacities allows the unique advantages of each vehicle type to be exploited, thereby underscoring the importance of continued research in this area. The development of rules and heuristics to incorporate the specifications of electric buses into network design emerges as a key area of research, especially in combination with autonomous buses, thereby broadening the scope of study in this area. Furthermore, the optimization of a network operated by autonomous electric buses represents a promising avenue for future investigation.

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