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Impacts of On-board Energy Storage Devices on the Energy Consumption of Train Operations

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ABSTRACT: Urban rail transit systems consume significant electrical power, with traction accounting for 50% of the total energy (from China Urban Rail Transit Association [1]). As operational mileage and vehicle counts rise, so does energy consumption, underscoring the importance of vehicular energy conservation. This study evaluates the impact of on-board energy storage devices on train energy efficiency. Using operational data from Changsha Metro Line 5 and incorporating literature reviews and simulations, the energy-saving potential was assessed. Integrating these storage devices with vehicle energy monitoring systems shows promising potential for energy conservation and operational efficiency. This research presents a viable strategy to reduce energy consumption in urban rail vehicles, enhancing system competitiveness.

KEYWORDS: Urban Rail Transit, On-board Energy Storage, Operational Energy Consumption, Vehicle Energy Monitoring, Energy Conservation.

1 Introduction

With societal advancement, the scale of urban rail transit systems has rapidly expanded, and their energy-saving and emission-reduction challenges have become increasingly prominent [2]. Due to the frequent mode transitions and substantial short-term power surges characteristic of urban rail transit operations [3], energy wastage is particularly acute. It has been demonstrated that employing the electric braking technique can recover up to 45% of the energy during the electric braking of a train. This prodigious amount can effectively fulfill the power demand of certain auxiliary systems (9%-20%) [4, 5]. Hence, effectively utilizing and storing this energy has become a research focal point.

On-board energy storage devices are energy collectors installed on rail transit vehicles, using batteries, supercapacitors, or flywheels as storage media [6]. During regenerative braking, the traction motor acts as a generator, converting part of the kinetic energy into electrical energy [7]. On-board storage devices recover and reuse the converted energy, assisting the train's acceleration/deceleration to enhance energy efficiency and ensure stable operations.

Numerous studies have delved into the utilization of regenerative braking energy in subway vehicles and the application of on-board energy storage devices. For instance, Shen and Cao examined the factors affecting the utilization rate of regenerative braking energy and provided energy-saving guidance for rail transit through scenario analysis and simulations [3]. Zhang Bolun et al. studied electric trains with on-board hybrid energy storage devices for auxiliary traction and recovery of regenerative energy. It proposed a time-based mixed-integer linear programming (MILP) model. The results show that on-board HESDs with a higher capacity do not necessarily lead to a higher energy-saving rate; a lower or excessive initial SOC could undermine the energy-saving potential; considering the long-term train operation, the degradation of the Li-ion battery will influence the energy-saving considering the long-term train operation, the degradation of the Li-ion battery will influence the energy-saving operation for electric trains, as well as result in an energy-saving rate that ranges from 41.57%～31.90% [8]. Lin explored the application of inversion feedback thermal energy storage devices in rail transit, analyzing their principles and categories. Using real operational data from Beijing Metro, he elucidated the energy-saving and economic impacts of different types of thermal storage devices, revealing an average regenerative energy return rate of 10% and the energy returned by medium-voltage inverter feedback type is approximately three times that of the low-voltage type [9]. Giuseppe Graber and others researched the sizing and energy management of hybrid on-board energy storage systems for urban rail transit, designing a hybrid system integrating lithium-ion batteries with supercapacitors (H-ESS). They determined the total on-board storage size and volume and validated the performance of H-ESS through real route measurements. The on-board H-ESS reduced line losses and SSE peak current by 43% and 32%, respectively [10]. Moreover, experimental tests on a Bombardier Transportation light rail vehicle prototype demonstrated that energy obtained using supercapacitors resulted in approximately 30% traction energy savings [11]. However, the paper did not focus on their energy management.

From the above, it's evident that regenerative braking energy in subway vehicles and on-board storage devices has received considerable research attention. However, there remains a deficiency in the research on applying vehicle energy monitoring and management systems to precisely control and utilize regenerative energy, especially in powering auxiliary systems like air conditioning and lighting. Therefore, this paper emphasizes the integration of on-board storage devices with energy management systems to achieve more efficient utilization of regenerative energy and overall energy efficiency enhancement.

2. METHODS

The methodology employed in this study is divided into three primary phases: data collection, model establishment and simulation, and qualitative and quantitative analysis.

2.1 Data Collection

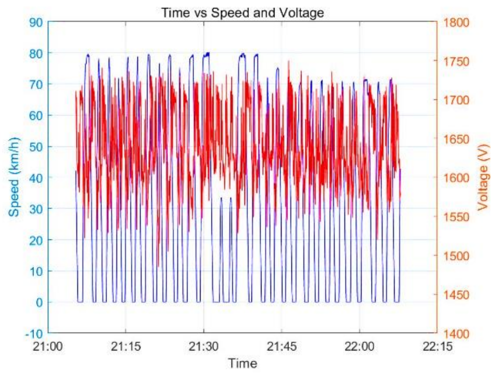
For this study, a 20-day operational tracking was carried out on train numbers 23-24 on China's Changsha Metro Line 5. Through TCMS, data such as traction energy consumption, SIV energy consumption, regenerative energy, total distance traveled, as well as running current, voltage, and speed were gathered. Table 1 presents a summary of the energy consumption data over these 20 days.

Table 1: Sample of energy consumption data for 20 days

Category	Traction energy consumption（kWh）	SIV energy consumption（kWh）	Regenerative energy（kWh）	Kilometers' operated（km）
Day 1	3,673	1,032	2,384	2,96
Day 2	2,673	846	1,692	236
Day 3	2,354	785	1,409	217
*Day 4	244	43	146	22
Day 5	3,209	841	1,876	279
Day 6	3,664	1,029	2,372	292
…	…	…	…	…

Traction energy consumption: The amount of electrical energy in kilowatt-hours (kWh) consumed by the train during operation.
SIV energy consumption: is the energy consumed by the auxiliary inverter on the underground train when providing power to non-traction equipment, also in kilowatt-hours (kWh).
Regenerative energy: is the regenerative energy generated by the train during braking, which can be stored or fed back into the catenary, in kilowatt-hours (kWh).
Kilometers' operated: The total distance a train has operated in a given period of time, expressed in kilometers (km).

The current and voltage data for vehicle operation underwent initial parsing using TMCS and subsequent statistical organization with MATLAB. Figure. 1 displayed some of the current and voltage-speed curves intercepted during vehicle operation, revealing unique features during start-up, braking, and stable operation.



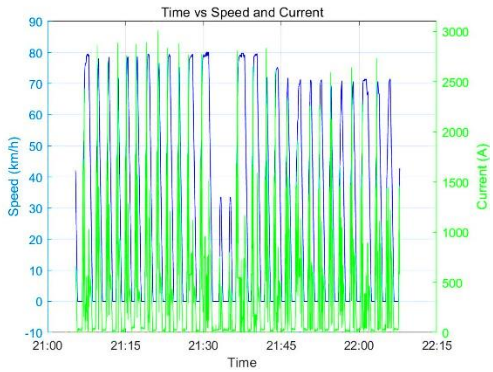


Fig. 1 Vehicle running current, voltage- speed curves.

2.2 Model Establishment and Simulation

The collected vehicle operation-related parameters such as rated power parameters of each system of the vehicle, typical operation curves of the vehicle, vehicle mass, as well as a supercapacitor with an energy storage capacity of 3.46 kWh and a charging/discharging current of 840 A are selected as the on-board energy storage device [12]. Building on the energy conservation control system design strategy that features on-board energy storage devices, as pioneered by Ciccarelli et al. and Barrero et al. [7, 13], this study enhances the MATLAB/Simulink model with the integration of three additional modules: the TCMS data module for real-time energy consumption monitoring of each subsystem, a data analysis and decision-making module, and a power supply logic module. The advanced control strategy now integrates a vehicle energy consumption monitoring and management system [14], which facilitates the determination of optimal charging and discharging intervals, as depicted in Figure 2.

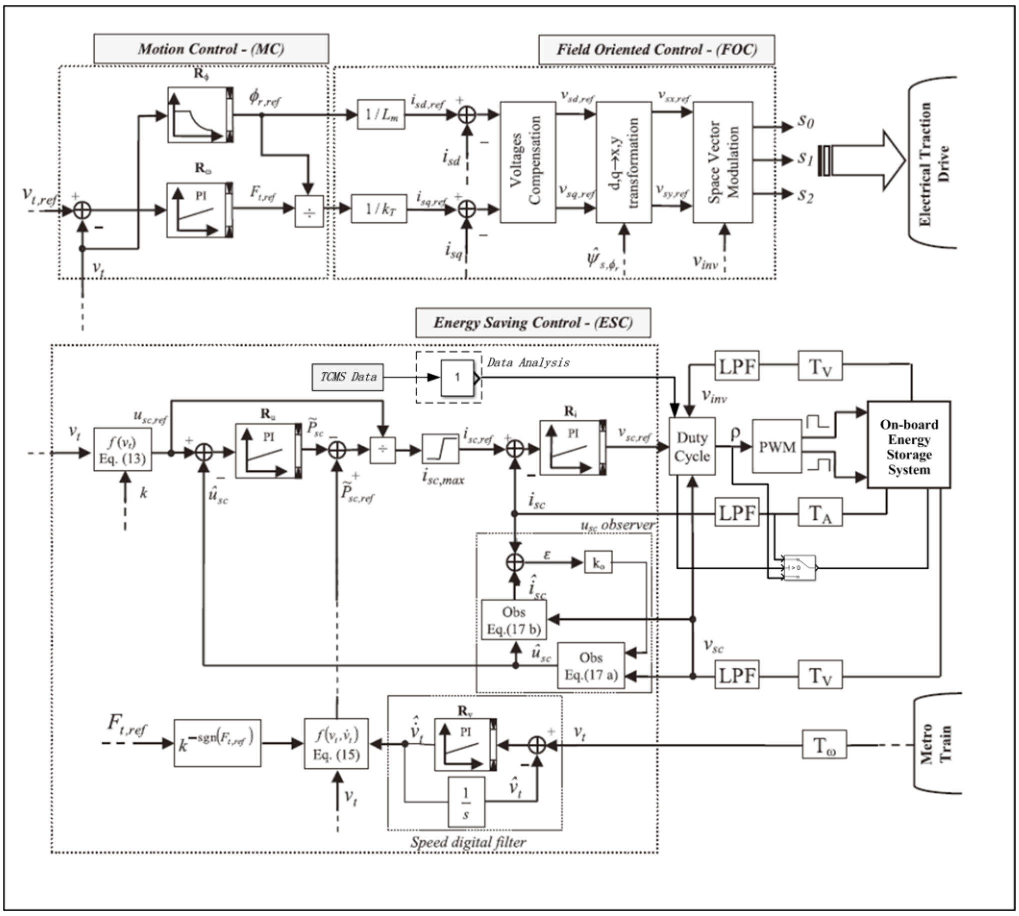


Fig. 2 Control system strategy block diagram style

In Figure 2, the Motion Control (MC) module is responsible for the vehicle's speed and position control, while the Field Oriented Control (FOC) is utilized for the control of the traction motor. The newly added modules are integrated into the Energy Saving Control (ESC) system. The data analysis and decision-making module primarily processes real-time data from the Train Control and Management System (TCMS), based on which it ascertains the optimal timing for charging and discharging the energy storage devices. The power supply logic switch module oversees the power selection for the auxiliary systems, ensuring that components such as the air conditioning and lighting are powered by the on-board energy storage when sufficient charge is available, thereby guaranteeing independent power supply from the on-board storage and enhancing energy utilization efficiency.

2.3 Qualitative and Quantitative Analysis

In this study, we conducted both quantitative and qualitative analyses to examine the effects of on-board energy storage devices on vehicle energy consumption. The results provide a thorough understanding of the impact of on-board energy storage devices on energy consumption in vehicles. We analyzed 20 days of vehicle operational data using MATLAB software, focusing on key parameters such as current, voltage, speed and braking. The actual energy consumption data without an on-board energy storage device is compared with the simulated data with an on-board energy storage device. This reveals the specific advantages of installing an energy storage device on energy consumption. Additionally, through qualitative analysis, the potential contribution of on-board energy storage devices in optimizing the catenary currents and improving the overall stability and efficiency of the system is explored.

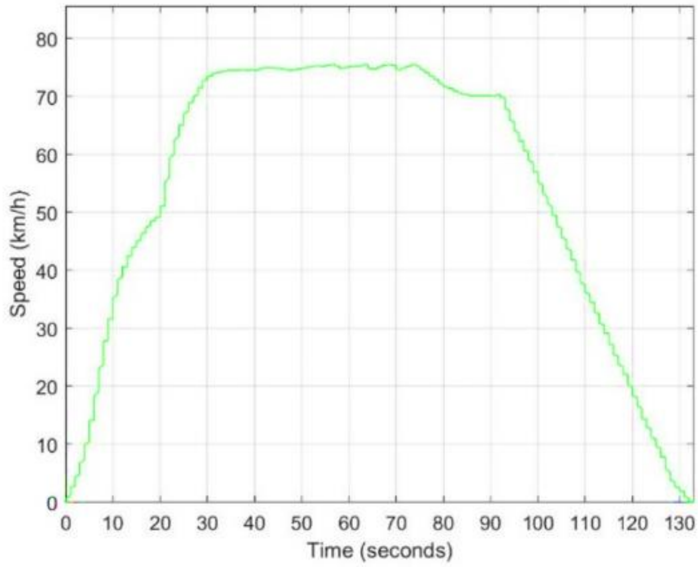


Fig. 3 Typical Vehicle Operating Curves

3. RESULTS AND DATA ANALYSIS

Referring to the research conducted by Arboleya et al. [15] and Steiner et al. [11], this section focuses on the use of on-board energy storage devices in metro vehicles and their impact on energy consumption during vehicle operation. To evaluate this technology, we will comprehensively examine the following aspects.

3.1 Reductions in Energy Consumption during Vehicle Operation

According to previous data statistics, a significant amount of the train's regenerative energy generated during operation can be recaptured and saved in the on-board energy storage device. We noticed that in the same load condition, the total energy consumption of the train using the on-board energy storage device was markedly lowered.

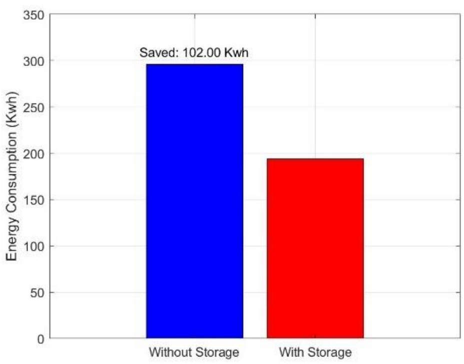


Fig. 4 Comparison of energy consumption of vehicle operation

The energy consumption of the vehicle for 33 km of operation is shown in Figure 4, which clearly illustrates the decrease of energy consumption and energy efficiency. As shown in the figure, the energy consumption of the vehicle without the on-board energy storage device was about 300 kWh, with an energy consumption of about 9.1 kWh per kilometer; whereas the energy consumption of the vehicle with the on-board energy storage device was below 200 kWh, saving 102 kWh of energy, with an energy consumption of about 6 kWh/km. This implies that the energy consumption of the vehicle with the on-board energy storage device was 3.1 kWh lower per kilometer compared to that of the vehicle without the on-board energy storage device, with an energy saving rate of about 34%.

3.2 Catenary current and voltage stability

This section explores in depth the influence of the on-board energy storage device on the stability of the catenary current and voltage. Figure 5 and Figure 6 present the comparison of the catenary current and voltage under the conditions with and without the on-board energy storage device, throughout the process of the train from start, acceleration, coasting, braking to stop.

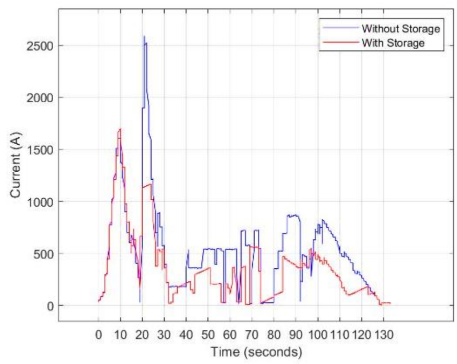


Fig. 5 Comparison of catenary current

The current changes of the vehicle throughout the operation process are shown in Figure 5. As shown in the figure, the current fluctuations in the two cases have significant differences. The train without the on-board energy storage device rapidly rises to about 2500A when starting, then swiftly drops and fluctuates during the whole cycle. This indicates that the train without the on-board energy storage device requires a large amount of electric energy from the catenary when starting, which results in the peak of the current. And when braking, the regenerative energy produced by the train cannot be timely and effectively recycled, leading to the decline and waste of the current.

The train with the on-board energy storage device has a more gentle rise of the current when starting, and the highest point is only about 1700A, and keeps a relatively stable low current state during the whole cycle. This implies that the train with the on-board energy storage device can release energy from the energy storage device when starting, thereby decreasing the demand for electric energy from the catenary and lowering the peak of the current. And when braking, the regenerative energy produced by the train can be stored in the energy storage device, thereby enhancing the utilization and recovery rate of energy.

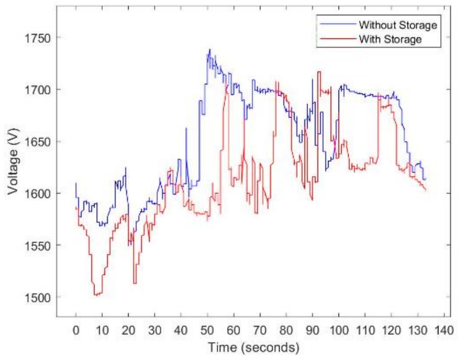


Fig. 6 Comparison of catenary voltage

The voltage changes of the vehicle throughout the operation process are shown in Figure 6. As shown in the figure, the voltage drop during acceleration and the voltage overshoot during braking of the train with the on-board energy storage device are markedly lower than those of the train without the on-board energy storage device. This indicates that the train without the on-board energy storage device has a higher voltage demand from the catenary when starting and braking, which results in the decrease and instability of the voltage. And the train with the energy storage device can release or recycle energy from the energy storage device when starting and braking, thereby decreasing the voltage demand from the catenary and enhancing the voltage stability.

To compare the voltage fluctuations in the two cases more intuitively, the voltage standard deviations were calculated separately. The voltage standard deviation of the train with the on-board energy storage device was 32.8V, and the voltage standard deviation of the train without the on-board energy storage device was 14.4V.

In conclusion, the on-board energy storage device can effectively reduce the current fluctuations of the train, reduce the load on the catenary, and enhance the efficiency and saving of energy. This not only helps to lower the peak power, but also helps to ensure the stability of the catenary voltage. On the other hand, it can effectively enhance the voltage stability of the train, decrease the voltage fluctuations of the catenary, improve the matching of the train and the catenary, and increase the reliability and life of the catenary.

4 CONCLUSION

This study revealed that the on-board energy storage device based on the vehicle energy consumption monitoring and management system can accurately control the timing of charging and discharging. As a result, compared to the original baseline, the train reduced about 3.1kWh of energy consumption per kilometer, with an energy saving rate of 34%, while the peak power lowered and the catenary voltage stability enhanced. This study did not perform a vehicle load test, so the actual space requirement and layout of the on-board energy storage device remain unclear. How to effectively incorporate this device into the limited vehicle space is an important aspect of future research.

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