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Selection of energy storage systems for a special purpose rail vehicle based on simulation analysis

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The issue of power supply to electric rail vehicles leads to a separation of the rail network into electrified and unelectrified portions, where the sections lacking electrification exclude the operation of electric rail vehicles powered from the overhead lines. The potential solution to this problem was found in adding energy storage systems to electric rail vehicles to allow them some range of travel beyond the electrified lines. A simulation analysis of a special-purpose rail vehicle traveling across a non-electrified section of a railway line was conducted to assess the energy consumption rate and the necessary energy storage capacity. Three energy storage solutions were simulated, showing the travel range they can provide, with the aim of finding the lowest battery capacity solution that would still allow the vehicle to safely complete the simulated drive. The final selection of energy storage system capacity was done based on the assumed expected range outside the electrified railway weighed against the mass and cost of the extra energy storage system added to the vehicle. For a vehicle with a mass of 65 tons, a battery system with a capacity of 600 Ah was found to be sufficient.

Key words: *rail vehicle, energy storage, battery, simulation, drive system*

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1. Introduction

As countries continue to pursue increasingly more pro-ecological solutions for their industry in an effort to minimize their environmental impact, particularly their carbon footprint, solutions based on electrification have become the new goal [24]. This solution has not been widely adopted in road transport before. However, it has been widely present in the past for the rail transport sector [1]. The aspect of electrification of railway lines has been, so far, subdued in line with their perceived economic viability [19]. Due to the high cost associated with electrifying and maintaining electrified rail lines, conventional solutions based on combustion engines have been provided a wide range of applications for rail transport. This cost-to-value equation has changed with the increasing pressure to decarbonize the industry, however [2]. As a result, new solutions are needed to fulfill the role of the aging and replaceable conventional rail vehicles, especially given the increased focus on limiting the exhaust emissions and fuel consumption of rolling stock [6, 12, 14, 20].

In the case of Poland, the UTK (Office of Rail Transport) concluded in its 2022 report that a total of 17.6% of the total track length in Poland is prepared for travel at the speed of 160 km/h (15.5% at 120–160 km/h and 2.1% at speeds exceeding 160 km/h) [26]. Although new investments were expected for the year 2022, reaching the value of almost 11 billion PLN, a portion of which was to be spent constructing an additional 789 km of railway lines. In the year 2022, a notable lowering of the mean age of passenger rolling stock was observed. This was a reduction in mean age compared to 2021 for electric locomotives from 33.76 to 32.16 years, for diesel locomotives from 43.81 down to 41.94 years, and for EMUs from 25.79 to 24.43 years. The youngest group was the dual-drive multiple units, at a mean age of 0.82 years. This helps visualize the recent rise in popularity of dual-drive systems and other vehicles that are neither strictly diesel nor electric. A similar continued trend was observed for freight rolling stock, where the mean age of electric locomotives decreased from 36.57 to 33.82 years, while for diesel locomotives, the mean age lowered significantly from 38.31 down to 33.51 years. Most importantly, the report notes that about 62.5% of the total track length was electrified (12,126 km of track), leaving the remaining 37.5% (or 7267 km) non-electrified. This means that over a third of all track length in Poland did not have an overhead catenary. This poses a real problem in adjusting the plans of purchasing new rolling stock to the realities of the Polish railway network. Especially given the low rate of growth of electrified railway length in Poland. Between the years 2020 and 2021, it increased by just 210 km (from 11,946 km to 12,156 km).

Since the easiest solution, of buying more conventional vehicles to replace the old ones, would stand in conflict with the environmental goals set by most developed countries, other solutions need to be considered. This problem could be solved by simply expanding on the already existing solutions, such as electric vehicles driving on electrified railway lines. This, however, would require substantial investment in infrastructure improvement. In order to avoid the costs of electrification where possible, the concept of a battery powered rail vehicle was introduced. It is a solution that allows a rail vehicle to partially or temporarily operate outside of the overhead power network using its onboard energy storage systems [7, 17]. This has often been introduced in parallel with other solutions based on ultracapacitors or hydrogen fuel cells [16]. Many solutions for locomotive energy storage systems have been proposed. Spiryagin et al. have concluded that a flywheel system in a diesel locomotive could reduce fuel consumption in heavy haul operations by as much as 12.4% [22]. For light rail systems, Gee et al. predicted a flywheel solution to offer energy savings of 21.6% [10], while Rupp et al. estimated 31% [18]. Despite these results the flywheel technology has many limitations and, along with the further development of battery technology, seems to be increasingly less competitive to battery solutions, as noted already back in 2015 by Spiryagin in [21]. As a result, battery-based energy storage was considered the more modern solution. The addition of a battery energy storage system on rail vehicles opens the option of also integrating supercapacitors into the system to allow for braking energy recovery. The energy loss on braking represents a large energy waste in rail transport. Many studies have been performed, claiming various levels of efficacy of such a solution. Mayet et al. claimed a 25% fuel consumption reduction when using a battery/supercapacitor energy storage system in a diesel-electric locomotive [13], while Steiner et al. from Bombardier have recorded 30% energy traction savings in a light rail vehicle using a similar system [23]. Teymourfar et al. reported an even greater 44% energy savings for a stationary supercapacitor system on a metro line [27]. Despite all of these encouraging results, supercapacitors remain heavy and expensive, thus making their use more feasible in power substations and stationary systems rather than mounting them onto rail vehicles themselves. Ultimately, creating Multi-Purpose Vehicles (MPV) that don't rely primarily on a diesel engine has proven difficult. Some examples do exist, such as the first fully electric MPV operating on Citybanan in Stockholm created by company Railcare AB.

The solution discussed in the article is that of a special-purpose rail vehicle, designed for track maintenance, equipped with a diesel engine and a lithium-ion battery system that enables it to travel through non-electrified sections of railway lines. This is done to effectively extend the vehicle range beyond the electrified portions of the rail network. Effective use of such a power supply system in rail vehicles can result in a significant reduction of its carbon footprint while eliminating its exhaust emissions [4]. The selection of the technological solutions and devices that are to provide this ability is a key factor in increasing the overall efficiency of rail vehicles. These solutions, the type of energy storage systems used, their capacity and properties, energy recovery systems [15], and additional safety systems all need to be selected with the expected parameters in mind, as well as the intended type of operations the vehicle is to be used for. This can prove particularly difficult for MPVs, as they are often expected to perform a diverse range of tasks. Depending on the solution and technology used, further optimization of energy management (called the Energy Management Strategy or EMS) can further magnify the benefit of the chosen technological solution [5, 11]. This further complicates attempts to assess the overall vehicle efficiency or energy consumption. Furthermore, optimization of the overhead supply system, the substations, timetable organization, and driving speed [9] can also significantly impact the potential level of energy consumption of rail vehicles and maximize the efficiency of braking energy recovery up to even 95% [28]. Unfortunately, these solutions each come with their own drawbacks, whether in the form of additional mass or increased cost. This means that whatever solutions are considered for any given vehicle should be highly contextualized and specific to that vehicle's expected operating conditions and types of tasks performed. Minimizing the cost and size of newly added technological solutions is the key aspect of finding the right balance and maximizing vehicle efficiency.

Increasing the efficiency of rail vehicles is additionally helpful in fulfilling the goals of the Green Rail program (Zielona Kolej), which aims to reduce the CO_2 emissions of rail transport by 85% by the year 2030. It's initiatives like these that promote the development of new energy-saving and energy-recovery technologies while also promoting the use of electric drive systems in rail vehicles to be powered by renewable energy. Similarly, the rail infrastructure is also planned to be modernized. Aiming to increase the total length of electrified railway lines to 14 000 km by 2030. Thus increasing the total share of electrified lines from 62.5% in 2020, to over 72% by 2030. This would classify Poland as the European country with the 7th highest share of electrified railway length, behind Bulgaria at 74.4% and ahead of Austria at 71.9% (as of 2021) [26]. Due to its decreasing ecological impact, rail transport could significantly contribute to reducing greenhouse gas emissions whenever rail is chosen as the transit method instead of road transport. The same report estimated that in 2022, about 342.2 million passengers contributed to reducing CO_2 emissions by 2.6 million tons by opting to travel by rail instead of using road transport. Further electrification of railway lines, along with the modernization of the rolling stock operated, especially for vehicles in the dual drive or electric categories, should lead to steady improvement in the environmental impact of human transport activities.

2. Aim

The main goal of the article was to assess the necessary energy capacity of an on-board battery system for a proprietary special purpose vehicle. The new vehicle was designed as part of a project to be an innovative special hybrid drive MPV improved with independent power storage designed to transport equipment for the construction, diagnosis and measurement of rail infrastructure. The vehicle was expected to have three independent drive systems: a catenary line, a battery system, and an emergency power generator. It should reach a travel speed of 160 km/h with a catenary line power supply. In case of grid failure or lack of catenary lines, it could use its batteries, which can be charged from catenary lines while driving or from a charging station when parked. The main advantages of the vehicle include being able to operate with zero-emissions and a functional braking energy recovery system. The energy is to be stored and used for propulsion to prolong its operation supported by power supplied by batteries. One of the key assumptions of the designed vehicle was to ensure it could travel at a speed of 60 km/h for at least 30 minutes powered by its battery systems alone. This was to ensure emission-free transit from one work location to the next, irrespective of whether the line is electrified or not. Assessing the viability of meeting all the goals and assumptions for the prospective vehicle required a number of tests and simulations. 3 drives were simulated for different variants of the vehicle. These variants were based on the energy storage capacity of the on-board batteries. The battery system was a set of 4, 6, or 8 batteries for each of the 3 variants, respectively, where each battery had a capacity of 100 Ah, nominal voltage of 666 V DC, max. voltage of 770 V DC, charging current of 80 A, discharging current of 100 A, and a nominal energy of 66.6 kWh.

3. Data and methods

The theoretical test drive was designed based on a proprietary program created in the Matlab environment described in this section. To solve the vehicle motion equation, the program operated using the vehicle characteristics, the route profile data, the speed limit, and the timetable as input provided by the user. The simulation relied on the CBTK formula for multiple units and the Röckel formula for calculating the resistance in the track curvature in a similar process as described in previous research [3]. The intended vehicle specifications were also listed (Table 1), and the selection and implementation of its drive system was discussed in previous research [8, 25].

Table 1. The target technical specification of the proposed 501EH vehicle

Parameter	Value
Service mass	65 t
Max. speed (self-propelled)	160 km/h
Tractive power	65 kW electric motor; 340 kW combustion engine; 100 kWh batteries
Max track gradient	30‰
Gauge	1435 mm
Max track cant value	180 mm

The three performed simulation drives were labeled as drives 1, 2, and 3 for the three vehicle variants having 400 Ah, 600 Ah, and 800 Ah capacity battery systems, respectively. The three battery sizes were selected based on the assertion that the battery's reserve energy should not drop below 300 kWh. Thus the first variant used was given a battery system with only 100 kWh excess power to use, which was shown to be the approximate power needed to travel the distance, based on preliminary calculations. Further variants had their battery capacity increased in 200 Ah increments. The route selected was based on the driving profile of a real rail line often used for testing, which included slope, stops, and a gap in catenary in between for a length of 30 km of track out of the total of 40 km (Fig. 1). The selection of the size of the battery system was to be based on which smallest battery system was able to meet the requirements set for the new vehicle in the project, while ensuring that the vehicle still operates effectively. The general problem was to assess the tradeoff between a larger energy storage system with greater capacity and range, and reducing the vehicle curb weight and cost as much as possible. Simulation tests were used to measure several parameters, such as: vehicle speed, vehicle acceleration, power at the wheels, sum of motion resistances, main circuit power, energy flow through the pantograph system, energy balance at the battery system, battery state of charge (SoC), and traction force for each of the tested vehicle variants. The simulated system was described in block form (Fig. 2) using known properties and parameters of the systems and devices used in the design. This assumes inverter efficiency of 98%, transformer efficiency of 98%, and traction engine efficiency of 94%. The battery system was assumed to have a 92% overall efficiency of charging and discharging for the purposes of the simulation. It should be noted that the choice of battery system brand and type may cause these parameters to vary.

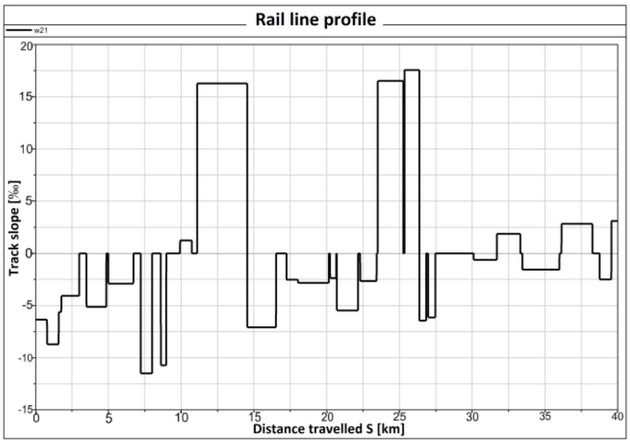

Fig. 1. Track incline profile for the test route

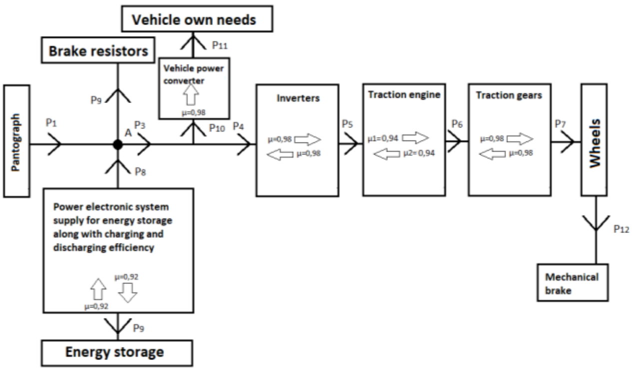

Fig. 2. Schematic of the energy flow in the vehicle drive system

4. Simulation results and discussion

The obtained results indicated that while even the lowest capacity battery system (of 400 Ah) could successfully travel the required 30 minutes at 60 km/h, the depletion of the battery SoC had a more significant impact on the available power output, thus affecting the vehicle traction properties (Fig. 3). This can be seen in the greater values of Power generated at the wheels for drive 3 as compared to drive 1, which also resulted in the motion resistance peaks correlating with uphill climbs to be shorter, as they were being overcome quicker. This also reduced the overall drive time from about 44 minutes for drive 1 down to about 41 minutes for drive 3. It was found that the minimum amount of battery energy needed to travel the 30 km distance without overhead supply was slightly less than 100 kWh for the simulated track profile (Fig. 4). For each of the drives the battery system expended the necessary energy to arrive at the other side of the non-electrified track section, and began to draw power from the overhead catenary again once it became available. This was in line with the expectations, as the vehicle was to be able to recharge purely from the catenary-supplied power. The rate of power drawn and used need to be monitored by the BMS, so as not to overheat or overload the batteries. This was the side effect of deciding to forgo using supercapacitors for their ability to rapidly store large quantities of charge and equally rapidly release that charge when needed. It was decided that batteries alone, although less effective in that regard, would suffice if properly managed.

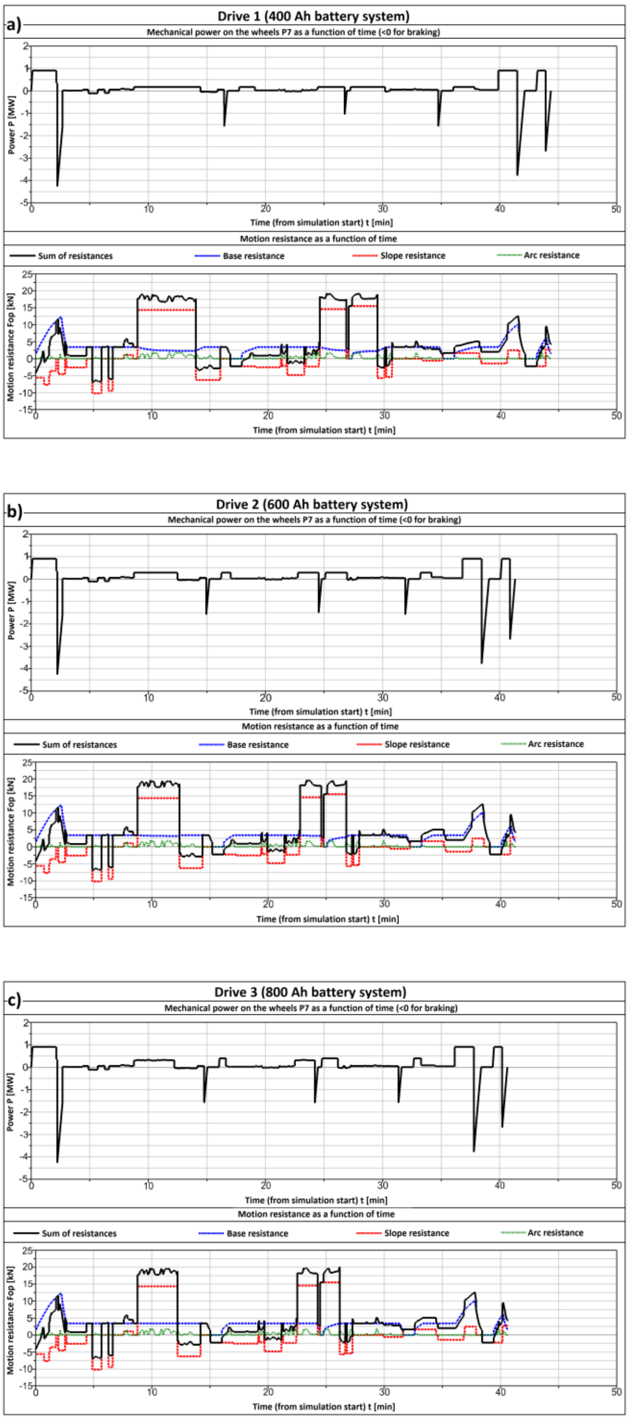

Fig. 3. Vehicle power at the wheels and movement resistance of the simulation drive for each vehicle variant: a) drive 1, b), drive 2, c) drive 3

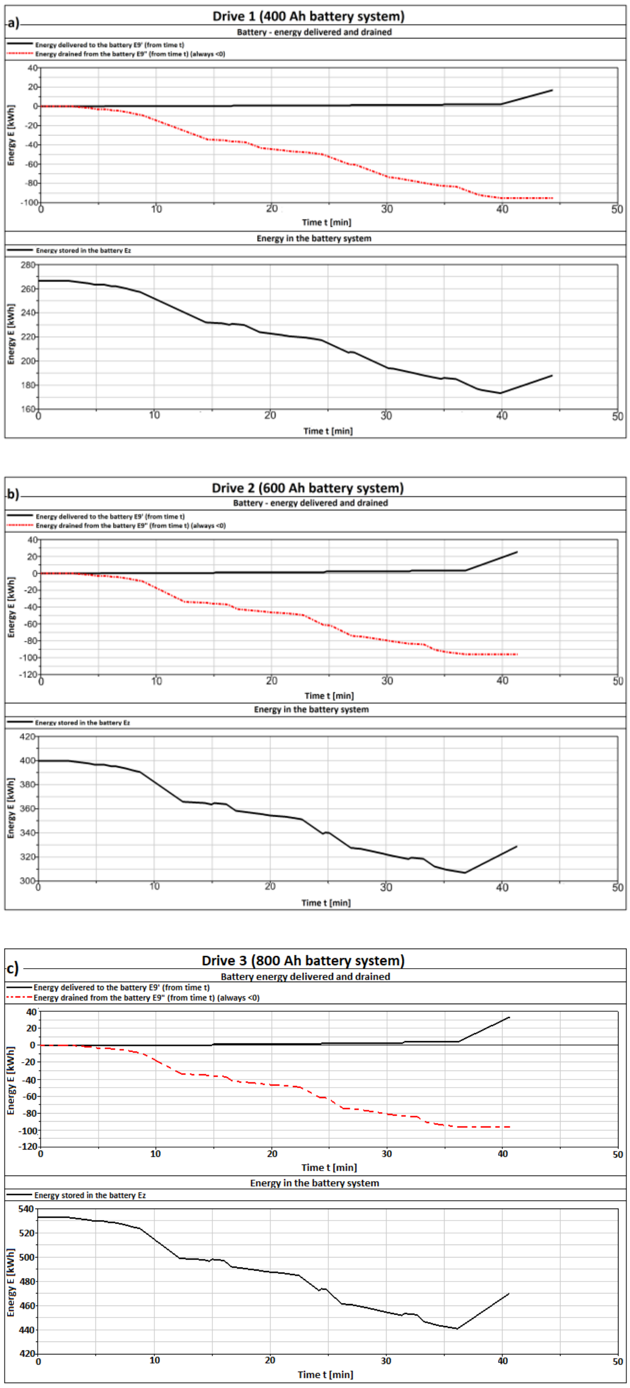

Fig. 4. Energy storage system state of charge and Energy depletion in the simulation drive for each vehicle variant: a) drive 1, b) drive 2, c) drive 3

It should be noted that in each test case the vehicle batteries started fully charged (with ~67 kWh of energy per battery), at approximately 465 kWh for 4 battery system, 400 kWh for the 6 battery system, and 530 kWh for the 8 battery system. This will not necessarily be the case in real operation, as keeping the batteries at full charge most of the time can accelerate their degradation. A proper BMS could be integrated with the rail network information to enable the vehicle to predictively charge up the batteries before their full charge is needed while still driving through an electrified rail section. The total energy used to travel the simulated distance was about 150 kWh. Each vehicle variant drew approx. 100 kWh of energy through the pantograph and returned over 10 kWh from regenerative braking. The mechanical power peaks when driving without an overhead power supply were flatter and smoother for variant 1 (400 Ah) while being higher and more rugged for variant 3 (800 Ah). Each vehicle managed to reach its peak driving speed of 160 km/h before slowing down to 60 km/h for the unpowered section of the track. Stops were added to simulate waiting time on crossings or switches (Fig. 5).

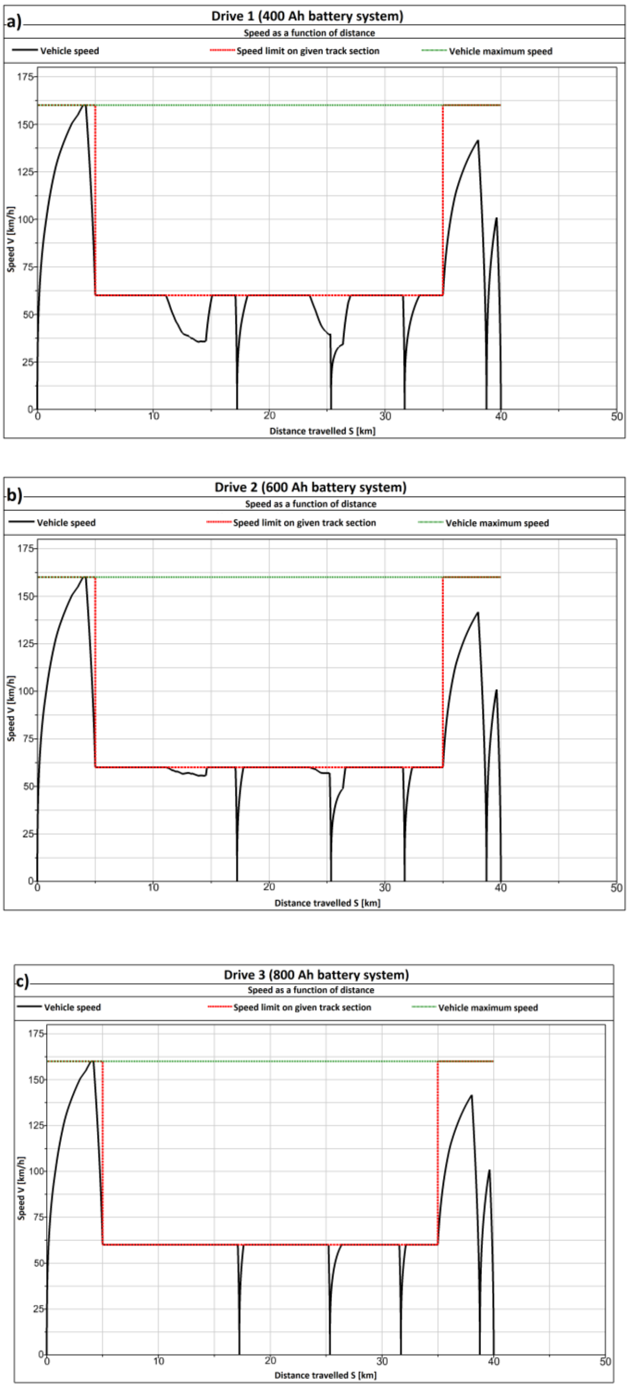

Fig. 5. Vehicle speed profile for the test route using each vehicle variant: a) drive 1, b) drive 2, c) drive 3

The obtained battery charge values at the end of the simulated drives show sufficient charge for continued driving and operation without the overhead power supply. Thus, the total remaining charge in the batteries was not the limiting factor on its own. However, due to the properties of battery systems the available power was affected by the battery SoC. It was therefore necessary to account for the drop in available traction force as the battery charge decreases due to basic battery current-voltage characteristics. This effect could be observed by the deeper drops or slower increase in vehicle speed for sections where the simulated track had an upwards slope. Especially for the section between the 10–15 km distance from the start point, where the train encountered an upwards climb, presenting an unintended drop in travel speed (Fig. 5a and 5b). This effect was not observed for the vehicle variant 3, equipped with the highest capacity battery system of 800 Ah (Fig. 5c). Thanks to the higher power reserve, and a batter response to the sudden power demand despite some energy depletion on the batteries, such drops in speed can be mitigated to a point where they are no longer noticeable. Although it is not always a significant enough issue to warrant the extra weight and cost of more batteries.

While a momentary drop in travel speed is unwanted, it is to some degree unavoidable. It was noted that vehicle variant 2 experienced a travel speed decrease of less than 5 km/h, which was deemed acceptable given the nature of the vehicle operation. Vehicle variant 1, on the other hand, was shown to significantly lose speed on the climb (decrease of over 20 km/h). Such a drop in speed can be noticeable and may cause unnecessary delays in how the vehicle performs its designated tasks. Ideally, the slowdown would not occur, such as in the case of variant 3, where the large reserve power still held by the 8 batteries was sufficient to ensure full tractive force.

Conclusions

The obtained power characteristics on the vehicle wheels indicated that the lower capacity battery system, while having sufficient energy to support the whole test drive, could not provide the power needed to safely travel the whole distance without a notable drop in speed. Such a situation was deemed dangerous, especially in the potential case of a track with a more significant slope. Vehicle speed curves show a drop in speed for variants 1 and 2 after 10 minutes of driving, where the track meets an incline of over 15‰. While variant 2 did not slow down more than 5 km/h, variant 1 slowed down by 25 km/h (down from 60 km/h), and variant 3 was unaffected. This was mostly caused by the drop in usable power due to the lower battery charge and the associated voltage drop as the on-board battery system charge level was drained when traveling. Variant 1 was deemed insufficient in order to ensure smooth travel on hilly terrain. Hence the lowest capacity battery system needed in such a vehicle was concluded to be 600 Ah, as tested for vehicle variant 2. The vehicle should be able to climb an incline of 15‰ without significant loss of speed even after its batteries were drained by driving for 30 minutes. This also ensures a sufficient battery capacity to support track operations after the vehicle arrives at its destination. Ideally the incline could be overcome with no loss of speed, but this was only possible for variant 3, with the highest reserve power thanks to its 8 batteries. Such slowdowns may be unacceptable for passenger rail vehicles, as they are jarring to the passengers on board, however, sue to the nature of the tested vehicle's operation, the result obtained for variant 2 was deemed acceptable. An MPV does not necessarily need to provide a completely smooth drive, and most of its work is expected to be performed while either stationary or moving at a low steady speed. Each of the tested variants used up 100 kWh of energy on the 30 km long non-electrified section of the track while also recovering about 10 kWh of energy back using regenerative braking. This means that the total effective vehicle range without power supply was approximately 10% greater than estimated, thanks to the energy recovery from braking.

Further research is planned using a real vehicle prototype, to validate the obtained results. Such validation should be performed in the form of a real drive on a selected rail section. It should be noted, however, that the chosen battery management system (BMS) is expected to have a significant effect on the obtained results, as well as any energy savings. The BMS defines how effectively the energy storage system is operated, while the EMS determines the overall energy use efficiency in the vehicle. Thus, the proper adjustment of these management systems will play a key role in increasing the efficiency of the vehicle drive system. Such solutions are especially important in order to ensure steady and stable operation of the entire energy storage system, as well as to monitor its operating parameters to prevent excessive heating or overloading. Another aspect would be predictive charging, which should prevent the vehicle from regularly moving on electrified railway lines with fully charged batteries. For longer term, modern lithium-ion batteries prefer to be kept at SoC at no greater than 80%. Hence the need to predict when a fully charged battery may be needed and charge it up while on the way to the non-electrified track section, or work location.

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Nomenclature

BMS	battery management system
DC	direct current
EMS	energy management strategy
EMU	electric multiple unit
MPV	multi-purpose vehicle
SoC	state of charge

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