Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 12.2
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.12.2

Learning from Battery Train Projects for Retrofitting Diesel Trainsets in Cuba

B. Ebrecht

**Railway Operations and Infrastructure Department,
Technische Universität Berlin
Germany**

Abstract

The operation of battery electric trains in Germany and Cuba has a history of over 100 years. The technology is experiencing a renaissance in the context of the climate movement, with technological innovations leading to hybrid vehicles known as BEMU.
TU Berlin has provided scientific support for several BEMU-related projects during the recent years. This includes assistance in the development, introduction and passenger operation of a demonstrator BEMU as well as feasibility studies.
A corresponding Cuban project is investigating the modification of current CB-10 diesel multiple units to battery trains for suburban services in Havana.
The retrofit project shall benefit from the findings of current BEMU projects by a cooperation: General requirements and appropriate components for use in Cuban suburban operation are to be identified by analysing structures of modern BEMU. The aim is to develop a basic vehicle conversion concept for existing CB-10 vehicles that is preferably non-complex and still allows robust operation under given circumstances. Vehicle dynamics simulations with energetic considerations are carried out for dimensioning of the battery system. As a result, vehicle parameters are derived which can be used in the further planning of a prototype retrofit.

Keywords: decarbonization, electromobility, battery train, retrofit vehicle, vehicle concept, charging infrastructure, Havana suburban railway

1 Introduction

One of the long-term goals of global transport policy is to encourage electromobility in rail transport. This should contribute to increase the modal split of public transport and reduce environmental impacts. In this context, the topic of alternative propulsion systems has also gained importance in recent years among the transport authorities responsible for the organization of local rail passenger transport. One measure to achieve these goals can be the use of battery vehicles instead of diesel-powered trainsets.

The use of battery trains in local rail passenger transport has a history of over 125 years [1]. In the context of the climate movement, battery vehicles are experiencing a renaissance on rail as Battery Electric Multiple Units (BEMU). Modern technologies such as fast-charging lithium-ion batteries are used and there is the possibility of selectable power supply via the overhead contact line or the traction batteries. The latter can be recharged via the existing catenary interface, making the vehicle design particularly well suited for partially electrified lines.

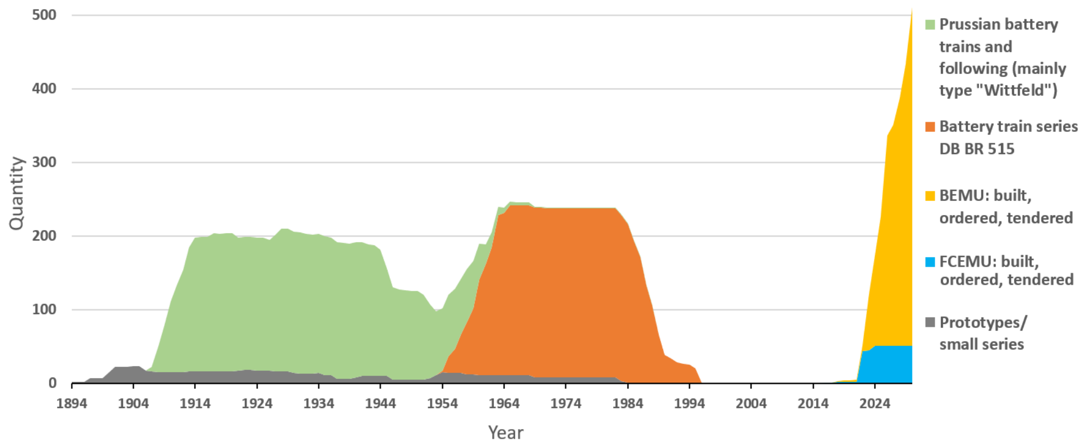

Figure 1: stock development of commuter trainsets with alternative drive systems in Germany as at August 2023. Based on [1], updated data status.

After the first BEMU prototypes were tested in Japan in the 2010s, the first vehicle of this type started passenger test operation in Germany in 2022. There, the replacement of several diesel fleets with over 500 vehicles is henceforth imminent, which are currently in various phases of studies, tenders, production and commissioning as shown in Figure *1*.

In contrast, rail operations in Cuba are still predominantly based on diesel traction. Decreasing passenger volumes in Havana's suburban traffic have led to targeted measures being taken to make the operation more attractive again [2].

One part of this package of measures is the conversion of the existing diesel vehicles to battery-powered railcars. Specific conditions of railway transport in Cuba have to be taken into account. In order to achieve this, a cooperation between Centro

Investigación y Menajo Ambiental del Transporte (CIMAB) in Havana and Technische Universität Berlin (TUB) is being established. The aim of this work is to support the development of a concept for the conversion of suburban transport vehicles in Havana, with the findings from battery train development in Germany being considered.

2 Related Work

Von Mach showed a BEMU concept for regional railway lines in 2012 [3]. This approach was continued as part of a Research and Development project (R&D) by Alstom (former Bombardier Transportation) and TUB up to the homologation and operation of a demonstrator that is shown in Figure 2. Within the scope of this project, a conventional EMU was converted to a BEMU and tested in passenger service while equipped with a data logger. Test operation was carried out for several months in southern Germany generating many datasets. The evaluation yielded numerous findings, e.g. on energy requirements, operational processes that is to be used for the further establishment of BEMU fleets in regular operation [4]. Stadler Rail also presented a BEMU prototype in 2018, which was supported by an R&D project participated by TUB [5].

Figure 2: Alstom BEMU demonstrator in battery mode operation.

While the prototype vehicles demonstrated traction battery system (TBS) recharging via overhead contact line, Wittig describes how plug-based recharging at 400 V or 1 kV can be carried out using standardized power connections to the landside bearing in mind that the charging power is reduced [6]. Furthermore, Dschung showed an adapted landside charging hardware for applications of small charging stations using a Scott-T transformer for recharging using two phase AC. It has become clear that recharging via a near-grid power system interface can have a positive effect on the overall operation of battery-powered vehicles and its efficiency [7], [8].

Numerous feasibility studies commissioned by transport authorities weigh up the use of different propulsion concepts such as fuel cell hybrid vehicles (FCEMU), BEMU and electric multiple unit (EMU) including full electrification as an alternative to diesel operation in the context of the replacement of diesel fleets in specific operation networks. In many cases, BEMU is a suitable option, especially as it can be converted to conventional EMU later in case of full electrification.

An example of this is the study on two eastern German operating networks worked on by a consortium in which TUB was involved: the economic system decision for a vehicle technology as well as positioning and dimensioning of recharging infrastructure was determined by driving dynamics simulations using datasets of market available vehicles. The results allowed to derive guidelines for redundancies in the vehicle concept as well as for mitigating unforeseen operational events [9].

Furthermore, different hybridization options for a diesel fleet with a large remaining service lifetime such as diesel-battery operation as well as catenary-battery hybridization were investigated in another study [10]. No practical vehicle retrofit has resulted from this study. Not all hybridization concepts are practically realizable as the whole drive chains are affected what leads foreseeable to the need for a new vehicle homologation [11]. The EcoTrain project – pursuing the conversion of a 20-year-old existing diesel vehicle – did not progress beyond prototype status [12].

3 Basic conditions of the Cuban project

The Cuban railway system is one of the sectors that needs the most innovation in the context of the country's modernization. Passenger numbers in Havana's suburban rail transport have fallen by more than 95 % in the past 10 years [2]. It can be assumed that the traffic potential of the existing railway lines is currently not being used. The identified bundles of measures include a change of traction and the rolling out of electric trains on the Cuban railways [ibid].

The frame conditions in Cuba include low financial possibilities for the establishment of electric transport, which has an impact on the choice of the type of drive: for this reason, the use of new vehicles is not an option and therefore the approach is to obtain retrofit vehicles in the simplest possible way. As a further result, the young and complex propulsion technology of hydrogen fuel cell vehicles (FCEMU) is not considered here. Instead, a conversion of existing vehicles is being pursued. Alternatively, the use of alternative fuels such as Hydrogenated Vegetable Oils (HVO) could be examined, which is currently being tested in pilot projects in various countries, but which cannot foreseeably offer the advantages of electric traction in local rail operations and is therefore not considered here [12].

Name	Departure	Destination	Length [km]
Línea Central	La Coubre	Aguacate	62
Línea Guines	La Coubre	Palos	76.5
Línea Rincón	La Coubre	Rincón	23.3
L. Sur Rml. Batabanó	Tulípan	Batabanó	31.5
Línea Oeste	Tulípan	Artemisa	27.3
Línea Sur	Tulípan	San Antonio	23
Línea Mariel	La Coubre	Mariel	64

Table 1: Relations and lengths of the Havana Metropolitan Railway network lines.

One package of measures includes the electrification of Havana's suburban services by using retrofit battery vehicles. This project is being pursued at the CIMAB institute in Havana.

There are 8 local passenger rail lines originating from the capital, which can be grouped together as the Havana Suburban Railway. The Hershey Railway is the only one equipped with 1.2 kV DC catenary but is not currently operating electrically. The other seven lines that are the focus of the retrofit project are not electrified and are between 23 and 77 km long as shown in Table *1*.

These lines are operated by diesel multiple units (DMU) of Russian manufacturer Muromteplovoz built as of 2013 [14]. The vehicle family with 300 units consists of two-axle vehicles with diesel-mechanical drive. A bi-directional single vehicle ("Alisa") or a composition of SV-10 railcars with a driver's cab and optional VS-5 trailers can be used. The following compositions (named CB-10 by the National Railway Company of Cuba) are formed [15][16], [17]:

- "Alisa" (20 seats)
- SV-10 + VS-5 (90 seats)
- SV-10 + VS-5 + SV-10 (138 seats)

The project focuses on the conversion of 7 units from this vehicle series to battery operation. In the process of the project, it will have to be examined how this can be implemented as simply as possible and which components are required.

4 Retrofitted battery train

A robust vehicle design must be based on the entire operating schedule of the vehicles, including disruption scenarios [9]. In regular operation, the timetable structure influences the traction and auxiliary power demand. Furthermore, the determination of vehicle circulation with its turning and standing times as well as the location and design of the recharging infrastructure have an influence on the total energy demand during the operating days [ibid]. For this reason, it is essential to include the target timetables, circulation plans and the intended recharging concept in the vehicle design. Case-by-case considerations are necessary to specify an operational range for specific lines to be served. Therefore, various infrastructure scenarios will be examined in this project by means of simulations.

With a view to the technology available on the market, LTO and NMC-C are suitable cell chemistries for the traction batteries, which differ in energy density, cycle stability and other properties. The following applies to all battery types used in BEMU: a charging window is defined within which the state of charge is during regular operation to maintain the battery in good health and enable long battery lifetimes. To optimize the battery's lifetime, the depth of discharge should be kept as low as possible and the use of the battery reserve should be reduced to a minimum. In several studies by TUB, an additional buffer area was therefore defined within the regular charging window in order to be able to absorb minor operational irregularities without requiring the battery reserve. The buffer shown in Figure 3 is measured based on additional standstill times or start-ups to be covered.

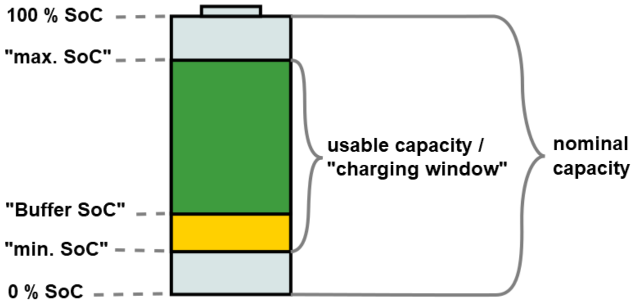

Figure 3: Principle diagram of the usable battery capacity in mobility applications.

The pilot project comprises the conversion of 7 units with planned daily running performances of 2 - 3 train pairs per line, which add up to approx. 1,500 train-km per operating day. The full operating program of the 7 lines includes further train runs and must be included in the design so that the retrofit vehicles are also able to fulfil this in the future.

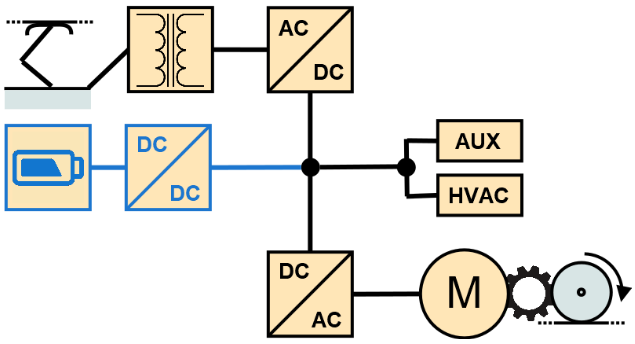

Figure 4: Structure of a typical BEMU. The components of a conventional EMU are framed black and the additional components of a battery train are framed blue.

Figure 4 shows the basic structure of the BEMUs currently being established in Germany. Whilst there is a degree of electrification with overhead contact line of over 60 % and the vehicles can be operated like conventional EMUs on every electrified section, in the Cuban network only one line is electrified, but it is currently not completely electrically operated [18]. For this reason, the pantograph as a charging interface is not assumed here; the question of the charging interface will have to be answered later.

In the CB-10 vehicles, the auxiliary power supply includes a 24 V on-board power supply system that powers the components required for driving and ensures the lighting [2]. In contrast to the German BEMU, whose auxiliary converters are designed to supply up to 100 kW for heating, ventilation and air-conditioning (HVAC), significantly lower outputs can be expected here. This will reduce the energy demand in a direct comparison, as up to 1/3 of the energy demand is required for HVAC purposes under mid-european conditions. Accordingly, a low-dimensioned on-board converter is sufficient here instead of large-scale auxiliary converters. Since the energy demand is for the most part no longer dependent on the weather without HVAC supply, only small variations in the energy demand are to be expected during the course of the year.

This makes the energy chain between the battery system and the traction motors even more important for retrofitting. Depending on the charging interface, which has still to be defined, it is questionable to what extent a defined DC link level with constant DC voltage is necessary at all, or whether combined converters consisting of a charger and traction converters can be used.

5 Methods

For vehicle design, it is initially determined which energy requirements are generated by each vehicle tour on a line. The "EROSS" simulation environment developed by the author is used for this purpose. This dynamic driving simulation environment receives numerous vehicle and route parameters (infrastructure and timetable data) as input in the form of datasets.

The simulation of a BEMU run is carried out using a time step method according to [19]. For each time step, the tractive force to be applied at the wheel-rail contact is first determined, overcoming driving resistances such as rolling resistance, air resistance and gradient resistance, in order to achieve the best possible trajectory for the target speed according to the route profile. Driving strategy is minimum travel time. The required traction power per time step $P_{traction}$ [t] makes it possible to determine the time discrete traction energy $E_{trac,wheel}$ [t] to be applied for each time step of the entire journey as given in equation (1).

$$E_{trac,wheel}[t] = P_{traction}[t] \cdot \Delta t \tag{1}$$

The structure of the BEMU as shown in Figure *1*Figure 4 is mapped (without pantograph here, c.f. chapter 7) and each component is attributed with an efficiency factor. Considering a constant auxiliary power P_{Aux} and P_{HVAC} = 0, the TBS load $E_{bat,trac}$, while traction power is provided, can be calculated for each time step as given in equation (2).

$$E_{bat,trac}[t] = \frac{\frac{E_{traction}}{\eta_{Motor} \cdot \eta_{DC/AC}} + \frac{P_{Aux} \cdot \Delta t}{\eta_{Aux}}}{\eta_{DC/DC} \cdot \eta_{Battery}} \tag{2}$$

Similarly, the maximum possible electrical braking performance corresponding to the vehicle parameters is utilized during braking. The converted electrical recuperation energy is primarily used to supply the auxiliary systems and leads either to a reduced TBS load or even to charging the TBS with $E_{bat,recu}$ during the recuperation phases [19]. Further braking forces are applied using the air brake and are irrelevant when considering the battery load.

In addition, the available charging facilities must be modelled and the charging potential $E_{bat,chg}$ [t] is to be calculated up to the full charge of the TBS. As a result, the state of charge per time step SoC_{TBS} [t] can be determined as shown in equation (3) if an initial state of charge SoC_{TBS}[t=0] is given.

$$SoC_{TBS}[t] = min\{SoC_{max};\ SoC_{TBS}[t-1] + E_{bat,trac}[t] + E_{bat,recu}[t] + E_{bat,chg}[t]\} \quad (3)$$

6 Retrofitted battery train

The lowest state of charge plus the above-mentioned buffer areas determines the nominal capacity of the traction batteries, insofar as recharging is only possible at one end of the line. Once the capacity requirement is determined, the power demand of the inverters can be determined. It should at least allow adequate supply to the traction motors and auxiliaries in any operational situation. Since the distribution of the recharging locations, the battery capacity and vehicle power are interdependent, an iterative optimization process up to an overall concept is to be expected, which can be scenario-based under variable boundary conditions. In the following example, the traction power of the diesel vehicle was slightly increased and a battery capacity of nominally 360 kWh was set. The main parameters used as a basis are shown in Table *2*, and the mass difference was assumed according to [20] for LTO batteries.

Composition	CB-10 DMU	CB-10 Battery Train
Mass [t]	22 + 20	29 + 20
Traction power [kW]	176	200
Traction battery capacity [kWh]	-	360
Max. speed [km/h]	100	
Seats	45 + 48	

Table 2: Main assumptions for simulating BEMU in comparison to diesel trainset before retrofit.

Assuming some boundary conditions and parameters, which are still to be verified and refined in the project progress, Figure 5 shows the state of charge curves for a converted two-part unit of the CB-10 series for the Havana - Mariel line and back. The three different curves result from the following boundary conditions and have been determined with turnaround times of 15 min in Mariel and 30 min in Havana:

- V1: CB-10, charging station Havana
- V2: CB-10, charging station Havana + Mariel
- V3: CB-10 with double recharging and recuperation power at the same 200 kW traction power, charging possibility Havana + Mariel.

It can be seen that despite the slightly increased power in the driveline compared to the diesel vehicle CB-10 (recharging designed for the same battery power), there are long standstill charging time requirements that will exceed one hour per round trip. This is significantly reduced in scenario V3.

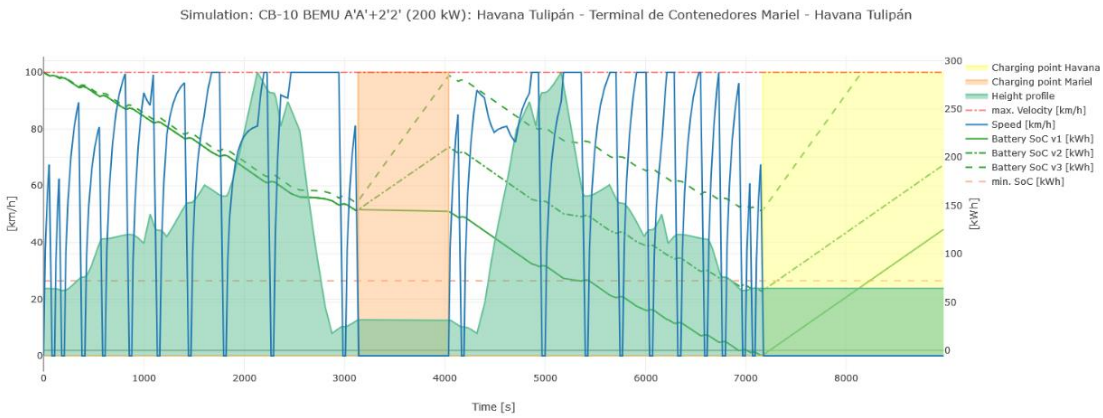

Figure 5: Driving dynamics simulation for a retrofit CB-10 BEMU using driving strategy minimum travel time.

Furthermore, doubling the recuperation power per round trip results in an additional battery charge of about 20 kWh. It is therefore advisable to maximize the electric service braking quota by driveline design, even if lower power is required for acceleration. Depending on the vehicle structure, this is also a prerequisite to enable higher charging capacities as shown in Figure 5 (c.f. belowFigure *6*). The assumed nominal battery capacity of 360 kWh is not sufficient to be able to drive a round trip in a stable manner. At best, an additional charging option in Mariel and an increased recharging capacity should be aimed for. With the concretization of the assumptions and the operating program, the other lines will be examined analogously.

In the project progress, the requirements of all 7 network lines will be contrasted. According to the maximum energy demand of all lines, it will be determined whether the given installation space, mass reserves, etc. of the vehicle allow for such equipment, or whether additional charging infrastructure must be built. In principle, the goal should be to achieve a fleet that is equipped with a uniform TBS, but that can operate on all lines in the network (cf. recharging infrastructure).

With regard on the special availability situation in Cuba, the choice of the specific components for the propulsion system is of central importance. It is to be investigated if used components of existing Cuban vehicles such as traction motors/gearboxes, can possibly support the retrofit project for the CB-10 vehicles, or if components made from scratch are needed. Components enabling regenerative braking should be used at minimum what is possible, for example, using 4-quadrant controllers as converters.

In the case of a fleet retrofit, fully redundant drivelines by using multiple, compactly dimensioned electronic components are desirable, but initially a lower priority.

7 Recharging infrastructure

The situation for the creation of a recharging concept for Havana's suburban railways is challenging: due to the low degree of electrification of the Cuban rail network, not only the recharging locations are to be determined but also the vehicle-landward interface and recharging power are open. These many open parameters require strategically sensible decisions.

The Cuban rail network has one electrified line (Hershey Railway) with catenary of 1.2 kV DC, which is currently only partially in operation. While in Europe new electrification networks are planned with 15 or 25 kV AC, an AC catenary is not foreseeable in Cuba. According to a CIMAB study, a medium-term alternative would be the extension of the 1.2 kV DC system, which, however, is not expected until towards the 2030s [2]. The CB-10 vehicles to be retrofitted will then already be more than 20 years old, so that depending on the lifetime of the retrofit CB-10s, there may only be a minor time overlap. For this reason, it does not currently seem necessary to focus on recharging via the pantograph catenary interface. However, it is advisable in any case to provide for an DC link level of 1.2 kV and to consider upgrading pantographs at a later date.

Technically, it is possible to transmit the foreseeably necessary recharging power of several hundred kW via plug [6]. However, an adaptation under Cuban climatic conditions must be examined.

Cuba's electricity grid is operated by the state-owned operator UNE. In addition to a nationwide 220/110 kV high-voltage grid, there are also medium-voltage grids of various voltages, in a few cases also island solutions [21], [22]. These distribution grids operate primarily at 33 kV with three phases at 60 Hz [23], [24]. Assuming that the charging stations of the battery trains are supplied from the national power grid, a connection to this medium-voltage system (possibly with lower voltages such as 13 kV in the wider distribution grid) is the basis.

On the one hand, a charging connection to the DC link of the vehicle can be attempted. For this, a DC charging option of constant voltage would have to be created on the landside by the use of converter technology. When implementing this option, it should be checked whether the converter system can possibly be used later in the context of a route electrification. For this, the recharging voltage would have to be set at 1.2 kV DC. This fits in with the idea of setting the DC link to 1.2 kV what is within the range of market standard components to simplify a later addition of a pantograph.

Another possibility would be to simply transform the voltage on the landside to a potential matching the traction motor voltage range and to transmit it to the vehicle using an AC three phase plug. In this case, the vehicle's own traction converter would be used for conversion and a switch to a recharging mode would be performed when the vehicle is at a standstill. Consequently, in this case the design of the drive line also determines the available recharging power. The two alternatives are shown structurally in blue and brown in Figure 6.

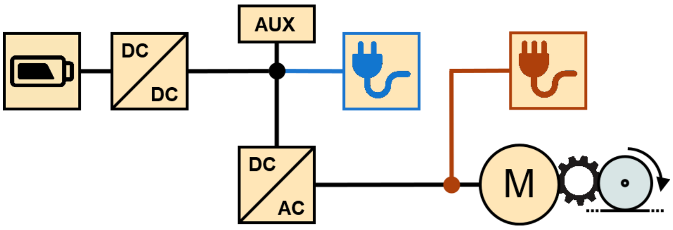

Figure 6: Two resulting structural options for CB-10 retrofit to battery trains using three phase AC recharge (brown) or DC recharge (blue).

A charging interface directly connected to the battery system is ignored here: it would have to be operated with variable voltage, which requires coordination respectively communication between the vehicle (battery system) and the landside (charger) and complicates the overall system.

A first, rough estimate of the CO2 emissions shows that, assuming the Cuban electricity mix in 2023, the emissions will not be lower when only switching to battery operation compared to diesel operation. In view of the volatile conditions of the electricity supply in Cuba, the emissions balance of battery-powered trains can even be significantly worse than that of the current diesel train operation if the conditions are disadvantageous. This refers to fuel-intensive SV10s from [2], what is about five times as much as for modern DMUs in Germany. Thus, if the efficiency of diesel operation were to be increased, the emissions comparison of battery operation would be even worse. In addition, blackouts or power cuts in the Cuban national grid are currently to be expected on a frequent basis [25], [26]. These considerations show the urgency that a future-oriented battery train operation can only succeed if the energy supply is designed adequately.

It therefore seems strongly advisable to connect the introduction of battery trains to advances in the transformation of the electricity mix or even to supply charging stations with renewable energies through isolated solutions.

The short range of battery trains leads to the need for several charging processes per operating day. As a result, even short-term blackouts in the power grid can cause battery train operations to come to a complete standstill if the charging stations are exclusively supplied directly by the national power grid. One way to mitigate this risk is to use local, landside buffer batteries at the charging stations. These can not only contribute to fail-safety, but also buffer the energy generated when using renewable energies like PV systems that do not generate energy at night. Details of the charging station design will have to be determined when the distribution of the daily energy demand per station is known after completion of the operational study.

From an operational point of view, the positioning of the plug-based charging stations appears appropriate at the turnaround stations of the lines. While planning a uniform fleet, it is to be expected that there will be a need for recharging at both ends of the long-distance lines. From a supply point of view, it must be evaluated whether efficient connections to the medium-voltage grid are feasible at these locations.

8 Conclusions

This examination has shown that battery trains for use in Havana's suburban transport should be conceived differently from prototypical BEMUs that are currently being tested and put into operation in Germany. The vehicle requirements identified for Cuban retrofit battery trains are summarized below:

- Redundant design of traction line and TBS as far as possible
- Use of recovery-capable converter technology
- Increase the driveline power to maximize recuperative battery charging
- short-term development of electric grid allows plug-based recharging interface
- Connect recharge plug to DC link (DC charging) or to traction converters (AC-3~ charging)
- Provide for retrofitting of a pantograph in the case of DC electrification of the railway network and fix DC link voltage to expected catenary voltage

Furthermore, the first requirements for the necessary recharging infrastructure already emerge at this early stage of the study, which are summarized below:

- Provide sufficiently powerful grid connection at respective charging locations
- Use buffer storage to increase reliability and integration of renewable energies
- Recharging with three-phase AC requires a landside transformer; if DC recharging plugs are chosen, additional converter technology is required.
- Use increased share of renewable energy to current electricity mix, otherwise using battery trains can worsen emission balance compared to diesel operation

In the further process of the project, the assumptions of the vehicle dynamics simulations are to be revised. Simulations for the entire suburban network in Havana are to be completed and vehicle parameters must be determined. From these basic parameters, requirements of the power electronics for the retrofit vehicles can be derived to answer if there are limits of the installation space and the mass ratio of the vehicles. On this basis, it can be estimated whether parts of existing diesel-electric Cuban vehicles can be used or whether all components must be acquired from scratch.

Furthermore, the desired operating schedule and the simulation results can be used to determine the recharging power requirements for each daytime. For the resulting overall concept, a verifying emissions calculation is to be attempted to determine whether an ecological advantage results from the design decisions made.

The implementation of the retrofit, and the vehicle homologation and installation of the infrastructure are currently not part of the cooperation between CIMAB and TUB. A possible prototype conversion is to be tested in follow-up projects.

Acknowledgements

The Author thanks José A. Olmo Pérez (CIMAB) for getting information on Cuban railways, electric grids and CB-10 vehicle technology. A thank goes to Dianeisy

Delgado López for establishing contacts and interpreting and to Ulrich Zimmermann for proofreading and giving valuable comments.

References

[1] B. Ebrecht, U. Zimmermann, “Forschung trifft Praxis: Alternative Antriebskonzepte im Schienenverkehr” [online] Available at: [https://www.static.tu.berlin/fileadmin/ www/10002264/ews/2020-wise/2020-11-02-folien.pdf], 2020 (accessed: 30th January 2024)

[2] J. A. Olmo Pérez, "INTERCAMBIO SOBRE TRENES ELÉCTRICOS A BATERIAS CON LA UNIVERSIDAD TECNICA DE BERLIN Y ALSTOM", Centro Investigación y Menajo Ambiental del Transporte, Havana, Cuba, 2023.

[3] S. von Mach, “A CONCEPT FOR NEW TRAINS ON NON-ELECTRIFIED REGIONAL PASSENGER LINES”, MSc Thesis, TU Berlin, Germany, 2012.

[4] P. Boev, B. Ebrecht, S. von Mach, U. Zimmermann, “Der Alstom BEMU Demonstrator im Fahrgasteinsatz – erste Erfahrungen aus dem Testbetrieb”, Eisenbahntechnische Rundschau, 2022, no. 9, 104 - 109.

[5] Stadler Rail AG, “FLIRT AKKU” [online] Available at: [https://www. stadlerrail.com/de/flirt-akku/details/] (accessed: 30th January 2024)

[6] K. Wittig, “Energieversorgung für abgestellte Elektrotriebzüge mit Akkumulator (ETA) – Rückkehr der Zugvorheizanlagen oder Neuauftritt der Elektranten?”. Eisenbahntechnische Rundschau, 2021, no. 1+2, 56 - 59.

[7] F. Dschung, “50-Hz-Schnellladestation für Batterietriebzüge”. EI – DER EISENBAHNINGENIEUR, 2022, no. 2 February, 31 – 34.

[8] S. Claus, “Vorstellung Projekt 50-Hz-Nachladestation für BEMU”, [online] Available at [https://www.now-gmbh.de/wp-content/uploads/2022/11/2.-Plattform-Schiene_Vorstellung-Projekt-50-Hz-Nachladestation-fuer-BEMU_Claus-SRCC.pdf] (accessed: 30th January 2024)

[9] Verkehrsverbund Oberelbe. “Vorbereitung des Einsatzes innovativer SPNV-Fahrzeuge im Lausitzer Revier” [online] Available at [https://www.vvo-online.de/doc/VVO-Broschuere-Alternative-Antriebe.pdf], 2021 (accessed: 30th January 2024)

[10] M. Hecht, “Hybridisierung - Etappen zum grünen Antrieb”. In “PRIVATBAHN MAGAZIN”, Bahn-Media Verlag, Suhlendorf, 2023, no. 1, 60 – 61.

[11] W. Klebsch, P. Heininger, J. Martin, “Alternativen zu Dieseltriebzügen im SPNV - Einschätzung der systemischen Potenziale”, VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V., Frankfurt am Main, 2019

[12] DB Regio AG, “Unter Strom – DB Regio rüstet Dieselfahrzeuge mit alternativen Antrieben aus”, Frankfurt am Main, 2018.

[13] DB Regio AG, “Biokraftstoff HVO” [online] Available at: [https://www.dbregio.de/innovationen/alternative-antriebe-kraftstoffe/hvo-alternativer-kraftstoff] 2023 (accessed: 30th January 2024)

[14] Freunde lateinamerikanischer Bahnen, “News Cuba” [online] Available at: [https://www.ferrolatino.ch/en/news/cuba/], 2013 (accessed: 30th Jan. 2024).

[15] Muromteplovoz, “Railway Bus«ALISA»” [online] Available at: [http:// muromteplovoz.ru/en/product/rail_alisa.php], 2016 (accessed: 30th Jan. 2024).

[16] Muromteplovoz, “Self-propelled and Non-self propelled Carriage SV-10, VS-5” [online] Available at: [http://muromteplovoz.ru/en/product/rail_sv10vs5.php], 2016 (accessed: 30th January 2024).
[17] Muromteplovoz, “Self-Propelled TrainSVg-10+VS-5+SVg-10” [online] Available at: [http://muromteplovoz.ru/en/product/rail_sv10vs5sv10.php], 2016 (accessed: 30th January 2024).
[18] Allianz pro Schiene e.V., “Elektrifizierung erklärt: Das Schienennetz muss unter Strom stehen” [online] Available at: [https://www.allianz-pro-schiene.de/themen/infrastruktur/elektrifizierung-bahn/], 2023 (accessed: 30th January 2024).
[19] B. Ebrecht, D. Bräuer, "Energetische Betrachtungen alternativer Antriebe in FBS," Eisenbahntechnische Rundschau, 2023, no. 3, 57 – 62.
[20] I. C. Zedlitz, “Ersatz für konventionelle Dieseltriebwagen mit kleinen Sitzplatzkapazitäten im schienengebundenen Personennahverkehr in Deutschland: Status Quo und Anforderungen an Fahrzeuge mit batterieelektrischem Antriebsstrang“, BSc Thesis, TU Berlin, Germany, 2023.
[21] Deutsches Büro zur Förderung von Handel und Investitionen in Kuba, “Factsheet Kuba - Dezentrale Energieversorgung mit erneuerbaren Energien inkl. Speicherlösungen” [online] Available at: [https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Kurzinformationen/Technologiefactsheets/2023/fs-kuba.pdf?__blob=publicationFile&v=3], 2023 (accessed: 30th January 2024).
[22] CR Technology Systems S.p.A. "N. 62 E-Houses 13.8kV and 34.5kV for electrical grid - Havana (Cuba)" [online] Available at: [https://www.crtsgroup.com/en/projects/62-e-houses-for-the-cuba-national-grid/], 2020 (accessed: 30th January 2024).
[23] Deutsches Büro zur Förderung von Handel und Investitionen in Kuba, “KUBA - Erneuerbare Energien und Energieeffizienz in der Lebensmittel- und Tourismusindustrie - Zielmarktanalyse 2018 mit Profilen der Marktakteure” [online] Available at: [https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Marktanalysen/2018/zma_kuba_2018_erneuerbare-energien-energieeffizienz-in-der-lebensmittel-und-tourismusindustrie.pdf?__blob=publicationFile&v=4], 2018 (accessed: 30th January 2024).
[24] Generator Source LLC, “List of Voltages & Frequencies (Hz) Around the World” [online] Available at: [https://www.generatorsource.com/Voltages_and_Hz_by_Country.aspx], 2023(accessed: 30th January 2024).
[25] L. Latozke, “Kuba kämpft mit Stromausfällen: Vierter Ausfall innerhalb von 10 Tagen” [online] Available at: [https://www.kubakunde.de/neues/kuba-kaempft-mit-stromausfaellen-vierter-ausfall-innerhalb-von-10-tagen], 2023 (accessed: 30th January 2024).
[26] Mondial21 e. V., “Energiekrise in Kuba: Stromrationierungen erreichen Havanna” [online] Available at: [https://amerika21.de/2022/08/259352/energiekrise-kuba-havanna], 2023 (accessed: 30th January 2024).