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Design Methodology for the Electrification of Urban Bus Lines with Battery Electric Buses

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Abstract

Electrically powered buses reduce CO_2 and noise emissions in urban areas and thus promote the trend towards more livable cities. Upon this reason, more and more cities are introducing their first electrified lines as pilot projects. However, no standardized technology has yet emerged, which is why statements on interactions between vehicle, operation and infrastructure in public transport are proving to be difficult to make. In order to be able to make statistically significant statements in this respect, a simulation model was developed that depicts the three subsystems vehicle, operation and infrastructure. On the basis of measurement data from the PRIMOVE research project in Mannheim, in which an urban bus line is operated with two electrically powered buses, the simulation model was validated and a data basis was laid for further investigations. As a result, simulation studies with more than 700 simulated operating days could be carried out, the results of which represent the input for the following statistical analysis. Based on this analysis, the interactions described above will be demonstrated in the design of the main technical parameters, the battery lifespan and the energy demand of electrical bus lines.

Through the findings of these simulations, an optimized version of the already electrified bus line in Mannheim will then be presented. Finally, a novel design methodology for electrification based on a multi-objective optimization is introduced. All parameters of the system are variable in order to apply the presented methodology to other projects and thus underline the general validity of the work.

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Keywords: electromobility; electric bus; battery lifespan; energy demand; design methodology; multi-objective optimization; particle swarm optimization

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1. Introduction

Due to the social and political trend towards more ecology, combined with increasing noise and exhaust emissions, a change towards electromobility has taken place in the transport sector in recent years, not only in individual transport but also in local public transport. United Nations (2015); European Commission (2011)

The urban bus is very well suited for the electrification of its driveline due to its high visibility, its high mileage and the very good plannability of daily routes. With this motivation, a large number of major cities worldwide are currently pushing ahead with the introduction of electric buses in order to improve the quality of life in cities through reduced noise emissions. European Commission (2014); ZeEUS (2016)

Driven by ever stronger political requirements for air pollution control in cities, European cities are now also intensifying their efforts to electrify inner-city bus transport. Cities such as Paris, Hamburg and Amsterdam are aiming to electrify their bus fleets by 2025. International Association of Public Transport (2017) However, Europe and North America are still far behind China when it comes to the use of electric buses. In 2016, more than 99% of all electric buses worldwide were located in China, with the city of Shenzhen being a prime example, electrifying their entire network with more than 16,000 electric buses by the end of 2017. International Energy Agency (2017); Lauer and Dickhaut (2018)

Currently, a wide variety of technologies can be observed for electric buses. In addition to fuel cell buses, there are buses that are equipped with supercapacitors, use a hybrid solution or are operated purely on battery power, usually with a lithium-ion battery as an energy storage. Wu et al. (2015); Mahmoud et al. (2016) Due to the further expected technological leaps in the field of lithium-ion batteries, based on the great focus of the automotive industry and consumer electronics, the focus of the presented work is on precisely this technology. Blomgren (2016)

Apart from a few major projects, so far only individual lines have been designed as pilot projects. These show a comprehensive technology spectrum, especially in the dimensioning of the battery capacity and the choice of charging technology. Public transport operators usually focus on the initial gain of knowledge, in which the electrification of a single bus line is to be regarded as an initial step towards the electrification of an entire urban bus network. Therefore the purpose of this research is to develop a comprehensive design methodology for the electrification of urban bus lines. This allows cities and public transport operators to survey a wide range of design options with their impact on energy demand and battery lifespan by varying the input parameters. Vehicle manufacturers and other technology providers can also benefit from the findings of the parameter studies.

An example of such a pilot project is the PRIMOVE project in Mannheim, which forms the data basis for this research. PRIMOVE (2017) Since 2015, two battery-powered 12 meter long buses have been in passenger service on city center line 63. The 60 kWh battery can be charged inductively at six selected charging stops during passenger change with a connected load of 200 kW, so called opportunity charging. This research project was scientifically accompanied in the period between January 2013 and June 2016 by the Institute of Rail System Technology (Karlsruhe Institute of Technology). The findings of this study are intended to increase the acceptance of electric buses in the long term so that operation can be guaranteed regardless of weather conditions with the best possible system for each respective line. This increase in public acceptance in turn promotes the trend towards more livable cities with lower CO_2 and noise emissions. Borén et al. (2016)

The ability to quantify major factors of influence on the battery lifespan and energy demand depending on the overall system configuration based on a validated simulation model helps public transport operators immensely in the introduction and optimization of existing electric bus lines. Based on these findings, the first step is to identify a configuration that exhibits the slowest possible aging process of the battery, which is exposed to a high cyclic load during operation, and is also as energy-efficient as possible. Based on this, an optimized design of the already electrified line 63 of the Mannheim bus network is proposed as an example. For the electrification of urban bus lines, a design methodology based on a multi-objective particle swarm optimization by Kennedy and Eberhart (1995) and Coelle et al. (2004) is presented, which calculates technically feasible configurations for the electrification of a bus line under given constraints.

Because of the large-scale electrification of urban bus lines worldwide, the degree of novelty of the technology results in a multi-layered and complex challenge for cities and public transport operators. In order to support these institutions, the results from this paper, which are based on a validated simulation model, are used to facilitate technology selection and further optimize existing lines. With realistic results, the foundation is also laid for further economic considerations, in which a Total Cost of Ownership analysis (TCO) can determine not only a technically, but also a technically and economically optimal configuration over the lifespan of a bus. Ly et al. (2016); Lajunen (2018)

Rogge et al. (2015) and Sauer (2016) have already carried out other work on the simulation of electric buses, but this paper differs in the degree of detail of the modelling of the technical system and in the development of the design methodology.

This paper starts with the description of the known trade-offs in the design of electric bus lines and the overview of the simulation studies intended for proving and quantifying them. The third chapter then presents the description of the underlying simulation model and the validation of said model. In the fourth chapter, the individual influences on battery life and energy demand depending on the overall system configuration are quantified using a one factor at a time method. With those findings an optimized configuration of the already electrified line 63 is presented. This is followed by an introduction to the methodology for designing electric bus lines based on a multi-objective optimization problem. Finally, the fifth chapter draws conclusions, identifies potential for improvement and takes future developments into account.

2. Design of electric bus lines and simulation studies

The electrification of urban bus lines is subject to conflicting design objectives. The blue line in Fig. 1 represents a vehicle configuration with a low battery capacity, while the green line represents an equipment with a large accumulator. Due to the heavy battery, the bus on the green line is much less energy-efficient, resulting in fewer kilometers driven per charged kilowatt hour. Another point is the overall vehicle cost, which is lower when configured with a small battery, as battery costs account for a significant part of the overall vehicle cost. For this reason, long lifetimes are sought for accumulators in order to replace the battery as rarely as possible. Since a low-capacity battery is subject to higher cyclical loads during operation, it ages faster than a high-capacity battery and must therefore be replaced more frequently. Another advantage when designing with larger batteries is that less expensive charging infrastructure is required. For a vehicle with a small battery, for example, the costs are shifted to additional charging infrastructure. Furthermore the large battery is more resistant to charging with higher charging powers.

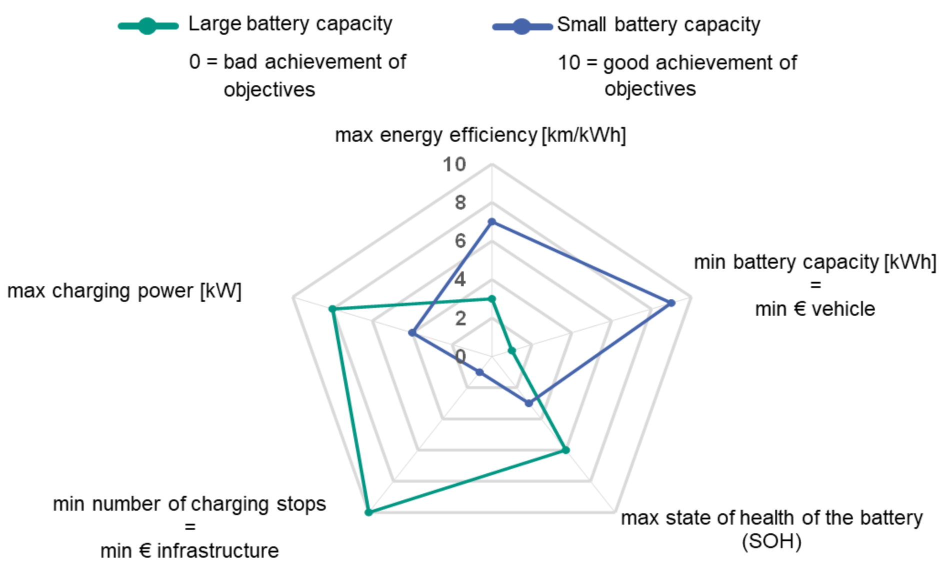


Fig 1. Conflicting design objectives for electric buses by Berthold and Gratzfeld (2016)

These conflicting design objectives make it clear that only an overall optimization can achieve the desired results. It is not sufficient to consider only the vehicle in isolation, but also to include the complementary systems infrastructure and operation in the optimization.

All of the described trade-offs now have to be identified and quantified by simulation. In addition, the aging factors of the battery and the energy demand of the vehicle are to be determined depending on the overall system configuration. Based on a simulation model presented which is further described in section 3, a large number of parameter studies are carried out in order to determine statistically significant interrelationships between the individual subsystems in the design of electric bus lines. Fig. 2 provides an overview of the simulation studies carried out.

In addition to current battery technologies, the influence of future forecast batteries (code 2025) will be investigated. These batteries can be charged with four different charging systems. On the one hand with a 200 kW inductive charging system and on the other hand with three conductive systems from 200 to 500 kW. These charging systems can be placed at the selected charging stations of three Mannheim bus lines 53, 60 and 63. Of these three lines, three days of operation are available based on GPS measurement data, enabling the influence of variable traffic conditions to be investigated. With the additional variation of climatic conditions, the number of charging stations, charging times, vessel size and the State of Health (SOH), different scenarios can be generated, which can be used to determine the correlations between the technical parameters by means of correlation and regression analysis. To generate results, more than 700 complete operating days were simulated on the three lines with variable input parameters.

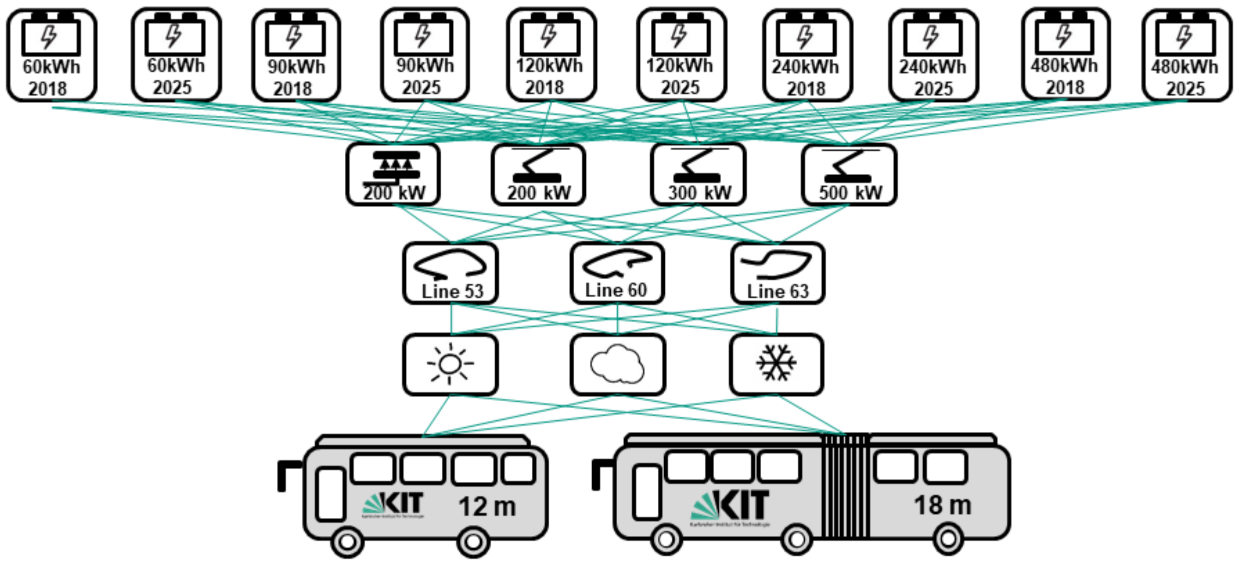


Fig 2. Simulation studies

3. Simulation model and validation

The overall electric bus system, consisting of the vehicle, operation and infrastructure subsystems, aims to map reality as accurately as possible. Too many simplifications in the model lead to far-reaching deviations in the subsequent optimization. For the detailed modelling of battery electric vehicles there is already a multitude of scientific work, for example: Butler et al. (1999) and Esfahanian (2014).

More than 150 parameters are taken into account in the modeling of the system components from the specification of a simulation that is as close to reality as possible. These parameters consist of the different subsystems vehicle, operation and infrastructure. The vehicle is modelled in detail according to Table A.1 in the appendix. The battery is determined by its energy density, the total weight of the battery system and the age-specific parameters for cyclical and calendar ageing. Other electrical subsystems such as the engine, power electronics and air conditioning as well as other auxiliary consumers are also included in the model. A further input parameter is the driving cycle of the operating day, which is stored with all stop data and the timetable. All preselected charging points are defined in there. Since the climate has a significant influence on the operation of electrically powered buses, environmental influences such as temperature and the prevailing solar heat radiation are specified.

This allows the behavior of the individual components in and on the overall system to be analyzed more precisely if required. The simulation model represents an energy flow simulation with a Graphical User Interface (GUI) on the highest level, which serves to simplify and error-prevent the multitude of required data. The generated input is transferred to a co-simulation of MATLAB, Simulink and IPG TruckMaker in which all energy flows are calculated. These calculated energy flows and the State of Charge (SOC) that is derived from those, represent the output variables of the overall system simulation. Thus the total energy demand as well as the energy demand of the individual subsystems such as engine, air conditioning and heating can be analyzed more precisely.

In the post-processing process the SOC can then be used to calculate further parameters of the overall system, such as the cyclic load of the battery and the associated influence on the aging of the energy store as well as the energy demand of the overall system. Fig. 3 illustrates the structure of said simulation environment.

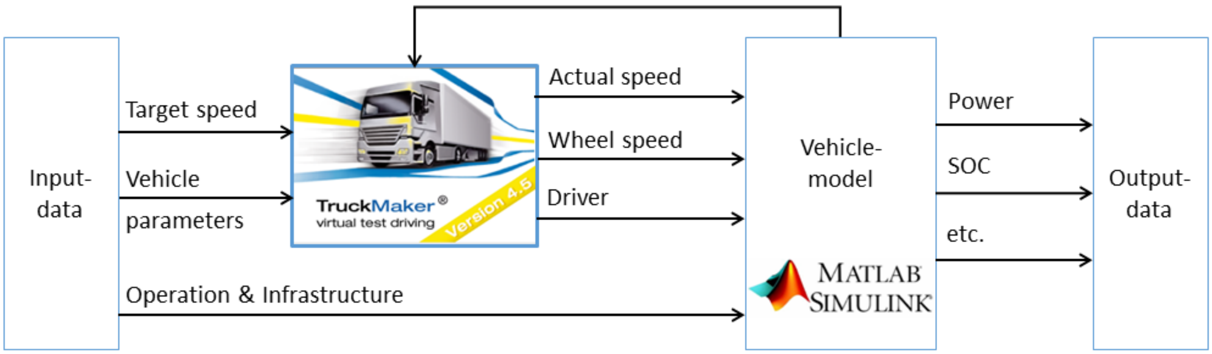


Fig. 3. Structure of simulation environment

3.1. Vehicle subsystem

For the vehicle subsystem, the focus is on realistic modeling of all components and the smooth interaction between MATLAB/Simulink and IPG TruckMaker.

The 12 meter long bus used in regular operation or an 18 m articulated bus can be selected as a vehicle model. Due to the possibility of vessel size variation, the effects of different passenger volumes on the bus lines can be investigated in the subsequent simulation studies.

A central component of the vehicle model is the battery model. With the Shepherd modeling approach used, the coherences in the battery are mapped based on formulas. Shepherd (1965) The parameters of the Li-NMC battery from AKASOL used in the research project are read from the discharge curves of the manufacturer's data sheets and stored in the simulation model to describe the system behaviour of the battery. AKASOL (2018) Since the dimensioning of the battery capacity is a central component in the design of the overall electric bus system, it is possible to scale the capacity. Simulations with predicted battery technologies can also be performed to investigate the impact of increased energy density and lower peripheral weight on the overall system. Fraunhofer ISI (2010)

Table 1 gives an overview of the total mass of the battery sizes and technologies used, where 2018 stands for an energy density of 100 Wh/kg, 2025 for 250 Wh/kg.

Table 1. Total weight of battery systems

Battery technology	Code 2018	Code 2025
60 kWh	900 kg	312 kg
90 kWh	1300 kg	457 kg
120 kWh	1680 kg	595 kg
240 kWh	3120 kg	1162 kg
480 kWh	6000 kg	2285 kg

During operation, the batteries are only operated at a net capacity interval of 15-65% in order to counteract deep discharges and surges and thus extend the lifespan of the energy storage device. The rainflow cycle count is used to quantify battery aging. This is a process from mechanical strength theory. There it is used to determine the fatigue strength of components. This method can also be used to determine the cyclic load of a battery by determining the charge and discharge cycles of the SOC curve. Nuhic et al. (2013) Within a given SOC cycle, partial cycles of identical charge and discharge depth are identified and then weighted with a depth of discharge-dependent correction factor. These correction factors are derived from manufacturer specifications on the number of full cycles depending on the depth of discharge. In addition to this cyclical damage, batteries are also subject to calendrical aging. For their calculation, the maximum calendar service life is taken from the battery data sheet. The aging of the battery manifests itself in an increased internal resistance and a reduced capacity. A battery reaches the end of its service life with a usable capacity of only 80 % or an internal resistance that has doubled. To counteract this effect over the lifespan of the battery, the net capacity interval is widened from 50% when new to 80% at the end of its service life. Further research conducted to the cycle and calendar aging of batteries was done by Stiaszny et al. (2014) and Stiaszny et al. (2014).

Under demanding climatic conditions, the energy required for temperature control of the interior is of the same order of magnitude as the electric drive. In the present case, this required energy is provided by the battery. Since air conditioning causes by far the largest energy demand of all auxiliary consumers, this subsystem is modeled in great detail. The temperature specifications for air conditioning correspond to the specifications of the Association of German Transport Companies (VDV). These state that the temperature in the interior should be 3 °C below the outside temperature in summer and at least 18 °C in winter. An air exchange with fresh air is also prescribed. VDV (2009) The main input parameters for air conditioning are the outside temperature, the number of passengers, the door status (open or closed) and solar heat radiation.

Other auxiliary consumers included in the model have a relatively constant power requirement of between 5 - 8 kW. These include battery cooling, lighting, onboard power supply and the air compressor.

3.2. Subsystems operation and infrastructure

Since the subsystems operation and infrastructure are strongly interlinked, they are dealt with together in a subsection. The electrification of a bus line has to adapt strongly to the given boundary conditions. These are primarily timetable specifications and the fixed route through the city bus network. Driving cycles can be derived from these boundary conditions, which in turn depend on dynamic factors such as the number of passengers, traffic volume and climatic conditions. The driving cycles available for the simulation are based on GPS measurements taken during the PRIMOVE project in regular operation.

In addition to the initial knowledge gained on the operation of electric buses, the research project is intended to lay the foundation for the electrification of entire bus networks. For this reason, in addition to the electrified line 63, lines 53 and 60 of the Mannheim bus network were also examined to investigate the use of electric buses. These lines were selected because they a have completely different topography to the line 63 considered so far. While line 63 coers a short distance at high intervals, line 53, with its long distance, in almost exclusively urban suburbs, and the few service trips per operating day, is a complementary application. Line 60 serves both the inner-city are as well as the area outside the city and can therefore be regarded as a hybrid of lines 63 and 53. For this reason it is also of interest for electrification concepts. Table 2 lists the key figures for the three bus lines.

Table 2. Key figures of Line 53, 60 and 63

Line number	Line 53	Line 60	Line 63
Length per service trip	35 km	21 km	9.5 km
Number of stops	72	46	25
Ø Distance between stops	463 m	466 m	412 m
Ø Number of buses in use	5	4	2
Duration of each service trip	100 – 120 min	80 min	40 min
Number of service trips per day	8	10	19
Ø Speed	19 km/h	16 km/h	12 km/h
Ø Stops per km	2.0	3.2	4.1

As lines 53 and 60 are operated with diesel buses, it was necessary to identify charging stations where the bus could charge its battery during the interchange of passengers. Based on the average stopping time and the stopping probability at the individual stops, measured over several days of operation, and taking into account potential synergy effects with supplementary public transport to simplify the connection to the electric grid, the basic configuration of line 53 was equipped with 10 and line 60 with 12 charging stations. The construction of charging infrastructure is proving to be very demanding both technically and economically and is currently in many cases a limiting factor in the electrification of bus lines. Rogge et al. (2015); Schroeder and Traber (2012) On the one hand, there is still no standardized charging technology that public transport operators and manufacturers can use as a guide, and on the other hand, the connection to the existing energy network is proving difficult due to the high-power requirements of these fast charging stations. Xylia et al. (2017). Further research conducted to location planning of charging infrastructure and the challenges can be found in Rohrbeck et al. (2018) and Kunith et al. (2014). Table 3 gives an overview of the charging technology used, including the make-ready times for charging.

Table 3. Charging technology for simulation based on PRIMOVE Charging (2015) and Siemens (2016)

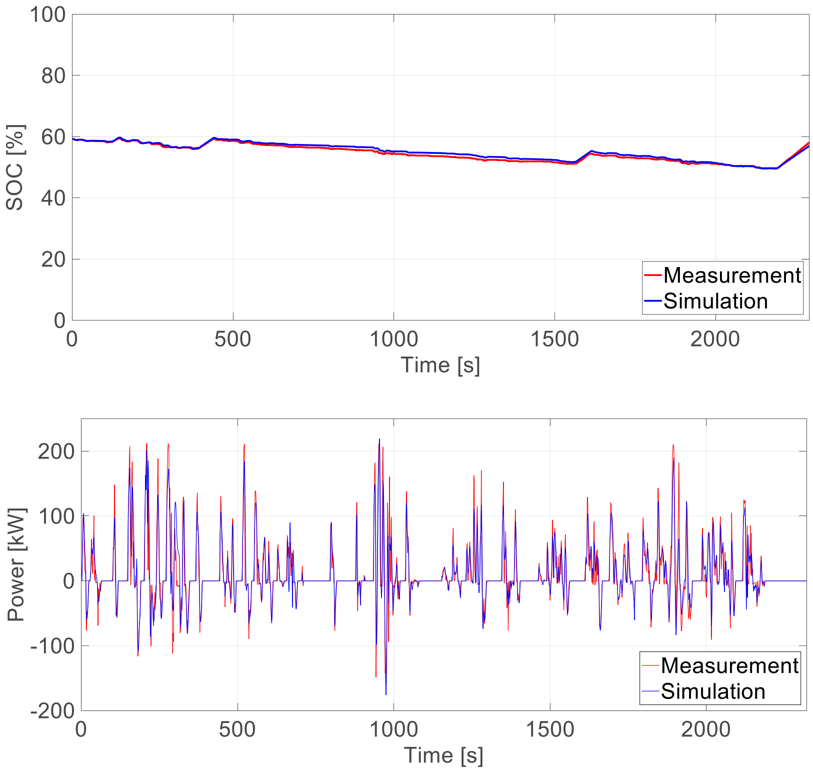
Charging system	200 kW inductive	200 kW conductive	300 kW conductive	500 kW conductive
Maximum transferable power	220 kW	220 kW	330 kW	550 kW
Efficiency charging system – bus	90 %	99 %	99 %	99 %
Efficiency charging interface – inverter	98 %	98 %	98 %	98 %
Efficiency battery charge	92 %	92 %	92 %	92 %
Effective charging power	179 kW	196 kW	295 kW	491 kW
Make-ready time for charging	6 s	6 s	6 s	6 s

In the depot the battery can be charged via a plug with 100 kW overnight. Due to the high set-up times, this system is not considered during operation.

3.3. Validation

In order to confirm the correct representation of reality by the software model, it is necessary to validate the presented simulation model by measured values from real operation. The focus here is on the course of the SOC and the engine power due to the objective of predicting battery life and energy demands as accurately as possible. The graphical comparison of the SOC curve and the engine power for one service trip of the measurement and simulation are shown in Fig. 4 (a) and (b).

This shows that both the SOC calculated in the simulation and the calculated engine power almost exactly correspond to the measured curves, which is why a validated simulation model can be assumed. The small deviations in the SOC curve can be explained mainly by the assumption of some constant auxiliary consumers. Based on these findings, simulation studies for the design of electric bus lines can now be carried out, on the basis of which generally valid results can be obtained.



a

b

Fig 4. (a) SOC; (b) engine power

4. Results and discussion

In this chapter, the presented conflicts of objectives in the design of electric bus systems are examined in simulations. In addition, it is demonstrated that the overall system can be designed by varying the technical parameters. First, some examples of correlations between the various influences on battery lifespan and energy demand are presented. In order to avoid interactions of the different influencing factors on the overall system, a one factor at a time analysis is carried out for the correlations listed here, in which only one influencing parameter is changed on the target variables in order to be able to precisely quantify the effects. Subsequently, the driving factors for the battery lifespan and the energy demand are determined based on a sensitivity analysis. Finally, after proposing an optimized design of line 63 in Mannheim, a general design methodology for the electrification of bus lines will be presented.

4.1. Battery lifespan

The aging of the energy storage is caused by a calendrical damage factor as well as a cyclical damage factor which can be attributed to the stress during daily operation. This cyclic load depends on the size of the battery and is greater with small batteries due to the deeper discharges than with large batteries. Fig. 5 (a) shows this correlation. The predicted battery life also increases with increasing battery capacity. This effect is weaker the higher the battery capacity is selected, as the cyclical load has a much more significant influence on the ageing of smaller batteries. For the cyclic load it is generally assumed that the bus operates 320 days a year where each operation day represents the simulated reference operation day. In the present case it turned out that under given boundary conditions the increase of the battery capacity by 30 kWh leads to an increase of the lifespan by 0.43 years.

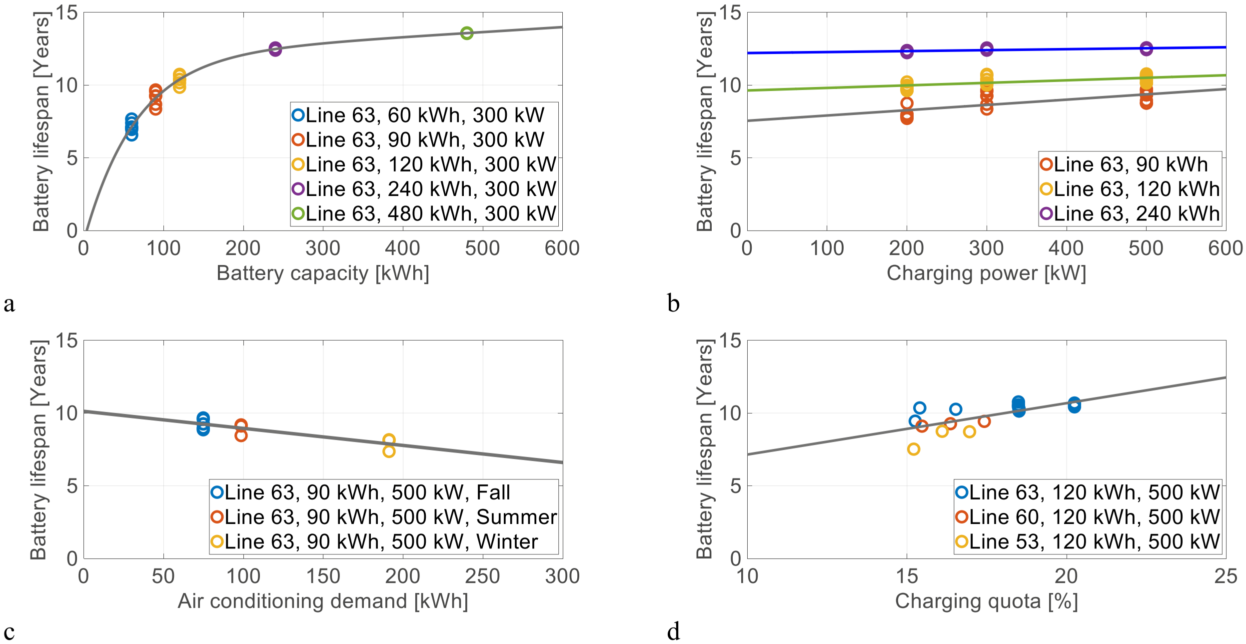


Fig 5. Correlations to battery life

The correlation coefficients and the coefficients of determination for these and for all other relationships are given in Table A.2 in the appendix.

Fig. 5 (b) shows that above a certain battery capacity, increased charging powers are beneficial for battery aging. This is due to the fact that more energy can be absorbed with each charge, which flattens the discharges in the battery and increases the average charge level. The higher the installed charging power, the lower the discharge strokes. As just mentioned, with a large battery capacity, the cyclic load is significantly lower, which is why the increased charging power is less decisive with large batteries than with small batteries. On average, the battery life can be increased by 0.36 years if the charging power is increased by 100 kW, assuming a constant battery temperature of 25 °C.

Fig. 5 (c) shows a comparison of the energy requirements for driving operation depending on the interior air conditioning. Assumptions regarding climatic conditions are set out in appendix A.3. The variation in climatic conditions can also be interpreted as a variation in energy requirements and degree of efficiency. It turns out that the winter conditions are particularly challenging for the operator. The resulting deep discharges are reflected in a reduced battery life due to the higher cyclic load. As soon as the daily energy requirement increases by 50 kWh, this results in a reduction in battery life of 0.59 years for the application.

Fig. 5 (d) shows the correlation between daily charging time and the battery lifespan. The daily charging quota specifies the percentage of the operating day at the selected charging stations where the battery is recharged. Comparing the battery lifespan with identical charging power on a bus line, an increase in daily charging time is conducive to battery life. In practice, this loss of charging time would have to be compensated by higher charging power. However, depending on the selected charging power, this can in turn lead to an increase in the state of health of the battery. The correlation shown in the figure confirms across all lines that an increase in charging time in relation to the duration of the entire operating day can be aimed at increasing battery life. The increase of the charging proportion can be achieved by longer dwell times at charging stations or by building additional charging infrastructure. The cross-line relationship shows that the 5% increase in the daily charging rate leads to an increase in battery life of 1.55 years.

The key findings of the battery life tests are summarized again in a sensitivity analysis in Fig. 6. The basic scenario in this case refers to a 12 meter vessel with a 90 kWh battery and a 300 kW conductive charging system. It turned out that the increase in charging time and the use of large capacities had a significant positive effect. The charging power and the energy density of the battery, on the other hand, have a manageable influence. In general, it can be seen that the overall system can be specifically optimized by targeted intervention in the three interlinked subsystems, vehicle, operation and infrastructure.

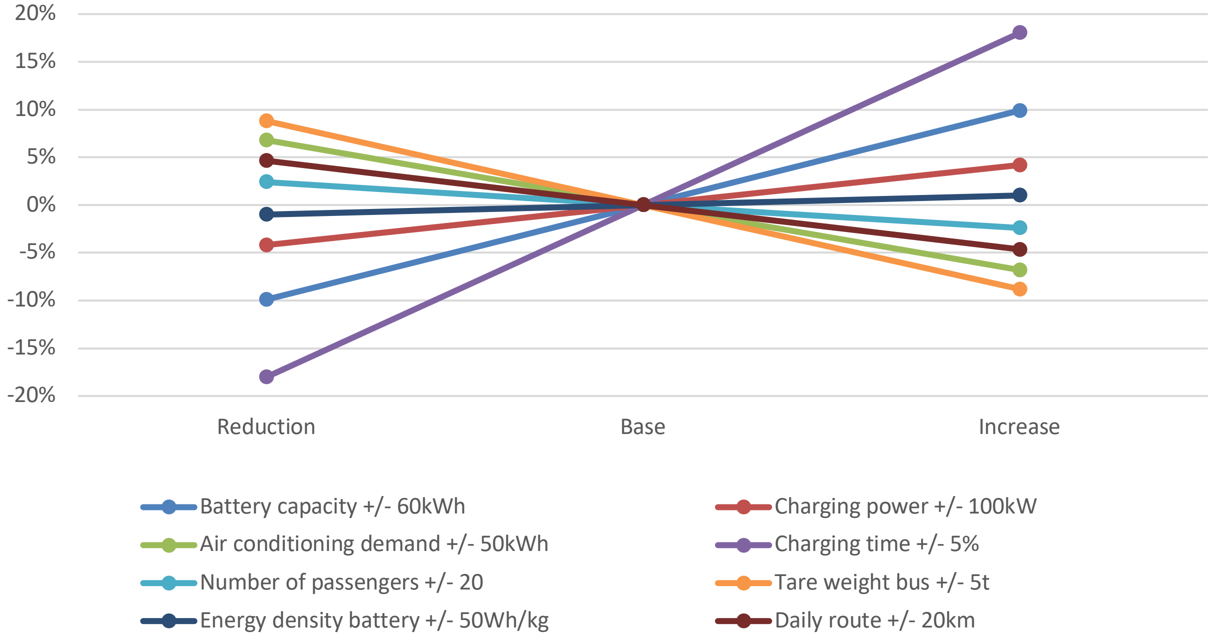


Fig 6. Sensitivity analysis battery lifespan

4.2. Energy demand

In addition to a long battery lifespan, a low energy demand of the entire system is a further optimization criterion for the design of electric bus lines. A system with high energy efficiency leads to fewer charging points and a smaller battery capacity, which also results in a cost-optimized overall system. Various correlations between the energy requirements of the entire system and exemplary influencing variables can be seen in Fig. 7. Once again, a one factor at a time method was applied.

Fig. 7 (a) shows the influence of the selected battery capacity on the energy demand. The higher the energy demand per kilometer, the faster the battery ages and the more frequently it needs to be recharged. This confirms the central conflict of objectives in the design of electric bus lines. A larger battery capacity leads to longer lifetimes, but reduces energy efficiency. Simulations on line 63 have shown that an increase of 30 kWh in battery capacity leads to an increase in energy consumption of 0.03 kWh/km.

Fig. 7 (b) shows, as expected, an increased energy requirement of the entire system in the event of an increased need for air conditioning. The increased energy demand due to climatic conditions can in turn be regarded as representative of further variations in energy demand or energy efficiency. When designing electric bus lines, it is generally advisable to take into account the most climatically demanding conditions and to dimension the line accordingly in order to guarantee maximum availability of the vehicles over the operating day.

As seen by comparing the daily charging quota of each line, the effects of the routing of lines 53, 60 and 63 in Fig. 7 (c) are compared using daily average speeds. This can be used to determine the extent to which the bus is affected by stop-and-go traffic on the day. Line 53, which largely bypasses the inner city area of Mannheim, covers a much longer distance per day than line 63, resulting in a higher average speed on line 53 over the day of operation. Line 60, which runs both through the city center and the outer districts, has a mixed characteristic of lines 53 and 60. In order to compare the individual lines without interaction, a passenger-free operation with a 90 kWh battery system and a 12 m bus is assumed. It can be seen that the slower the vehicle is driven over the day of operation, the higher the energy requirement. This confirms the dependence of the energy demand on the routing.

Since not only 12 m buses but also 18 m long buses are used in a transport operator's fleet, the effect of this variation in vessel size on energy requirements is being investigated. The higher tare weight of the 18 meter bus results in an increase in energy consumption as shown in Fig. 7 (d). By increasing the tare weight by 4900 kg, the energy requirement increases by 0.33 kWh/km using the example of line 63 in Mannheim. From a purely technical point of view, the choice of a larger vessel is not desirable. However, the size of the bus is selected according to the number of passengers expected on a line, which in some cases requires a larger vessel.

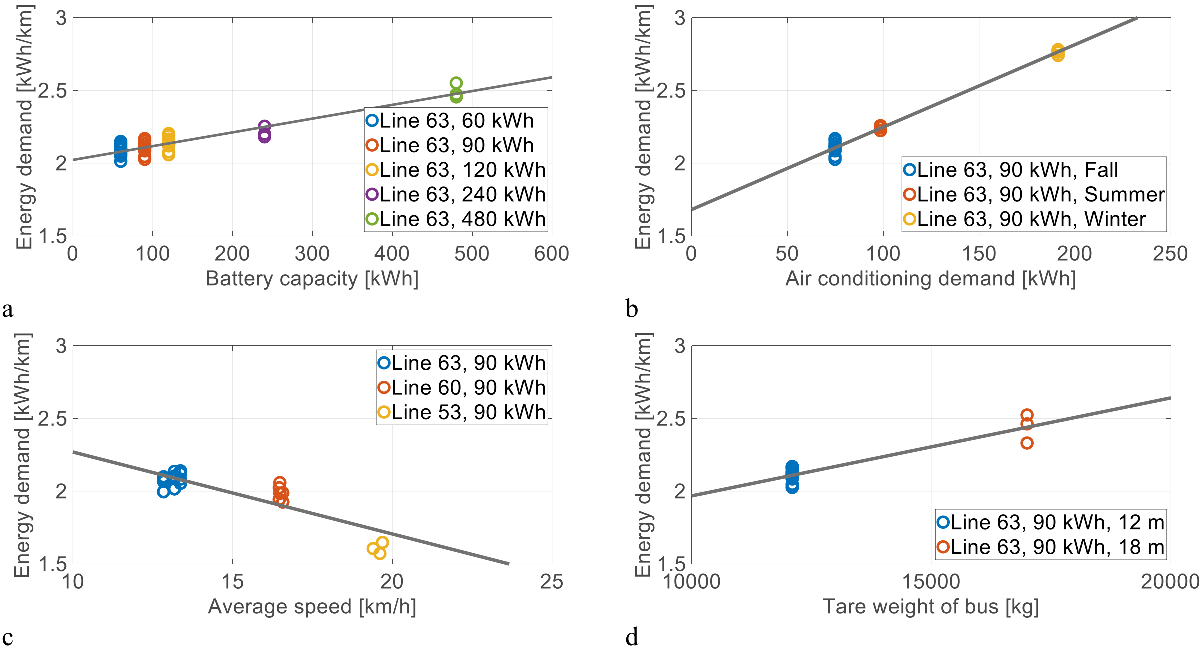


Fig 7. Correlations to energy demand

For the energy requirements, the central findings are also summarized in the form of a sensitivity analysis as shown in Fig. 8. The main drivers of energy demand are the average speed, the vehicle weight and the energy efficiency of auxiliary consumers. The energy density of the battery and the variation in the number of average passengers, on the other hand, have only a minor effect. This sensitivity analysis is also based on a 12 meter vessel with 90 kWh battery and a 300 kW charging system.

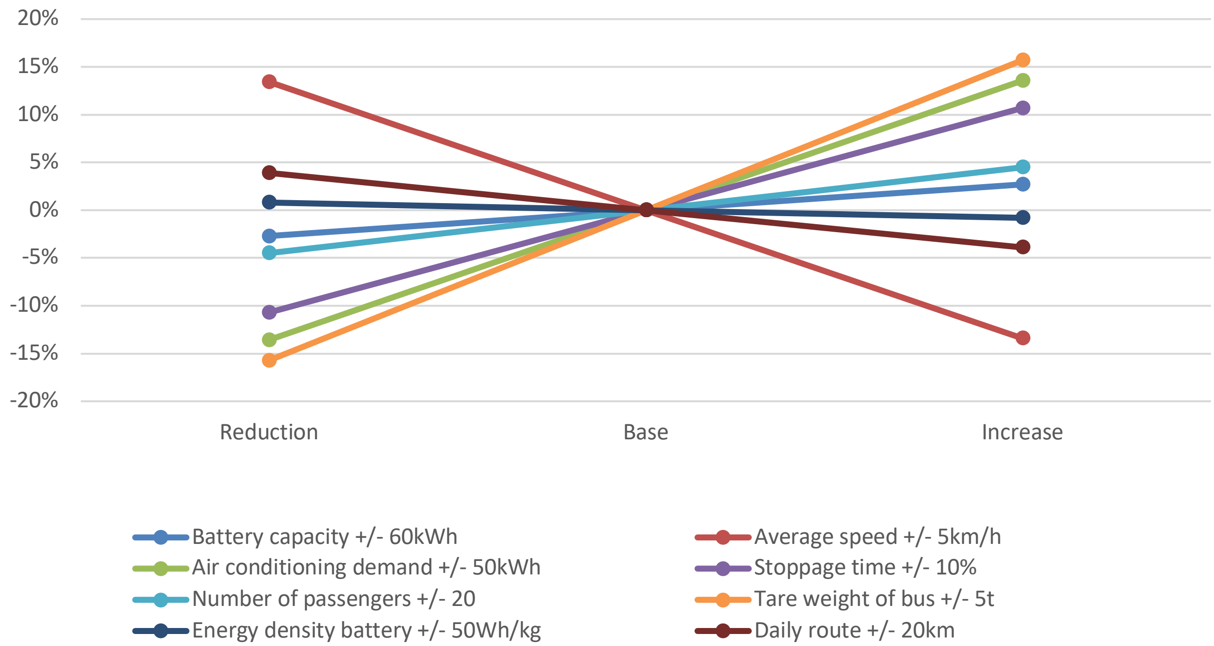


Fig 8. Sensitivity analysis energy demand

4.3. Optimized design of line 63

The findings of the simulation studies have shown that it is technically optimal to invest as much as possible in the charging infrastructure. As a result, the depth of discharge of the battery is reduced and the size of the battery can be reduced. This leads to an increased battery life and at the same time to an increase in the energy efficiency of the overall system. Since the construction and operation of charging stations with high connected loads is financially demanding and limited resources in the public transport sector can be assumed, a minimum design of line 63 will be carried out below with the aim of establishing as little charging infrastructure as possible. However, the trade-off in the design between battery aging, battery capacity and infrastructure depends on the size of the fleet. When electrifying several lines and using the infrastructure across all lines, it is possible that the investment in an additional charging infrastructure is worthwhile. In the case of line 63, the batteries are of little importance due to only two buses, which is why it is not economically viable to optimize battery ageing and capacity.

Fig. 9 shows that equipping the line with only the terminal stop as a recharging point with 500 kW connected load and increasing the battery capacity to 90 kWh is sufficient to cope with the operating day despite the demanding traffic conditions.

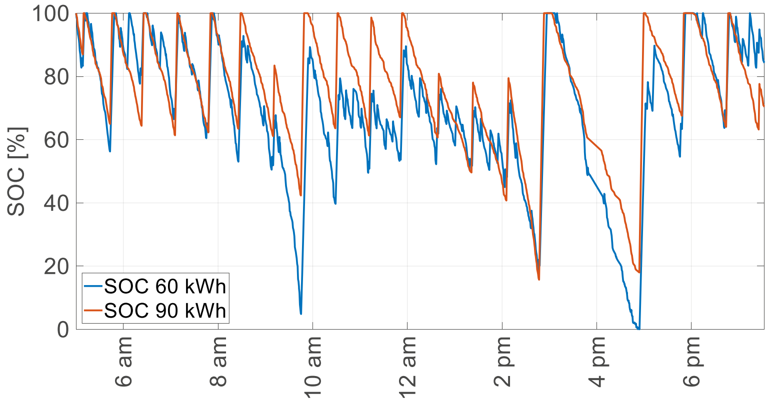


Fig 9. Optimized design of line 63 - SOC

Table 4 shows that this configuration also has a higher predicted battery life with a slightly higher energy demand of 0.03 kWh/km due to the less deep discharges.

Table 4. Comparison of two designs

Battery capacity	60 kWh	90 kWh
Number of charging stops	6	1
Charging power [kW]	200	500
Battery life cycle [years]	4.71	5.94
Energy demand [kWh/km]	2.07	2.10

4.4. Multi-objective optimization and design methodology

As already seen, the main objective in the design of electric bus lines is the choice of battery capacity, the charging system as well as the number of charging stations to be installed. So far such system designs could be made on the basis of individual simulations, however, a methodically structured process is aimed at in order to make the design as efficient as possible. For this purpose, various methods for multi-objective optimization are available, whereby a Pareto optimization based on a particle swarm optimization was selected for the specific application.

The solver of the optimization process is offered as usable battery capacities 60, 90, 120, 240 and 480 kWh with an energy density of 100 Wh/kg. It can also choose between a 200 kW inductive or 200, 300 or 500 kW conductive charging systems. The selection of charging stations to be built ranges from zero (no charging infrastructure provided on the way - only overnight charging in the depot) to ten. A cost factor is applied to the construction of charging stops in order to take financial restrictions into account and to ensure that as few loading points as possible are built.

By varying these input parameters, an overall optimization was carried out for line 63 under winter conditions, which is based on a worst-case scenario of the design. The optimization went through 20 iterations during the calculation in order to keep the influence of the heuristics of the algorithm as low as possible while maximizing the learning effect of the individual particles.

Fig. 10 clearly shows the formation of a so-called Pareto front. For points on this front, the improvement of an optimization target (energy demand or battery lifespan) can only be achieved by the deterioration of the other. All these points represent valid design configurations of the bus line, which is why feasibility studies can also be carried out with this method. Three of these Pareto-optimal points are specified more precisely using Table 5.

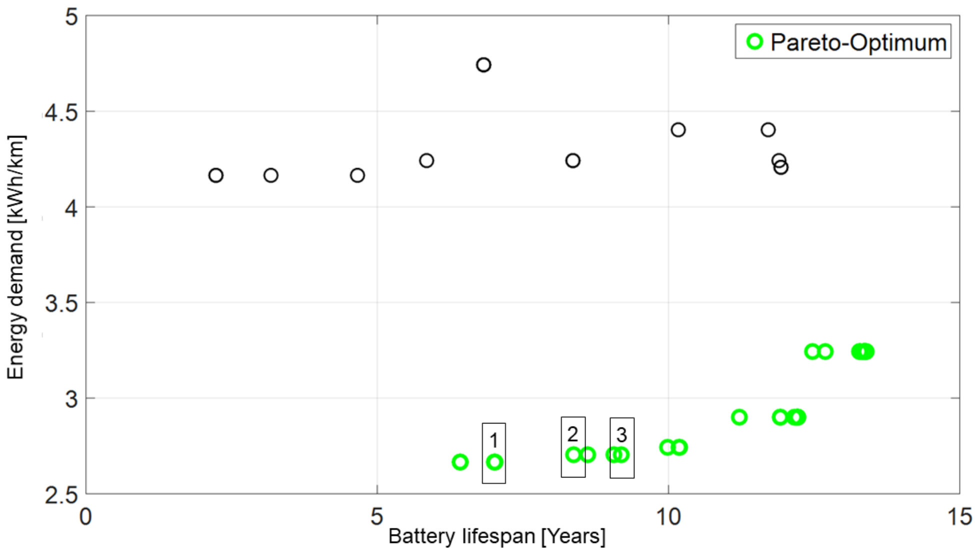


Fig 10. Pareto-optimization for the electrification of urban bus lines

Table 5. Highlighted Pareto-optimal points

Data points	Point 1	Point 2	Point 3
Battery capacity [kWh]	60	90	90
Number of charging stops	10	8	10
Charging power [kW]	300	200	300
Battery life cycle [years]	7.02	8.42	9.24
Energy demand [kWh/km]	2.68	2.71	2.71

This confirms the stated conflicting objectives in the design of electrified bus lines. The increase in battery capacity increases the predicted battery life, but reduces the energy efficiency of the vehicle due to the higher mass. Increasing the charging time reduces the discharge strokes and thus the cyclical damage to the battery, resulting in a longer service life. The increase in charging power also leads to an increase in battery life due to the same reduction in the cyclic load on the energy store.

For the design of an electric bus line, this result means that each point on the Pareto front represents an optimal, technically feasible configuration for the electrification of a bus line. The final decision lies with the public transport operator to choose the optimal configuration under given constraints.

5. Conclusion

Based on a simulation model validated with measured data from real operation, simulation studies of more than 700 operating days were carried out on different lines in order to quantify various factors influencing battery lifespan and energy demand on electrified bus lines using statistical analysis methods. The main factors influencing battery lifespan were an increase in charging time and the use of large battery capacities. For the energy demand of the overall system, it is shown that it is most strongly influenced by the vehicle mass and the auxiliary consumers. On the basis of these findings, a new, optimized design of the already electrified line 63 could be proposed. Subsequently, a novel design methodology for the electrification of bus lines based on a multi-objective particle swarm optimization was presented. A multitude of technically possible solutions for the electrification of a bus line under given boundary conditions could be calculated.

The approach of this research work benefits local public transport operators, cities as well as research. As all input parameters of the technical system can be varied, a design specific to the application can be carried out for electrified bus lines. A wide range of design variants with their advantages and disadvantages can be shown. Vehicle manufacturers and technology providers can also learn from the findings and further optimize their own products, thus accelerating the introduction of electric bus systems in cities. Furthermore, timetable adjustments and new operating schedules can be examined In addition, investigations can be carried out to determine with which overall system configuration overnight-charging is possible and thus no charging infrastructure provided during passenger exchange is required. In this way, important questions on the part of the operators are clarified at an early stage during design.

By means of the validated simulation model and the introduced methodology, the presented research results can now be used to make generally valid statements on the design for the electrification of bus lines. The simulation of other lines with different vehicle configurations and different charging technology is easily possible due to the modeling approach, which allows the transferability of the findings to other line designs. This transfer to further applications was proven by the electrification of lines 53 and 60 of the Mannheim bus network.

For further research work, it is conceivable that additional operating days could be added in order to be able to depict the variable influence of road traffic even more precisely and thus make even more detailed statements. Exact calculations of the investment costs of such an electric bus system can now also be made based on the calculations for battery lifespan and energy demand. Thus not only a technical, but also a technically and economically optimal solution for the entire system can be determined.

When electrifying entire bus networks, it is also necessary to take a more detailed look at the positioning of the charging infrastructure. The aim here is to make use of synergy effects between several lines when planning the charging infrastructure.

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Appendix A. An example appendix

A.1. Parameters of bus

Description	Value	Unit
Area roof	30.6	m²
Area front and back panel	3.2	m²
Area side panel	15.1	m²
Area outer panel	67.2	m²
Area windows	36.6	m²
Area door	1.2	m²
Height door	2	m
Mass outer panel	1000	kg
Mass installations	350	kg
Volume indoor air	55	m³
Tare weight	12100	kg

A.2. Correlations and coefficients of determination of battery lifespan and energy demand

Battery lifespan

Parameter	r	R^2
Battery capacity	0.8646**	0.7475
Charging power	0.6987**	0.4882
Air conditioning demand	-0.8669**	0.7515
Charging time	0.6997**	0.4896
Tare weight bus	-0.6629**	0.4394

Energy demand

Parameter	r	R^2
Battery capacity	0.9295**	0.8640
Average speed	-0.8618**	0.7427
Air conditioning demand	0.9903**	0.9807
Stop&Go-quota	0.8769**	0.7689
Tare weight bus	0.9105**	0.8290

** resembles a two-sided significant correlation at the 0.01 level

A.3. Climate conditions for simulation studies

Climate	Lowest temperature	Highest temperature	Maximum Solar heat flux density
Winter	-18 °C	-11 °C	120 W/m²
Fall	3 °C	22 °C	520 W/m²
Summer	20 °C	36 °C	1000 W/m²

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