Development of a Simulation Model for Predicting Energy Consumption of Battery-Electric Buses

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Abstract. This paper presents the development of a simulation model for battery-electric public transportation buses aimed at accurately predicting energy consumption and state of charge with minimal input data. The model considers driving resistances, elevation profiles, temperatures, and load conditions to closely replicate real-world operational scenarios. Validation with data from a Swiss public transport company shows high accuracy in the prediction of energy consumption and state of charge. The model facilitates precise route and charging infrastructure planning, enhancing efficiency and optimizing costs for public transport operators.

Introduction

In order to reduce CO2 emissions at European level, as outlined in the Paris Agreement, the EU Climate and Energy Framework, and the White Paper on Transport, an increasing number of companies in the public transportation sector are transitioning from combustion engine buses to battery-electric buses. This transition represents an important shift in the transportation sector [1, 2]. A significant challenge in this context is the variability in range depending on the driven route (elevation profile, rural track, urban track), temperature, and load [3]. To facilitate an effective transition to electromobility in public transport, it is important to consider the energy supply of the buses in advance [2]. To enable precise planning of the charging strategy (depot or opportunity charging) and the associated charging stations as well as network utilization, even before the ordering of a new fleet, a simulation model of an electric bus is created as part of this publication. A challenge in this task is that the transport companies usually have limited technical data and information about the electric buses. Thus, the planning of fleets size and charging stations is often done by assuming average consumption values determined in Standardized On Road Test cycles (SORT) [4, 5]. These data are often very inaccurate and do not reflect worst case scenarios or the exact local conditions (e.g. low environmental temperatures or elevations). The aim of this work is to develop a bus model with few data that reflects as accurately as possible the consumption and state of charge (SoC) of a battery-electric bus, including powertrain data, heating, air conditioning, and auxiliary consumers for different route sections taking into account altitude data, outside temperature and load. This should enable precise mapping of route sections, schedules, and extreme scenarios. The model should also be easily adaptable to different bus types. In the following sections, the functions and individual components of the simulation model are described in more detail. Furthermore, the input parameters and the verification of the model are discussed, an outlook for improvements and further applications is given.

1 Model Overview

This section provides an overview of the simulation model. The structure and individual components are described in more detail. The first step in developing the model is to identify the available data and determine how detailed the model should be.
For the initial setup of the model, the MAN Lion's City 12 E low-floor bus is selected, as data for verification purposes are available from a battery-electric bus fleet that is already in operation. The model is designed so it can be easily re-parameterized for other bus models through an initialization script. Due to the limited availability of technical data, electric drive train components such as the inverters are not physically simulated in detail, this also ensures fast computation times. Instead, an efficiency map based, purely longitudinal dynamic model was developed. Since the main focus is energy consumption, the longitudinal dynamics prove

ARGESIM Report 47 (ISBN 978-3-903347-65-6), p 137-141, DOI: 10.11128/arep.47.a4737

to be sufficiently accurate, as can be seen in the verification process.
Figure 1 provides an overview of the model. The model inputs are a speed profile over time, elevation profile over the distance traveled and average outside temperature. Due to the monitoring system, the fleet operators in this study have only access to sparsely sampled GPS positions (5.3 samples per minute) without altitude information. Consequently, these GPS points require a special preprocessing methodology to reconstruct the route data (including speed and road slope) to a sufficient sampling frequency of 1 Hz. The detailed methodology employed is described in [6].

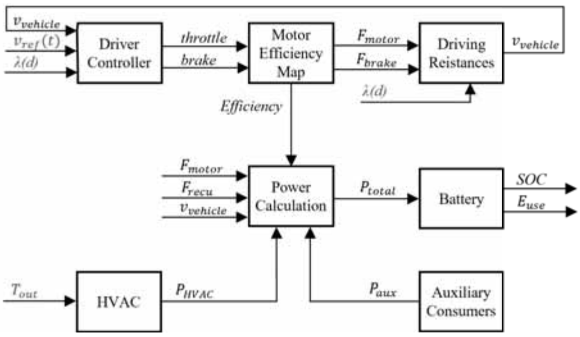

Figure 1: Simulation model overview

As driver controller, the "Longitudinal Driver" component of the Simulink vehicle dynamics blockset is used as a PI controller [7]. This controls the vehicle speed and outputs throttle and brake pedal position.
In the motor efficiency block, the current motor torque is then determined using the accelerator pedal position and the maximum possible torque for the current operating point. The maximum torque can be determined from a motor map using the motor speed calculated from the vehicle speed and the gear ratio.
From the motor torque, the motor force F_{motor} that drives the vehicle is then calculated using tire radius and gear ratio. The recuperation force F_{recu} of the motor is also calculated in this way. For strong decelerations, an additional mechanical brake is used. This results in the total braking force F_{brake}. Furthermore, the efficiency during driving and recuperation is determined using the motor map stored in a lookup table. As the specific motors installed in the MAN bus are not known, the map of an asynchronous electric motor with similar power data is used. Exemplary motor maps are available in publications e.g. [8, 9] or can be generated via simulation tools such as Matlab or Motor CAD.

The driving resistances block uses F_{motor}, the total braking force F_{brake}, and the road gradient λ(d) as inputs. Here, all necessary driving resistances of the bus are calculated. These are rolling resistance F_{RW}, air resistance F_{RA}, gradient resistance F_{RC}, and inertia resistance F_{RI}. This results in the total driving resistance F_R calculated in equation 1 using the individual resistances from equation 2. [10]

$$F_R = F_{RW} + F_{RA} + F_{RC} + F_{RI} \tag{1}$$

$$\begin{aligned} F_{RW} &= m_{ges} * g * \mu \\ F_{RA} &= cw * A * \frac{\rho_A}{2} * v^2 \\ F_{RC} &= m_{ges} * g * sin(\lambda) \\ F_{RI} &= a_x\ (e_i * m_{net} + m_{pl}) \end{aligned} \tag{2}$$

The result is the longitudinal vehicle velocity, which is fed back into the driver controller as $v_{vehicle}$. Since there are certain deviations between v_{ref} and $v_{vehicle}$ due to the driver controller, the road gradient λ(d) is given over distance and not over time. This way, the actual distance traveled can be calculated by integrating the vehicle velocity, and the appropriate road gradient at that position can be used.
To map power and energy consumption of the vehicle, the power calculation block is introduced. The driving power is initially calculated from motor force (F_{motor}), recuperated force (F_{recu}), and vehicle velocity ($v_{vehicle}$). Additionally, motor efficiency, determined from the efficiency map, is used to calculate the required driving power. For the gearbox and power electronics, a constant efficiency is assumed.
The consumption of the Heating-Ventilation Air Conditioning (HVAC) components also have a significant impact on the range of electrically operated buses. Consequently, the power of the heat pump is mapped depending on outside temperature via a lookup table [11]. Auxiliary consumers such as display boards, doors, and compressors are taken into account with a constant power consumption. The power of HVAC (P_{HVAC}) and auxiliary consumers (P_{aux}) are introduced into the power calculation block. Thus, the total power (P_{total}) can be determined by summing the power of the different components. By integrating P_{total}, it is also possible to determine the energy (E_{use})consumed for the driven cycle.

1.1 Battery Model

To be able to simulate the SOC of the vehicle, a battery model is added to the simulation model. Here, the table-based battery model from the Simscape library is used and populated with parameters from a nickel-manganese-cobalt battery cell, which was used in a previous work [12]. The cell has a maximum Open-circuit voltage (OCV) of 4.15 V (V_{ocv}) and a capacity of 14.44 Ah (C_{nom}). In the battery model, the OCV is calculated as a function of the SoC and temperature. The internal resistance also depends on the SoC and temperature (T) [13]. Self-discharge and aging are initially neglected. Only limited information is available about the battery installed in the MAN Lion's City, though it is known to be an 800 V system with 65 % of the 480 kWh battery capacity usable. Since the Simscape battery model is an electrical model, a current must be calculated from the previously determined total vehicle power (P_{total}). This is done using equation 3.

$$I_{bat} = \frac{P_{total}}{U_{bat}} \tag{3}$$

Here P_{total} is the total power of all consumers determined in the power calculation block. U_{bat} is the battery voltage measured at the battery model and delayed by one time step. This approximates the battery current. A controlled current source is then used to charge or discharge the battery model. The SoC of the battery is then calculated in the Simscape block using equation 4.

$$SoC(t) = SoC(t=0) - \frac{1}{C_{nom}(T)} \int_0^t (I_{bat}(t))\, dt \tag{4}$$

This enables simulation of any route sections and calculation of energy consumption as well as battery SoC.

1.2 Verification

To verify the functionality and parameterization of the model, precise data must be collected. For this purpose, data is provided by the Swiss transport company "Verkehrsbetriebe Zürich" which is already operating numerous electric buses and has a detailed monitoring system. The data used for verification are GPS position, vehicle speed, elevation profile, outside temperature, power of the heatpump, power of the powertrain, energy of auxiliary consumers and the SoC.
With this data, the exact consumption, divided into drivetrain (driving and recuperation), heat pump depending on the route and auxiliary consumers can be determined. The same routes are also simulated with the longitudinal bus model. A comparison between the consumption for driving, recuperation, air conditioning, and auxiliary consumers, as well as the SoC is made.
Since the available test data was collected in winter, the installed diesel heater was often recorded as active (activated at temperatures below 7 °C). The energy consumed by the heatpump is therefore very low. Further verification of the HVAC modeling for other seasons is planned.
Figure 2 shows the SoC progression of the real vehicle compared to the SoC progression of the simulation model. For this comparison, the speed recorded by the monitoring system is used as the input for the simulation model. Additionally, the altitude data is used to determine the incline over distance and also serves as input. The environmental temperature is also taken into account in the simulation. Here it can be seen that the two SOC curves show only small deviations.

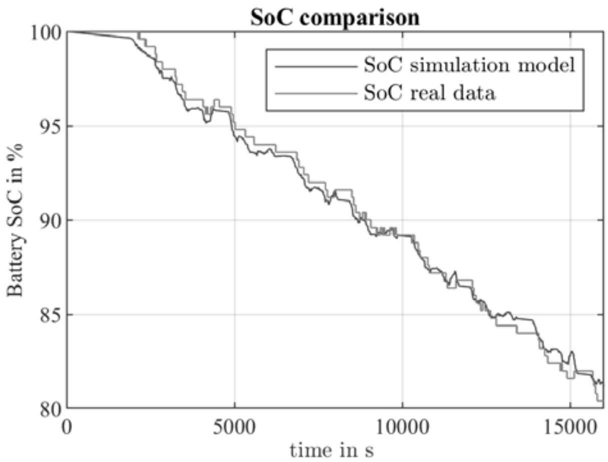

Figure 2: State of charge of the battery model compared to real vehicle data driving the same route

As route input, a round trip of 44 km length until a charger is approached is used. To quantify the differences, the maximum deviation and the Mean Squared Error (MSE) is calculated. The maximum deviation between the two SoC curves is 1.4469%. The calculated MSE is 0.31737, which indicates a high level of concordance between the two datasets.
Table 1 presents the energy consumption of the buses main consumers on the same 44 km round trip as in figure 2, broken down by drivetrain, HVAC and aux-

iliary consumers. This data also demonstrates that the energy consumption per component in the simulation model corresponds to the real-world data.

	$E_{drivetrain}$	E_{HVAC}	E_{aux}
Real data	57.07 kWh	0.84 kWh	11.98 kWh
Simulation	57.56 kWh	0 kWh	11.34 kWh

Table 1: Energy consumption by component for simulation and real data

2 Discussion

In this paper, a simulation model for a battery-electric bus is presented. This model is capable of accurately predicting energy consumption and state of charge with minimal input data. By considering driving resistances, elevation profiles, temperatures, velocity and various load conditions, a model is created which accurately represents a real electric bus. The validation of the model with data from a Swiss public transport company demonstrates high accuracy, highlighting the model's relevance and reliability, although only a minimal set of parameters are available.

The model enables public transport operators to precisely plan their bus routes, battery sizing and charging infrastructure before electrifying their fleets. This not only enhances efficiency but also optimizes costs and relieves the power grid. Additionally, the model allows for the simulation of extreme scenarios, such as full load at cold temperatures, which would not be possible with average consumption values.

In the future, the model is to be extended and includes battery aging, enabling better assessment of long-term performance. This will determine whether an old bus is still capable of covering all routes with the available charging points. Furthermore, additional parameter files for other buses should follow. Moreover, adding a more intelligent controller that can map different driver types is conceivable. Integrating different driving styles is a valuable addition to simulate the impact of driving behavior on energy consumption.

Overall, this battery-electric bus model represents a powerful tool for planning and optimizing electric bus fleets, supporting the sustainable transformation of public transport, as the application in the project FreeE-Bus funded by Interreg Alpenrhein-Bodensee-Hochrhein shows.

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Appendix

A	Cross sectional area
a_x	Acceleration in x direction
C_{nom}	Nominal battery capacity
CO2	carbon dioxide
cw	Drag coefficient
E_{aux}	Energy consumption of auxiliary consumers
$E_{drivetrain}$	Energy consumption of drivetrain
E_{HVAC}	Energy consumption of HVAC components
e_i	Moment of inertia addition-factor
E_{use}	Energy consumption total
F_{brake}	Brake force
F_{motor}	Motor Force
F_R	Total driving resistance
F_{RA}	Aerodynamic drag
F_{RC}	Climbing resistance
F_{recu}	Recuperation force
F_{RI}	Inertial resistance
F_{RW}	Wheel resistance
I_{bat}	Battery current
m_{ges}	Total vehicle mass with load
m_{net}	Vehicle mass without load
m_{pl}	Mass of load
MSE	Mean Squared Error
OCV	Open circuit voltage
P_{aux}	Power auxiliary consumers
P_{HVAC}	Power Heating-Ventilation, Air Conditioning
P_{total}	Total power
SoC	State of Charge
SORT	Standardized On Road Test cycle
T_{out}	Environmental Temperature
U_{bat}	Battery voltage
$v_{vehicle}$	Vehicle longitudinal velocity
v_{ref}	Reference velocity
$\lambda(d)$	Road gradient as a function of distance
ρ_A	Air density