Efficient Energy Management for Onboard Battery-driven Light Railway Vehicle

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Abstract

With the requirements for reducing emissions and improving energy or fuel economy, railway industries and researchers are focusing on developing battery powered LRT without overhead catenary wires. The battery-driven railway vehicles enable to recover braking energy while operating catenary-free sections. Therefore, a sophisticated energy storage system and appropriate battery-powertrain management are essential for obtaining the highest possible reduction of greenhouse gas emission and energy consumption and at the same time an increase of the vehicle performance. In this research, architecture of power electronic subsystems including onboard battery energy management is described. In addition, the advanced electrical eco-driving architectures to meet the demands for increased electric loads are analyzed and implemented. The requirements of power electronic components and battery management are presented by using a battery-driven LRT model under development. Finally, proposed eco-driving control strategies and performance evaluation with the sophisticated energy management are verified through simulations.

Keywords: Energy management, Energy efficiency, Battery, Light Railway Vehicle,

Introduction

With recent issues of global warming, greenhouse gas emission, and depleting energy resources, relatively high energy efficiency of rail transport is one of the greatest advantages, especially in view of the requirements of the Kyoto Protocol concerning the emission of carbon dioxide. Nevertheless, railway transit systems have still undiscovered potential for improving the energy efficiency even farther, and one which directly correlates to reduced emissions. Development of next generation railway vehicle with onboard energy storage capability can offers a significant reduction in energy consumption compared to conventional electrified train with overhead power feeding system. Moreover, improvement of energy efficiency through systematic and operational optimization can be another aspect to further improve the efficiency of railway energy[1].

For the better energy efficiency of railway vehicles, there is also the possibility to equip the vehicles with an energy storage system, such as rechargeable batteries[2], electric double layer capacitors (EDLC)[3], fuel cells[4] or flywheels[5,6]. Onboard energy storage system can provide up to 30% energy saving effects by restoring regenerative energy during braking and preventing regeneration cancellation problem of conventional railway vehicles. In addition, rapid development of the onboard energy storage system enables catenary-free operation of emerging railway vehicles. Therefore, many railway industries have recently developed energy efficient LRVs with onboard energy storage system. The various catenary-free LRVs are summarized in Table 1 and described as follows:

Bombardier has recently developed the Primove system that enables its Flexity tram to operate catenary-free over varying distances including on contactless power transfer buried in the ground. Its electric supply components are invisible, hidden under the vehicle and beneath the track. The Primove system uses the MITRAC energy saver that stores the energy released each time a vehicle brakes and improves the efficiency of operational energy consumption with the ultracapacitor-based storage unit. The Primove system also provides energy management control system that integrates energy awareness, efficiency and carbon control into an operator’s business[7].

Alstom has applied a ground-level power-supply system (APS), a third rail embedded among the tracks, for their Citadis trams. The APS ground-level power supply system allows trams to travel without overhead catenaries, and integrate harmoniously into the urban landscape. However, the main concerns of this system is to preserve the urban environment and the region’s historical heritage, but not to focusing improving energy efficiency. Moreover, the APS are rather expensive, at least more than a catenary-based powering system[8]. Ansaldo STS in Italy is currently offering similar ground power supply technology for light rail applications.

Kawasaki Heavy Industries in Japan has tested a next-generation LRV, called SWIMO (Smooth WIn Mover)[9]. The SWIMO is an articulated three-car, 15m long tram. Powered by the Gigacell, Kawasaki's proprietary nickel metal-hydride battery, it can operate over 10 km without additional charging. Alstom also applied their battery-powered LRV to the Citadis series and started its operation at Nice in 2007.

The Railway Technical Research Institute (RTRI) in Japan has also produced a hybrid LRV called Hi-Tram, which can be operated with or without use of an overhead or third feeder rail. The Hi-Tram can operate on both 1500VDC and 600VDC from the pantograph or on a 600VDC lithium-Ion battery[10]. This system can also reduce energy consumption as well as CO_2 emissions by activating regenerative braking technology and efficient energy management with onboard rechargeable batteries.

In addition, CAF in Spain has been developing its rapid charge accumulator (ACR) catenary-free system and Siemens has developed Sistras HES hybrid energy storage system that combines a double-layer capacitor with a Ni-MH traction battery.

Table 1 Various catenary-free or battery-powered LRVs

Developers	Vehicles	Energy Sources or storages	Characteristics
Alstom	Citadis	, Ni-MH Batteries	Ground-level power-supply system
Bombardier	Primove	MITRAC energy saver (Ultracapacitors)	Contactless power supply system
RTRI	Hi-Tram	Li-Ion Batteries	Contact-wire/battery hybrid LRV
Kawasaki Heavy Ind.	SWIMO-X	Gigacells (Ni-MH batteries)	Onboard battery powered LRV
Siemens	Sistras HES	Double-layer capacitor and Ni-MH battery	Hybrid energy storage system (DLC and Ni-MH)

Besides the development of energy efficient vehicles, mature technology for more energy efficient vehicles includes use of permanent magnetic motors, design of minimal aerodynamic resistance train, reduction of weight, and thermo efficient design of HVAC systems. While the improvement of vehicle technology takes time and cost in general, systematic and operational approaches can provide the greatest effects on improving energy efficiency. These systematic and operational methods include intelligent train control and optimized energy management system. In particular, LRVs with onboard battery are very limited to its power source. Without optimized management of the limited energy sources, the newly developed LRV will limit operational range of catenary-free section and its performance. Therefore, this research investigates architecture of energy management system by introducing a new onboard battery-powered LRV. In addition, strategic logic to maximize the driving distance with a limited energy storage system has been examined.

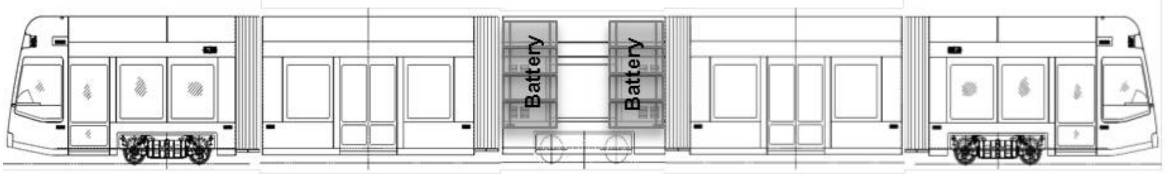
Onboard battery-powered LRV

Similar to many other onboard battery-powered LRVs, Korea Railroad Research Institute has been developing a new low-floor LRV with onboard rechargeable battery packs that enable running of the vehicle without use of overhead catenaries. The vehicle is equipped with newly applied lithium-polymer batteries as rechargeable energy storage device.

As summarized in Table 3, the battery-driven LRV is 31.2m long with five-car body and three-bogie low- floor articulated. The lithium-polymer rechargeable battery packs are positioned in the middle car. A major feature of the vehicle is that it can cover up to 30km running catenary-free section after a full charge of onboard batteries, which enables environmentally friendly operation with a high level of energy efficiency and a low level of CO2 emissions consequently. The vehicle recycles the regenerative power during braking and utilizes the energy stored in the battery as a power supply to drive the traction motors at starting or to power the auxiliary equipment. In addition, the vehicle can receive power from the overhead lines when it operates on the electrified sections with overhead wires.

Table 2 Specifications of the vehicle

Items	Specification
Structure	5-carbody, 2 motor bogies and 1 trailer bogie
Dimension	31.2m(L) x 2.45m(W) x 3.4m(H)
Floor height	320mm
Passenger capacity	Max. 200
Weight	32 ton
Power source 1	Lithium-Polymer rechargeable battery (144kwh)
Power source 2	750VDC from overhead wire (if needed)
Traction motor	45kW induction motor x 4 units/bogie
Acceleration	Over 2.5km/h/s
Max speed	70km/h
Braking	3.5km/h/s or 6.0km/h/s for emergency



Battery driving system

Figure 1 illustrates four steps of driving system with onboard battery-powered driving system in general. When the pantograph is in its up position at stops or stations, the system uses power to charge the batteries from the overhead lines and extra power is used to operate the auxiliaries such as HVAC systems and electric doors. When the pantograph is in its down position during operation at catenary-free sections, the battery bears all power loads of the vehicle. For acceleration or boosting, the batteries supply power to the traction motors and auxiliary equipment. In particular, the battery power is efficiently managed to minimize energy during coasting operation. When the vehicle brakes or decelerates during stopping, the power system charges the battery with regenerative energy released from its traction motors. The powering system in the LRV consists of up/down converter, inverters to control the connected traction motors, static inverter to control auxiliary components including HVAC and doors, and modular battery packs.

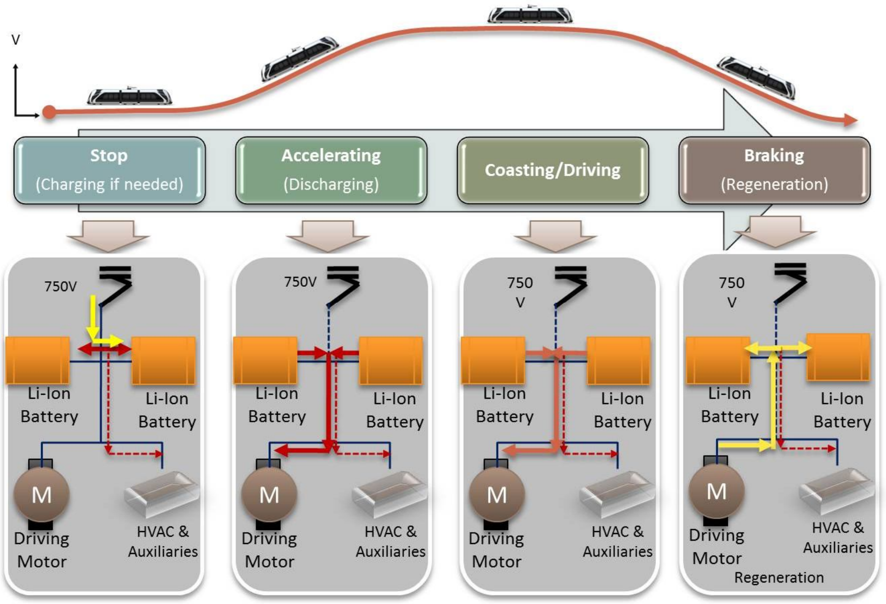


Figure 1 Operational steps of onboard battery-powered LRV

Onboard energy storage

Compared to lithium-ion batteries introduced for recent railway vehicles, the lithium polymer batteries (LPB) have less internal resistance, higher charge and discharge rate, no memory effect, longer life than those of other rechargeable batteries. In particular, the LPB applied in this system has the highest energy density among the rechargeable batteries previously applied for competitive LRVs.
The LPB battery system in our LRV contains two modular sets of pack. One LPB set consists of a series of 192 cells and a parallel of 8 cells for high energy capacity and voltage range. One battery set also consists of two column packages which are connected in series. Each battery column composed of a parallel of 8 cells and a series of 96 cells. The system weighs less than 2,000 kg including housing, frame, and cooling system.

The battery management system (BMS), which monitors the voltage, current, and temperature of each cell and adjusts any voltage imbalance among them, can help to improve the reliability of the powering system. Brief specifications of the LPB under development are summarized in Table 3.

Table 3 Specifications of lithium-polymer battery under development

Components	Specifications
Configuration	3072 Cells (8P-192S per set)
Energy density	150Wh/kg
Weight	<12000 kg (including housing and cooling system)
Type	Lithium-Polymer rechargeable battery
Energy capacity	150 kwh
Capacity (C)	15Ah
Nominal voltage	614V
Rated voltage	528V(min. discharging voltage) ~ 806V(max. charging voltage)
Max. power	530kW (discharging), 587kW(charging)

Energy Management System

With the very limited energy source from the lithium-polymer batteries, it is essential to implement efficient energy management system (EMS). The EMS controls energy flows between energy sources, mainly in batteries, and energy loads as shown in Figure 3. Key features of the EMS include: (1) monitoring battery status, e.g. charging/discharging level, health of batteries, (2) coasting and coordinating train trip conditions, e.g. boosting/stops and gradient of tracks, (3) managing auxiliary components consuming energy, e.g. HVAC control, opening/closing doors, indoor lighting controls, (4) reducing peak power consumption to avoid irregular power breakdown of train, (5) exchanging driving information between driver’s control panel and traffic control center.

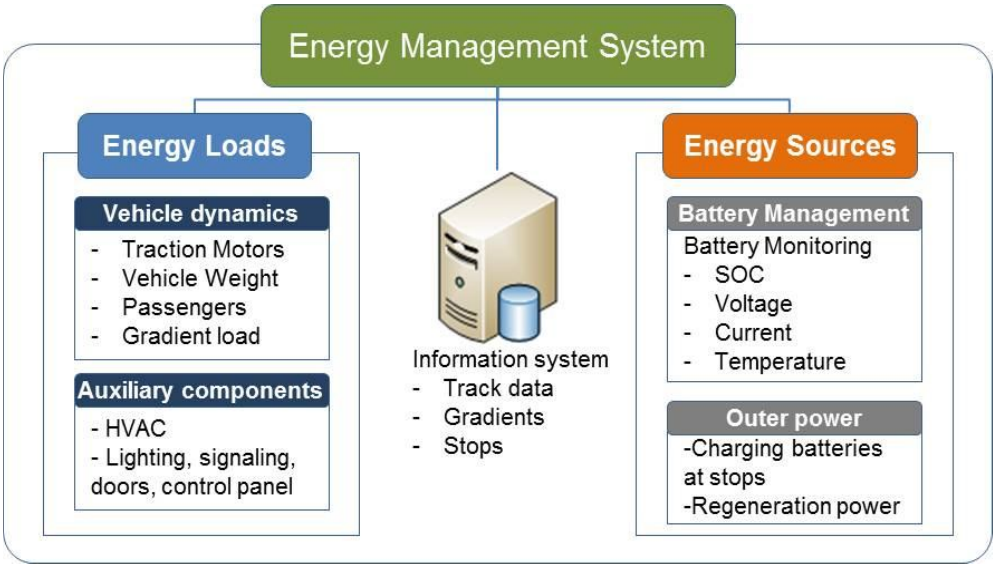


Figure 2 Structure of energy management system with power sources and sinks

As a part of energy sources, batteries play a major role as only energy source in the battery-powered LRV operation. Driving conditions can be systematically changed upon the status of batteries. A Key feature of the battery management system (BMS) is to decide the state of charge (SOC) of batteries which is dependent on voltage, current, resistance, and temperature of battery cells.

Battery management

The BMS works in real time in rapidly changing charging and discharging conditions as the vehicle accelerates and brakes. Thus, the BMS incorporate more vehicle functions than simply managing the battery. It can determine the vehicle's desired operating mode, whether it is accelerating, braking, or stopped, and communicate with the train energy management system.

As a part of energy management system, main objectives of the battery management system include a)protecting the cells or the battery from damage, b)prolonging the life of the battery, and c)maintaining the battery in a state in which it can fulfill the functional requirements of the LRV operation.

(a) Cell protection: monitor and control to protect the cells from out of tolerance ambient or operating conditions, e.g., turn on the cooling fans if the battery overheats.
(b) State of charge (SOC): monitor and calculate the SOC of each individual cell in the battery to check for uniform charge in all of the cells. The SOC can be estimated from various methods such as open circuit voltage, coulomb counting (current integration), and internal impedance. As the most practical method, however, we have applied a look up tables constructed from measured data from actual cells. Also, we have implemented the current integration or accumulation method.
(c) Operating range setup: under normal operational requirements for the LRV, maintain the SOC between 30% and 80%, which allows both high power capabilities for regenerative braking and high power discharge capabilities for boost. Over discharge of battery could shorten the life of the battery and full charge would diminish charge acceptance capability for regenerative braking.

Driving power control

Coupled with the battery management strategies, the vehicle driving control method for the battery-powered train was developed to ensure the operation of the vehicle delivered high energy efficiency and also maximized driving distance. The control method adopted is shown in Figure 1 and explained as follows.
(d) Departure and powering: at pull away from rest, when the train is in a boosting mode for acceleration, use battery to power the vehicle; minimize the use of battery to supply auxiliary demands.
(e) Coasting: when the battery is not empty, use battery to supply the auxiliary demands; when the SOC of battery is below the 30% or nearly empty, reduce the use of battery power in supplying auxiliary demands except unnecessary ones.
(f) Braking: using the regenerative (electric) brake to decelerate the vehicle, the regenerated energy is used to charge the battery and supply auxiliary demands, e.g. maximum HVAC operation.
(g) In station/idle: when the train is stopped in a station where the charger is implemented, recharge the battery until it reaches a full SOC and maximize the power supplement for auxiliary demands. If the train stops at a signal or in a station without any charging facilities, the battery is in an idle without feeding power to any demands.

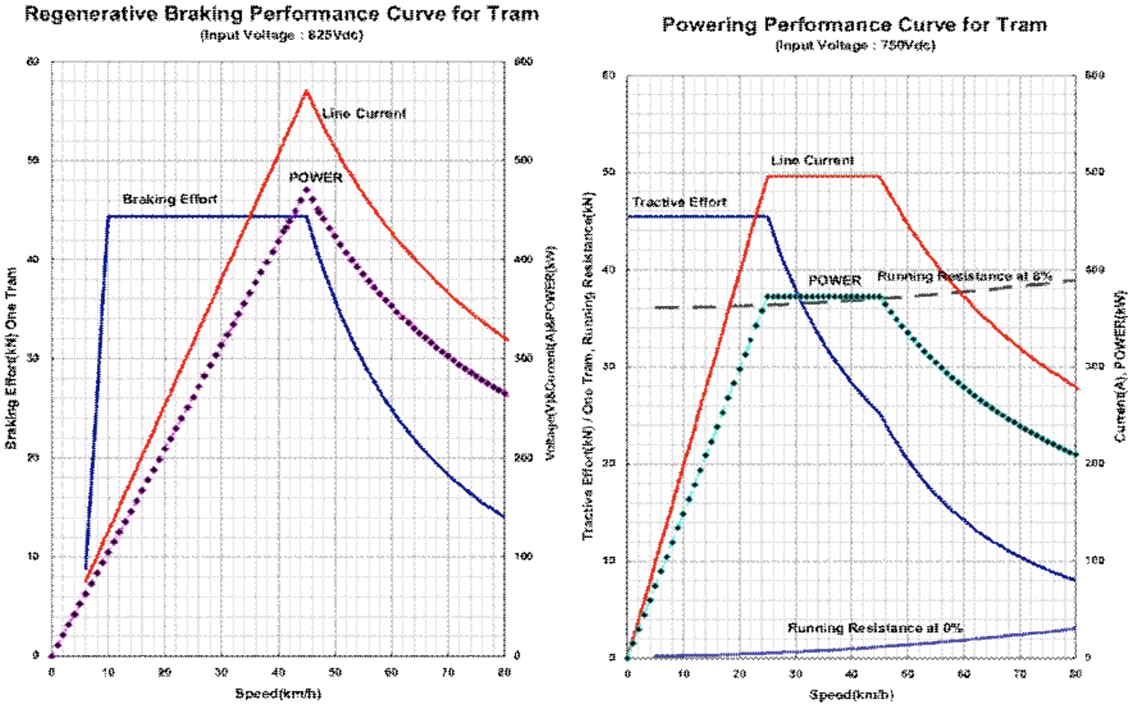
This driving power control cycle repeats until exhausting energy stored in battery.

Auxiliary components power control

Among many auxiliary components in the train, the heating, ventilation, and air-conditioning unit (HVAC) is a major target component to manage its use of energy. In spite of the limited onboard battery energy, the catenary-free LRV also requires adequate air conditioning, something which greatly increases their total energy consumption. Especially in the winter months, the energy requirement for auxiliaries such as heating, ventilation and lighting exceeds the amount of traction energy. Simulation results of operational power consumption in the next section also indicate that power consumption for HVAC operation is over 30% of vehicle driving energy consumption during regular operation. Therefore, energy management system has to include the thermal isolation of car bodies and window glasses as well as in reducing unnecessary door openings. By adjusting load of HVAC upon vehicle conditions, e.g., door opening/closing, number of passengers, and battery SOC, the Intelligent HVAC control in the EMS can save overall energy consumption by at least 10%.

Performance evaluation

With the onboard battery-driven LRV model described in this paper, various simulations have been conducted to verify the performance of the vehicle. The Figure 3 shows simulation results of vehicle power requirement both in boosting and regenerative braking. The line current is reference power requirement when the vehicle uses overhead catenary. Tractive effort is power of traction motors by discharging onboard battery and the braking effort is regeneration power that can charge the onboard battery.



(a)

(b)

Figure 3 Power curves of tractive efforts in LRV, (a) powering performance, (b) regenerative braking performance

Based on the performance of traction motors installed in the vehicle, overall energy requirement during actual operation has been simulated with an actual track profile including gradient, curvature, stations, and so on. For the vehicle model, fully loaded 46 ton of vehicle, 750VDC of boosting voltage, 825VDC of regenerative voltage and 72 kVA auxiliary power unit have been used. Detailed specification of the vehicle can be referred from the table 2 and 3. For the track profile,11.4km including 13 stations of LRV track in Seoul, Korea has been used. Based on the speed profile, power requirement results in Figure 4.

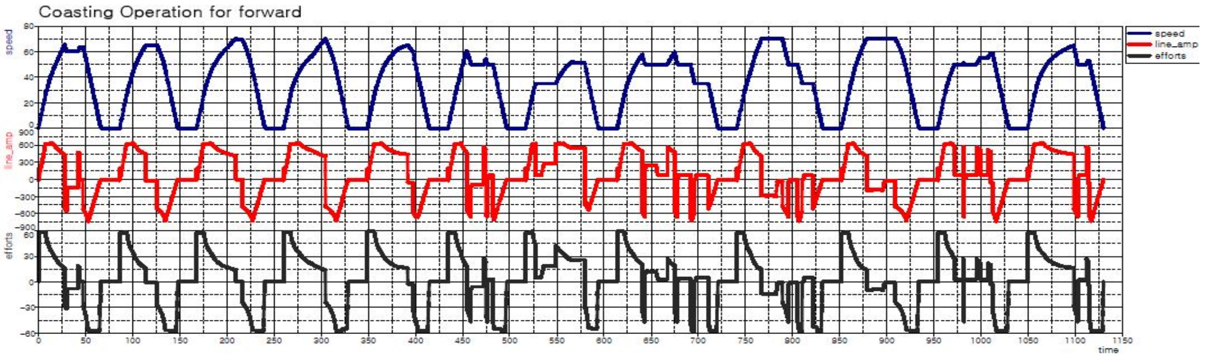


Figure 4 Power required in running the LRV [speed profile (km/h), line current (Amp), Traction power (kw)]

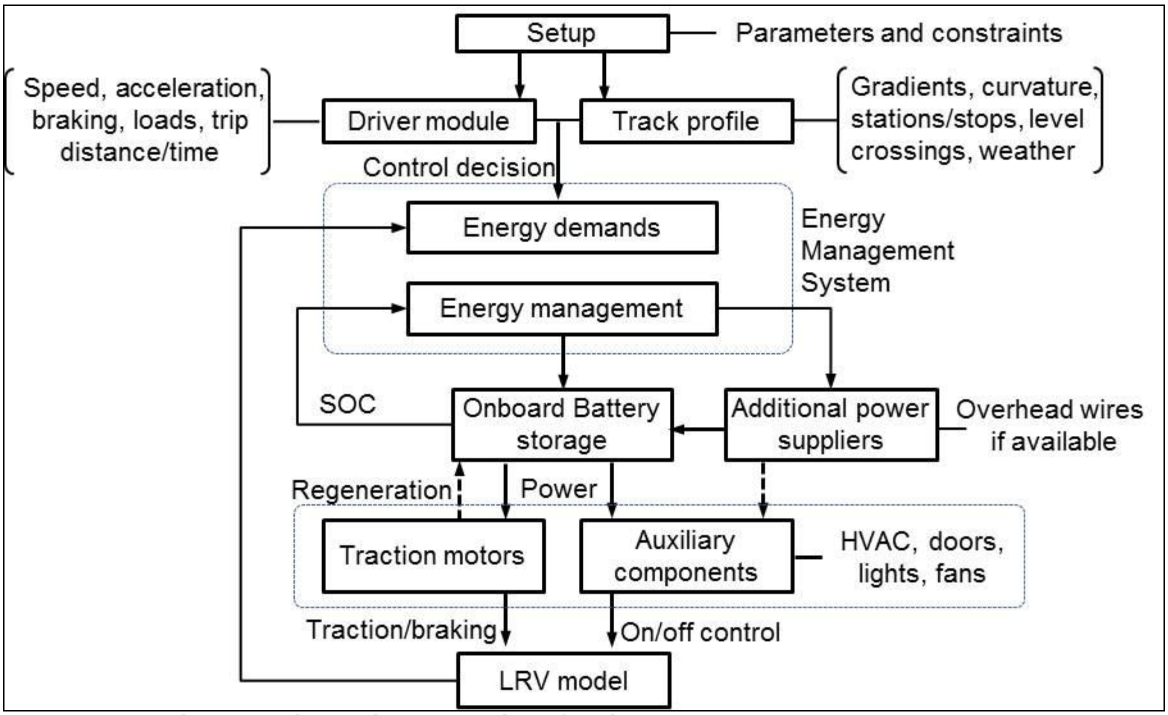


Figure 5 Simulation procedure for the energy management system

Table 4 Results of energy consumption according to HVAC status

Coasting speed	Round trip time (min)	HVAC	Energy consumption		Regenerative Energy	Net energy consumption
			Traction efforts	Auxiliary units		
40km/h	39.3 min	ON	112.5 kwh	47.16 kwh	50 kwh	109.66 kwh
40km/h	39.3 min	OFF	112.5 kwh	16.96 kwh	50 kwh	79.46 kwh
40km/h	39.3 min	Control	112.5 kwh	34.51 kwh	50 kwh	97.01 kwh

The overall procedure of the simulations for performance evaluation is illustrated in Figure 5. The procedure reflects main functions shown in Figure 2.

The energy consumption of the LRV operation is summarized in Table 4. Net energy consumption was 109.66 kwh when HVAC was turning on throughout the round trip of the vehicle. As a result, about 30% of total energy saved in the battery was used in operating HVAC component, which indicates that efficient energy management of the auxiliary power units can greatly reduce the net power consumption. In fact, over 10% of energy has been saved when the systematic energy management system was applied as shown in Table 4.

Conclusion

In spite of the mature technology of railway vehicle and system, many improvements concerning energy saving are still possible. The very different types of operation call for different methods of energy optimization. While the improvement of vehicle technology takes time and cost in general, the greatest effects will arise from a systematic and operational approach of the railway system based on sophisticated train control and management systems. As described in this research, the energy storage devices have reached a level of reliability that is necessary for transport application. Their benefits cover energy saving as well as improved system performance, together with possible reductions of greenhouse gas emission. In particular, intelligent control and management of auxiliary component can result in drastic reduction of energy consumption during catenary-free operation of the LRV. Local technical optimizations will result in smaller overall effects, most of which are attributable to the very mature level of technology that has been reached today.

Acknowledgements

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