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Multiphysics Simulation of a Battery Electric Train Operation

Application of an extensive simulation model of tracks, vehicle, timetable and environment to simulate the entire operation of a battery electric train

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Abstract

The changeover from diesel driven multiple units to battery electric multiple units is a challenge for operators due to the limited range of these trains. Therefore, in this paper a tool is developed and described that simulates the entire operation of a battery electric train. The tool contains a model of the track, the vehicle, the timetable and the environment. The model of the track is built on elevation profiles, radius information and speed limitation. The vehicle model is derived from an electric multiple unit suitable for local and commuter train operation. To do parametric studies or model different train units it is easily possible to change vehicle properties. Modeling the timetable and the environment allows the simulation of an entire operation day. The overall simulation model was validated and is consistent. Finally examples show the simulation possibilities and features of the tool.

Keywords: electromobility, battery electric train, battery train operation, simulation.

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1. Introduction

To reach global climate goals and improve air quality, train operators face the challenge of using alternative more eco-friendly trains instead of diesel powered trains, which are typically used when railway lines are not electrified. Recently the percentage of electrified tracks out of all tracks increased significantly worldwide. From less than 15 % in 1980 to more than 30 % in 2015 *UIC (2017).* Within the European Union the share of electrified railway lines varies considerably. Countries like Luxembourg or Belgium are at the forefront with over 85 % of electrification, the Baltic States, Greece and Denmark have less than 25 % of their train lines electrified *European Commission (2019).* In Germany roughly 46 % of line kilometers are without catenary wire *Destatis (2015).* Although the government plans to electrify further line kilometers in the next few years, catenary-independent trains will continue to be necessary in the coming decades *BMVI (2016).*

Besides technologies based on hydrogen storage, battery electric multiple units can run catenary independently without local emissions. In addition, they offer the possibility of using renewable energy sources directly and can therefore be operated more climate-friendly. The range of battery electric multiple units is highly limited because of the heavy and expensive batteries, limited space on the trains as well as high costs for recharging points. Enlarging energy storing capacity on the train by installing more batteries increases train weight which will automatically increase the driving resistance of the train. The overall efficiency is reduced. According to train manufacturers, prototypes of battery electric multiple units as well as future series vehicles will have ranges from 40 to 150 km. For example, Bombardier states a range of 40 km for its Talent 3 BEMU, Siemens quotes a range of 80 km for the Desiro ML ÖBB Cityjet and Stadler announced a range of 150 km under optimal conditions for its FLIRT Akku train. *Bombardier (2018); Siemens (2018); Stadler (2019)*

These range limitation are challenging for train operators. Recharging the train becomes an operational topic and has to be taken into account while designing operations. In an earlier phase of the changeover from diesel to other power sources it is necessary to make practicability studies to identify an optimum trainset configuration. Furthermore, on an infrastructural level, the intelligent planning of recharge points is necessary.

To solve these questions, it is necessary to simulate the entire operation of a battery electric multiple unit on real tracks. Recently, many train movement simulators have been developed, mainly focusing on simulating multiple trains on railway systems to improve timetables and overall operation *Ho et al. (2002); Nash and Huerlimann (2004); Baohua et al. (2007); Aly et al.(2016).* Due to this larger network-wide focus of these simulations, they lack a detailed modeling of trainsets. More detailed simulations of one particular trainset were done in *Gordon and Lehrer (1998), Jong and Chang (2005)* or *Kim and Chien (2010).*

To acknowledge the unique behavior of battery systems and their impact on the train operation, a more detailed simulation tool which focuses especially on the battery electric trainset modeling is necessary. This paper presents a simulation tool which is currently being developed at our institute.

Previous work was done by *Haag et al. (2017)* by developing a multiphysics simulation environment for train operation using the modeling language Modelica. In *Eller (2019)*, this work was extended by modeling and validating a battery model for diesel hybrid trains. The development discussed in this paper extends and adapts this work by modeling a precise model of the battery electric vehicle and the railway lines of interest. Furthermore, the simulation now focuses on simulating an entire operation day with changing numbers of passengers during the day.

The structure of this paper is as follows. After the introduction in chapter one the simulation model and the validation of the model are discussed in chapter two. The application of the software tool is described in chapter three. Operating two different branch lines with various cycle times is analyzed. Furthermore infrastructural influences are investigated and discussed. In addition to presenting conclusions, chapter four discusses future work as well as potentials of this simulation tool.

2. Simulation Model and Validation

The overall simulation model consists of a simulation model of the track, the vehicle, the timetable and the environment. The simulation model follows the standards for train simulations made in *DIN EN 50591 (2018)*. The vehicle model is derived from an electric multiple unit, the ET2010, which runs in local and commuter train service in Karlsruhe, Germany. The track, timetable and environment represent a local train service on tracks close to Karlsruhe. After building the simulation model it is validated to see if the results are reasonable.

2.1. Track

The track model consists of three data sets: An elevation profile, a radius profile and the local speed limitation. The discretization step of the track is one meter. To simulate real tracks the necessary information was obtained by automated analysis of geo information systems like Open Railway Map and Google Earth as well as on-site GPS and video measurements. By using several sources the radius and elevation information could be obtained with a high degree of detail. Because the permissible speed could not be obtained using online resources, speed signs along the track were filmed, analyzed and located. Results of these analyzations, exemplarily for one 10 km long track, are plotted in Figure 1 (a) altitude information and 1 (b) speed information. It should be noted that the speed limitations vary for inbound and outbound journeys.

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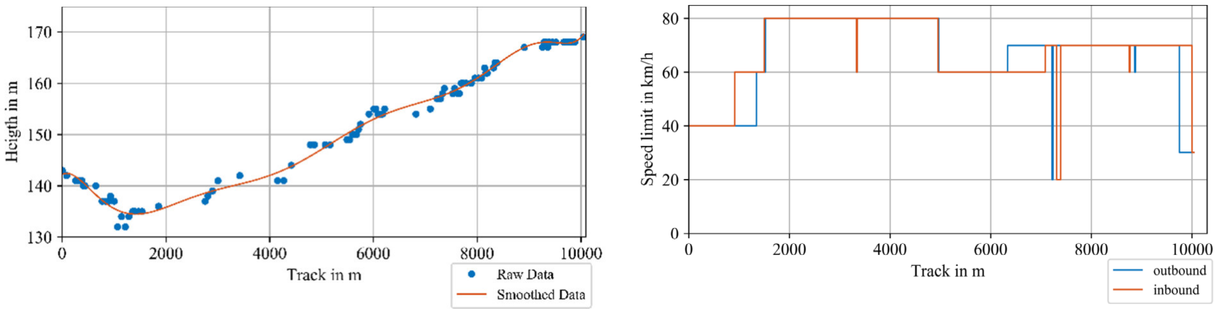

Fig. 1 (a) Altitude and (b) speed information for the 10 km long track Kurbahn

Besides this basic information the track dataset also includes other track dependent influences like railway crossings or tunnels. Railway crossings are important since trains often have to reduce their speed while passing. In rural areas where ungated crossings are common, speed limits at crossings are often 60 km/h or 20 km/h. The 10 km long track Kurbahn shown in Figure 1 has three of these ungated crossings. Tunnels are important as well since the pressure profile within the tunnel can increase the track resistance by a factor of two. Recharging is done automatically in the simulation when power sources are available. This information is also stored in the track model.

2.2. Vehicle

The simulation model of the vehicle is based on sub-models including a model for the driver, the power train, the battery and the power source. The driver model compares the simulated actual value of the speed with a predefined target value and, based on this, regulates a drive lever input signal for the power train. This predefined target value is given by the speed limitations of the track as well as the goal to reach a constant deceleration of 0.8 m/s^2. During acceleration phases the acceleration is not limited. As a first step, the train control implemented in the driver model is inspired by an automated train control system since the actual behavior of a real train has not been sufficiently investigated yet.

The model of the power train is based on the ET2010 electric multiple unit which has been in operation since 2014 in the Karlsruhe area. The power train of the ET2010 has two parts. It can run with 15 kV 16.7 Hz AC (high voltage part) and 750 V DC to operate on tram as well as train lines. The scheme of the power train is plotted in Figure 2 (a). The simulated battery electric version of the train is plotted in Figure 2 (b). As depicted, the battery electric version is derived from the normal version of the ET2010 by replacing the high voltage equipment with batteries. Although the battery weighs 2.4 tons, the overall weight of the train is unchanged. The battery model is modelling an NMC battery with a capability of 214.2 kWh.

Other parts of the powertrain were simulated strictly similar to the ET2010 power train which will later allow a comparison of simulated and real behavior to validate the simulation model. Most parts of the power train were modeled using look up tables containing the specific efficiency of the part to achieve a computing time efficient simulation. Another advantage of this approach is that it allows fast and easy adaptions of the simulated powertrain to investigate other train scenarios.

During simulation the information exchange between sub-models is as follows: The power train interprets the input data from the driver model and obtains power from the battery as well as the power source, if available. The power train then calculates place, speed and acceleration within the simulated environment. This information in turn serves as an input for the driver sub-model.

The power source is modeled as a 750 V DC power supply that charges the battery via the DC-to-DC converter in

the usual CC-CV-charging strategy described in *Korthauer (2018)*. The battery is considered empty when its state of charge (SOC) drops below 20 %, which automatically terminates the simulation, and is considered full with a state of charge of 80 % and greater. The battery is not charged above 80 % SOC.
Furthermore, the battery model considers aging effects of the battery. This is done using the variable state of health (SOH) of the battery. An SOH of 0 equals an old battery that needs to be replaced. In terms of internal resistance and loss of capacity an SOH of 0 is modeled as follows: The internal resistance is assumed to be 1.5 times the internal resistance of a new battery, the capacity of the battery compared to a new battery is assumed to be 20 % smaller.

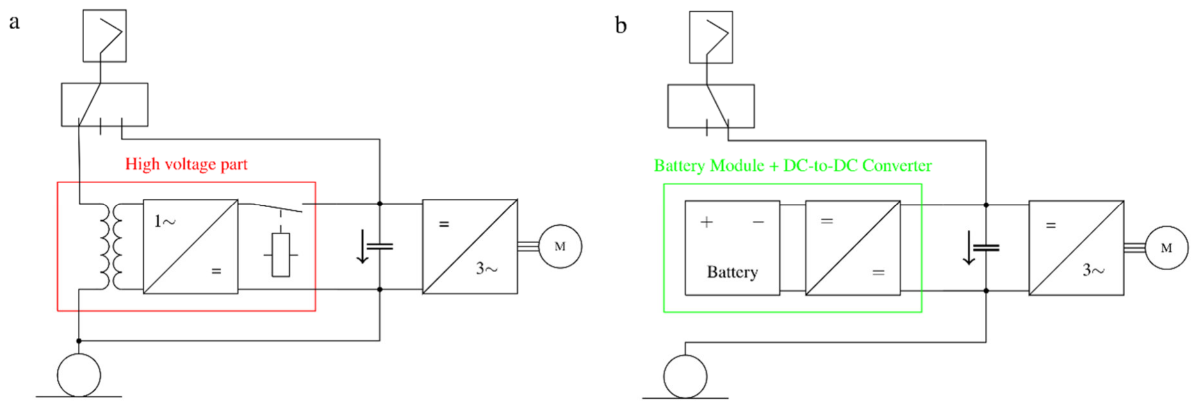

Fig. 2 (a) Scheme of the ET2010 power train; (b) Scheme of the simulated power train

2.3. Timetable and Environment

Besides modeling the track and the train, the detailed modeling of the timetable and the surrounding environment of the train is important to get reliable results. The timetable model is the key input for the driver model. The model is based on a dataset which contains travel times for each station. It includes waiting times at stations as well as turning times at the end of each line. Besides this, the timetable also includes the predefined target value for speed between stations. For this simulation the timetables were derived from real timetables on the lines of interest in spring 2019. Idle times at stations were modeled as follows: When the train arrives at a station, it will wait at least 20 seconds until departure. In addition, the train never leaves a station too early, so idle times can be longer.
Modeling the surrounding environment of the train includes numbers of passengers, outside temperatures and the usage of auxiliary devices. Since the simulation features the simulation of an entire day, the number of passengers changes according to the daytime. In morning hours the train is simulated as being full, during the day it is assumed to be 1/3 full and in the evening it is 2/3 full. In a first approach, the outside temperature and the needed power for auxiliary devices are modeled to be constant.

2.4. Validation

Validating the simulation model is complex because of the high level of detail and the lack of data of a real train. As there is no real battery electric ET2010 train yet, the validation of the simulation model is done by validating the power train model and the battery model separately. The battery model was validated in *Eller (2019)*. The power train is validated by comparing the behavior of an ET2010 electrical multiple unit with the behavior of the simulation model considering a constant power source along the track and not a battery. This is a reasonable approach since the power train model is modeled strictly similar to the real ET2010 powertrain and the overall simulation model can be considered valid if the sub-models are validated.
Since other values are difficult to detect the value that is consulted for validation is the local speed between stations. To obtain this information, the speed of a real ET2010 is measured using GPS. Accordingly, the operation on the same line is modeled and then simulated.
In order to make a reasonable comparison of the measured and simulated results it is necessary that the input values are the same for the real train and the simulation. Because of that the input value into the power train, given by the real and simulated driver, are documented. For the real train this is done via video. It should be noted that it is very difficult to detect the lever position from video, the detection is subject to ongoing work.

Figure 3 shows the speed value between two stations. The input values, not shown in the figure, were corresponding well. The behavior of the real train and the simulation is showing good consistency and it is therefore reasonable to assume a valid simulation model. At speeds above 60 to 80 km/h the speed level consistency is more vague, which is due to the human driver input.

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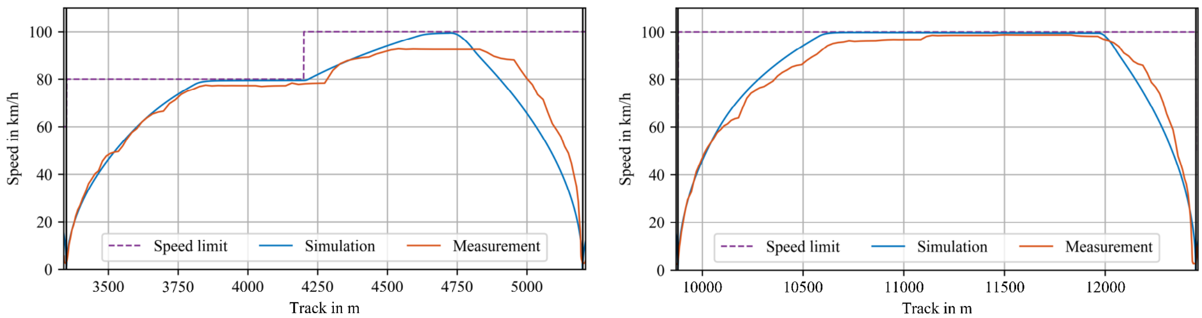

Fig. 3 Results of simulating and measuring the speed of the train between two stations

3. Application

In the following, a feasibility study and an infrastructure analysis is carried out to demonstrate two different applications of this simulation tool. Feasibility studies analyze whether a certain infrastructural and operational setup can be operated with a battery-powered electric train. An infrastructure analysis discusses which changes to the infrastructure have to be made to ensure optimal operation or make operation possible at all.

3.1. Feasibility Studies

In this study the operation of the battery electric ET2010 on two branch lines in the Karlruhe region is discussed. The branch line called Kurbahn connects the town Bad-Bergzabern with the main line going from Karlsruhe to Neustadt an der Weinstraße. The line is 10 km long and has 4 stops. The altitude and speed profile of the Kurbahn is shown in Figure 1. Another branch line close to Karlsruhe is the Wieslautertalbahn. Similar to the Kurbahn, this line connects some rural towns to the main line. The Wieslautertalbahn is 15 km long with 8 stops. The altitude and speed profile is similar to the Kurbahn one.

In the analyzed scenario the train shuttles between the main line and the last stop of the branch line. Since both branch and main lines are not electrified, recharging is only available at the last stop of the branch line. Two different cycle times are investigated. The long cycle time represents the present service hours while the short cycle time represents a more dense service on the line. Because the branch lines are single-track lines without a train crossing option, the short cycle time is limited to only one train on the line.

Figure 4 shows the used speed profile along the track including outward and return journey for (a) Kurbahn and (b) Wieslautertalbahn.

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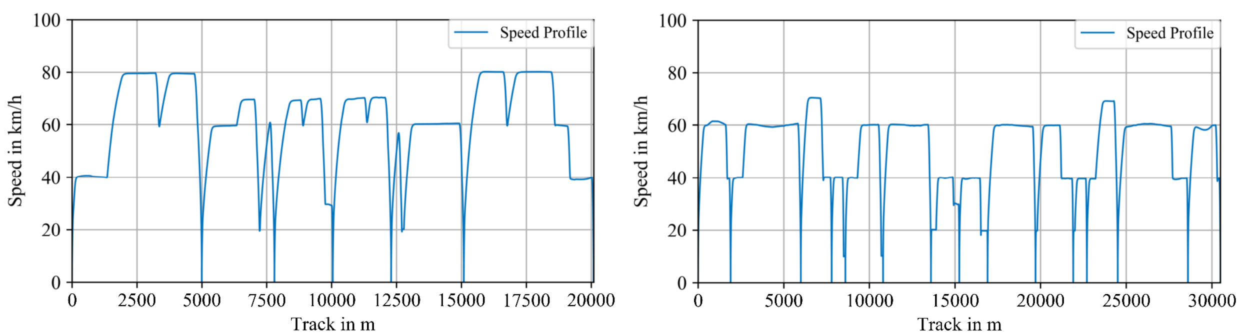

Fig. 4 Used speed profile including outward and return journey (a) Kurbahn (b) Wieslautertalbahn

Figure 5 and 6 show the battery's state of charge (SOC) on both lines for an entire operation day with present day cycle times. Figure 5 is the simulation result for the Kurbahn with 60 minute cycle time and Figure 6 is the result for the Wieslautertalbahn with 90 minute cycle time. Figure 5 (a) and Figure 6 (a), respectively, show the SOC of a new battery (SOH = 1) and (b) shows the SOC of an old battery (SOH = 0).

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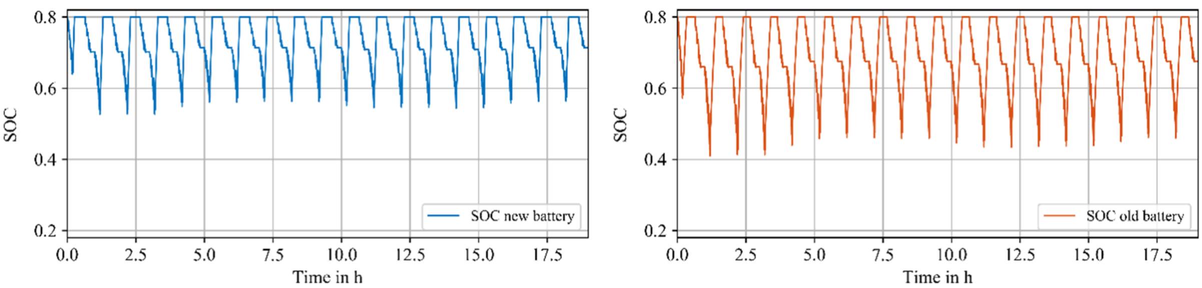

Fig. 5 State of charge during an operation day: Kurbahn 60 minute cycle time; (a) SOH equals 1 (b) SOH equals 0

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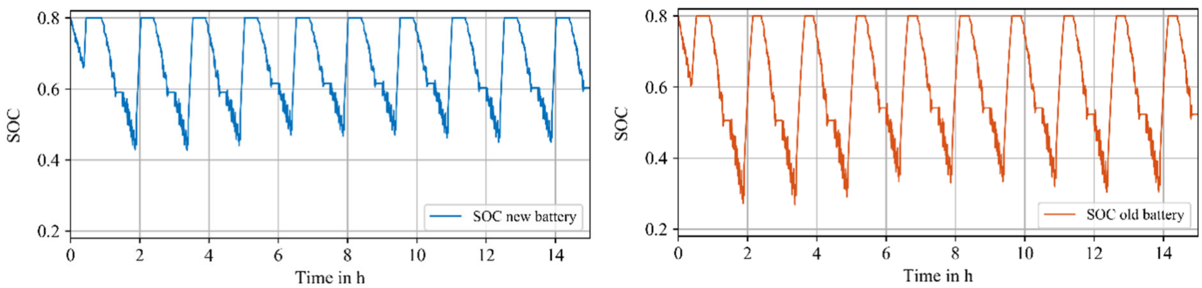

Fig. 6 State of charge during an operation day: Wieslautertalbahn 90 minute cycle time; (a) SOH equals 1 (b) SOH equals 0

The results show that a battery electric operation on these branch lines is possible under consideration of the above-mentioned structure. On both lines, the SOC of the battery never drops below 0.2. The simulated schedule leaves sufficient time at the changing station to fully recharge the battery.

In addition, different environmental conditions can be noted. The depth of discharge (DOD) changes during the day as the numbers of passengers changes. The DOD of the old batteries is greater than the DOD of the new batteries. This is to be expected because the amount of stored energy is smaller and more energy is needed since more is lost due to the higher internal resistance. The results of the Kurbahn simulations compared to the Wieslautertalbahn simulations show the different setups. The Wieslauterbahn is longer which leads to a greater energy demand between charging, this automatically affects the DOD, which is higher.

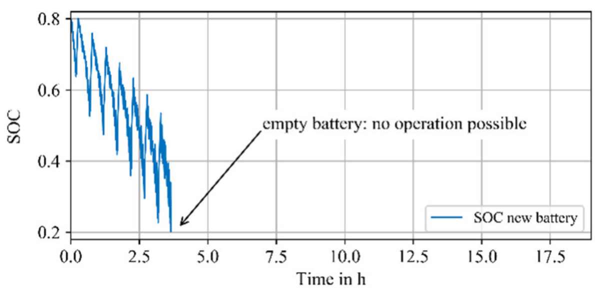

Fig. 7 State of charge during an operation day: Kurbahn 30 minute cycle time; SOH equals 1

Figure 7 shows the simulated SOC considering short cycle times on the Kurbahn. As displayed, operating the Kurbahn on a 30 minute schedule is not possible. There is not sufficient time to fully recharge the battery at the stop. The state of charge drops further in every circulation until the battery is considered empty at an SOC of 20 %. To enable a 30 minute schedule the train needs to cancel every seventh trip to fully recharge or further investigations into the infrastructure have to be made, see next paragraph. Since this scenario, which considers a new battery, is not feasible, an old battery has not been simulated.

The simulation results for short cycle times on the Wieslautertalbahn are depicted in Figure 8, (a) considering a new battery, (b) considering an old battery. The results show that operating the 60 minute cycle time on the Wieslautertalbahn is possible using a new battery, but is not possible using an old battery. For the old battery the time to recharge is not sufficient, only one circulation can be carried out until the battery is considered empty. The difference between old and new batteries is shown by two effects: the DOD of the old batteries is larger and the charging time is longer.

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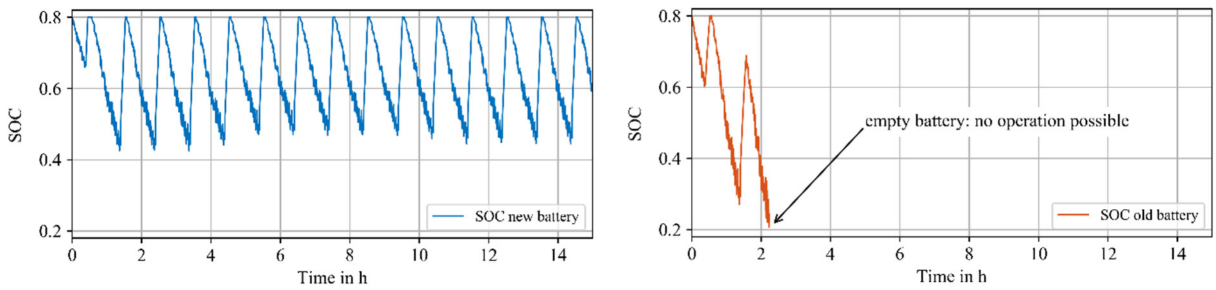

Fig. 8 State of charge during an operation day: Wieslautertalbahn 60 minute cycle time; (a) new battery; (b) old battery

3.2. Infrastructure Analysis

As examples for infrastructure analysis two different infrastructural topics are investigated: Firstly partial electrification of the track and secondly the influence of railway crossings.
To display electrification setups charts as in Figure 9 are used. They displays the electrification source, battery or catenary, the location of stops and the length of track between stops. Figure 9 (a) displays the electrification setup for the Kurbahn simulated and analyzed for the feasibility study discussed in the previous paragraph. Figure 9 (b) shows the now analyzed electrification setup with partial electrification between two stops. In total Figure 9 (b) shows a setup where 27 % of the line are equipped with catenary wire.

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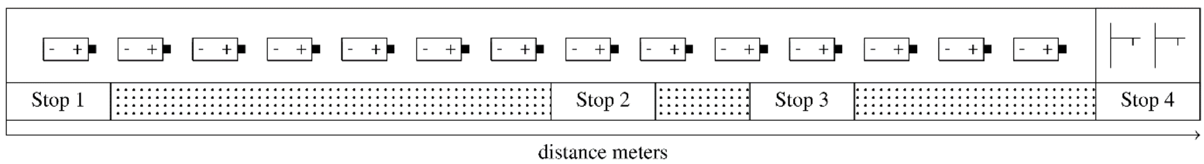

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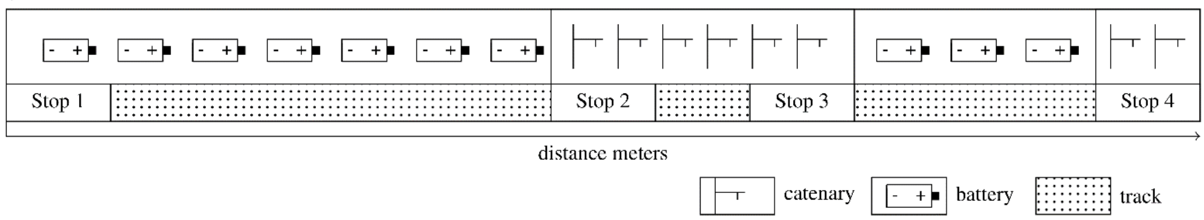

Fig. 9 Investigated electrification setups for the Kurbahn; (a) charging at endpoints; (b) additionally charging between stations

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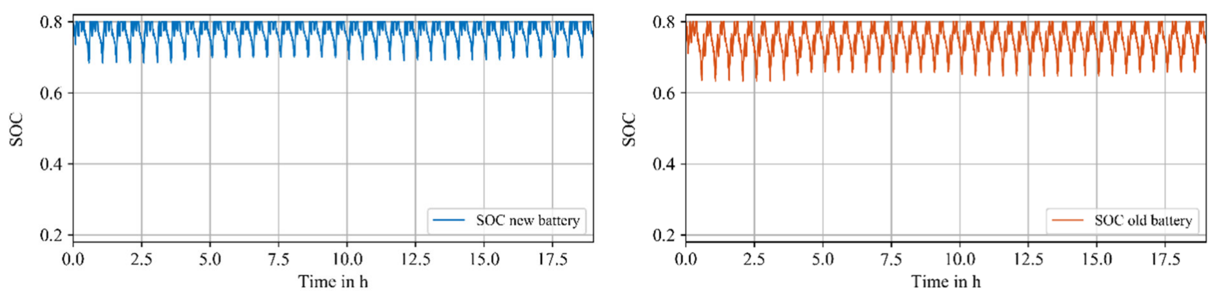

Fig. 10 Investigated electrification setups for the Kurbahn; (a) charging at endpoints; (b) additionally charging between stations

The simulation defines that energy from the catenary wires can be used for charging the battery and at the same time supplies the electric power train for traction. The simulation results are displayed in Figure 10.
The simulations show that with this partial electrification a 30-minute cycle time is possible, considering a new and an old battery. A comparison of the DOD with (Figure 10) and without partial electrification (Figure 7), shows that the DOD with partial electrification corresponds to only 40 % of the DOD without partial electrification, although only 26 % of the track is electrified. A small amount of electrification leads to a significant smaller DOD, since two positive effects of electrification on the battery overlap. On the one hand, the train has to draw less energy from the battery due to electrification and on the other hand, the train has more time to charge the battery. A smaller DOD allows operation with less turning time at the last station and a longer battery life can be expected.
Besides the infrastructural impacts of the recharging opportunities, other infrastructural impacts can be investigated as well. Hereafter the influence of railway crossings is analyzed. As mentioned before, unguarded railway crossings in rural areas have speed limitations of 60 km/h or 20 km/h, technical guarding of these crossings would make these speed limitations unnecessary.
Figure 11 (a) shows the simulated different speed profiles on the Kurbahn. Two railway crossings with a speed limit of 60 km/h and one of 20 km/h were neglected to simulate the track with technical crossings. Figure 11 (b) shows the resulting SOC during the operation day.

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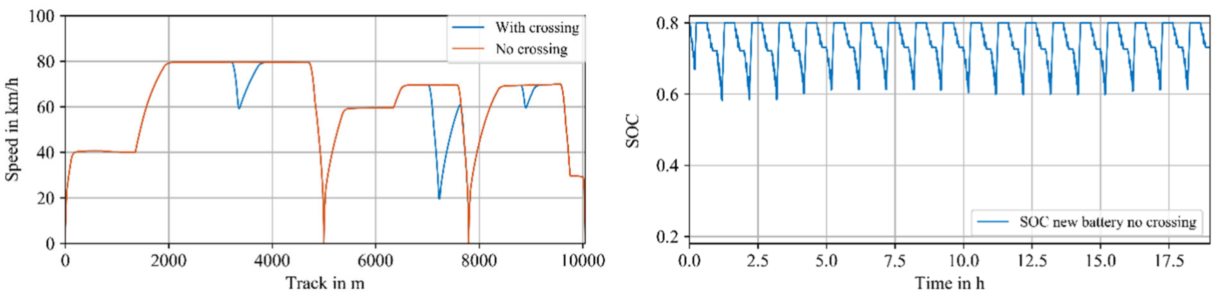

Fig. 11 (a) Simulated speed profile on the Kurbahn with and without crossings; (b) State of charge on the Kurbahn without crossings

The comparison of the DOD of the setups with (Figure 5 (a)) and without railway crossing (Figure 11 (b)) shows the significant impact of these speed limitations. The DOD is roughly 20 % smaller if the speed limitations are not considered. This shows that implementing technical guarding on these lines can significantly reduce energy consumption, a longer battery life can be expected.
By executing these infrastructural investigations the simulation tool features the possibility to quantify the influence of certain strategies to enable good and reliable battery electric operation.

4. Conclusion

This paper discusses a tool to simulate the operation of a battery electric multiple unit. Challenges of operating a battery electric multiple unit, considering enough recharging time, intelligent planning of recharging spots and the influence of the infrastructure are discussed.
A simulation tool is developed with a model-based simulation approach in the language Modelica. The overall simulation model consists of sub-models of the track, the vehicle, the timetable and the environment. The track model is based on radius, altitude and speed-limit information and information about the infrastructure, tunnels, railway crossings and recharging possibilities. To model real tracks different approaches of how to obtain the necessary information are presented. Geographic information systems and on-site observations are used. The vehicle model is modelled using additional sub-models: The power train model, the driver model, the battery model and the power source model. Besides discussing these models the interactions between them were analyzed and the model is validated.
Two different applications of this simulation tool are demonstrated. The feasibility of operating the simulated battery electric train on two branch lines is discussed and infrastructural impacts on the battery electric train are analyzed. The results of the feasibility study are: With present day cycle times the branch lines can be operated. The operation of a denser schedule is more challenging and often not possible. The infrastructural analysis initially discusses partial electrification of the track which shows a significant impact on the system. The technical guarding of railway crossings, which would allow speed limitations to be lifted, is analyzed as well. It is shown that a significant amount of energy can be saved and the battery life can be expended.
Subject of ongoing and future work is the extension of the presented simulation tool. One field of investigation is

the driver model. The goal is to implement a human acting driver to get more realistic results. This is necessary since the energy consumption of a real driver is expected to be higher than the energy consumption of an automatic train control system. Another field of investigation is the proper modeling of auxiliary devices. The development of a smart actuating procedure of auxiliary devices can be a key factor to extend the range of battery electric multiple units.

5. REFERENCES

Aly, M. H. F., Hemeda, H. and El-sayed, M. A. 2016: Computer applications in railway operation. – *Alexandria Engineering Journal* **55**(2): 1573–1580.

Baohua, M., Wenzheng, J., Shaokuan, C. and Jianfeng, L. (eds) 2007: *A computer-aided multi-train simulator for rail traffic*. IEEE International Conference on Vehicular Electronics and Safety.

BMVI (Federal Ministry of Transport and Digital Infrastructure), 2016: *Federal Transport Infrastructure Plan 2030.* https://www.bmvi.de/SharedDocs/EN/Documents/G/ftip-2030.pdf?__blob=publicationFile. Accessed September 20, 2019.

Bombardier, 2018: *World Premiere: Bombardier Transportation Presents a New Battery-Operated Train and Sets Standards for Sustainable Mobility.* https://rail.bombardier.com/content/dam/transportation/supporting-documents/news/2018/20180912_CEC_Hennigsdorf%20BEMU%20Train_EN_FINAL.pdf. Accessed September 23, 2019.

Destatis, 2015: *Means of transport and infrastructure, Railway infrastructure Length of railway lines, by Land.* https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Transport/Enterprises-Infrastructure-Vehicle-Stock/Tables/railway-infrastructure.html. Accessed September 30, 2019.

DIN EN 50591, 07.2018: *Specification and verification of energy consumption for railway rolling stock*. Beuth Verlag GmbH, Berlin.

Eller, M., 2019: *Prädiktiver Betrieb von Multi-Hybrid-Antrieben im SPNV,* PhD thesis, Karlsruhe.

European Commission, 2019: *Electrified railway lines.* https://ec.europa.eu/transport/facts-fundings/scoreboard/compare/energy-union-innovation/share-electrified-railway_en. Accessed September 20, 2019.

Gordon, S. P. and Lehrer, D. G. 2002, 1998: *Coordinated train control and energy management control strategies:* Proceedings of the 1998 ASME/IEEE Joint Railroad Conference: April 15-16, 1998, Philadelphia, Philadelphia, PA, USA, pp. 165–176.

Haag, S., Eller, M. and Gratzfeld, P. 2017: Methodical design of a hybrid propulsion for short-distance railcars. – *Elektrische Bahnen* **115**(5): 230–237.

Ho, T. K., Mao, B. H., Yuan, Z. Z., Liu, H. D. and Fung, Y. F. 2002: Computer simulation and modeling in railway applications. – *Computer Physics Communications* **143**(1): 1–10.

Jong, J.-C. and Chang, E.-F. 2005: Models for estimating energy consumption of electric trains. – *Journal of the Eastern Asia Society for Transportation Studies* **6**: 278–291.

Kim, K. and Chien, S. I.-J. 2010: Simulation-Based Analysis of Train Controls under Various Track Alignments. – *J. Transp. Eng.* **136**(11): 937–948. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000160

Nash, A. and Huerlimann, D. 2004: Railroad simulation using OpenTrack. – *WIT Transactions on The Built Environment* **74**.

Siemens, 2018: *Desiro ML ÖBB Cityjet eco für die ÖBB-Personenverkehr AG.* https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/mobility/rail/rolling-stock/commuter-and-regional-trains/desiro/desiro-ml/documents/datenblatt-desiro-ml-oebb-cityjet-eco-de.pdf. Accessed October 8, 2018.

Stadler, 2019: *Stadler supplies 55 battery-operated FLIRT trains for the Schleswig-Holstein local transport association.* https://www.stadlerrail.com/media/pdf/2019_0702_media%20release_flirt%20akku_en.pdf. Accessed September 30, 2019.

UIC, 2017: *Railway Handbook 2017, Energy Consumption and CO2 Emissions.* https://uic.org/IMG/pdf/handbook_iea-uic_2017_web3.pdf. Accessed October 1, 2019.