Review of Energy Saving Technologies for Urban Rail Vehicles

Jingjie Yan[1,2*], Wirogana Ruengphrathuengsuka[2]
[1]Shanghai Municipal Complete Equipment (Group) Co., Ltd.
Railway Transportation Research Center
[2]Master of Engineering Program in Engineering Management,
Graduate School, Southeast Asia University, Bangkok 10160, Thailand

Corresponding author:s6542b10005@sau.ac.th/yjj86411@gmail.com

Received: 3 November 2023 / Accepted : 1 December 2023 / Plblished online : 14 December 2023

บทคัดย่อ บทคัดย่อระบบขนส่งมวลชนระบบรางในเมืองต้องใช้การพลังงานไฟฟ้าจำนวนมากในการขับเคลื่อน โดยเฉพาะพลังฉุดเพียงอย่างเดียวคิดเป็นประมาณ 50% ของการใช้ไฟฟ้าของระบบ เมื่อระยะทางในการปฏิบัติงานและจำนวนยานพาหนะเพิ่มขึ้น การใช้พลังงานก็เพิ่มขึ้นตามไปด้วย ซึ่งตอกย้ำความสำคัญอย่างยิ่งยวดในการประหยัดพลังงาน การศึกษาครั้งนี้เป็นการวิเคราะห์การถ่ายโอนพลังงานและการกระจายตัวของยานพาหนะระบบรางในเมืองอย่างเป็นระบบ โดยเจาะลึกถึงผลกระทบที่อาจเกิดขึ้นในการประหยัดพลังงานด้วยกลยุทธ์และเทคโนโลยีต่างๆ รวมถึงการลดน้ำหนักยานพาหนะ การยึดเกาะของมอเตอร์แม่เหล็กถาวร การใช้งานซิลิคอนคาร์ไบด์ การจัดเก็บพลังงานเบรกแบบสร้างใหม่ การเพิ่มประสิทธิภาพอินเวอร์เตอร์เสริม เครื่องปรับอากาศแบบขับเคลื่อนด้วยความถี่แปรผัน และระบบไฟส่องสว่างอัจฉริยะ การศึกษานี้นำเสนอกลยุทธ์ที่มีศักยภาพในการลดการใช้พลังงานของยานพาหนะระบบรางในเมืองซึ่งจะช่วยเสริมขีดความสามารถในการแข่งขันโดยรวมของระบบขนส่งทางรางใน

คำสำคัญ :การขนส่งมวลชนระบบรางรถราง, การใช้พลังงานของยานพาหนะระบบราง, การประหยัดพลังงาน, การขนส่งสาธารณะ, ความคล่องตัวในเมือง

Abstract Urban rail transit systems have substantial power demands, with traction power alone constituting about 50% of the system's electrical consumption. As the operational mileage and number of vehicles increase, so does the energy consumption, underscoring the paramount importance of energy-efficient vehicles. This study systematically analyzes the energy transfer and the dissipation in urban rail transit vehicles. It delves into the potential energy-saving impacts of various strategies and technologies, including vehicle lightweighting, permanent magnet motor traction, silicon carbide applications, regenerative braking energy storage, efficiency enhancement of auxiliary inverters, variable-frequency drive air conditioning, and intelligent lighting systems. By elucidating these methods, this study offers potent strategies to curtail the urban rail transit vehicle energy consumption, thereby bolstering the overall competitiveness of urban rail transit systems.

Keywords: Rail transport, Rail vehicles, Vehicle Energy Consumption, Energy saving , Mass public transport , Urban mobility

1. Introduction

The expansion of urban rail transit networks has highlighted the issue of energy consumption. The China Urban Rail Transit Association has reported that in 2022, China's urban rail transit consumed 22.792 billion kWh of electricity, of which 11.315 billion kWh (49.65%) were consumed by traction [1]. China is working towards achieving "dual carbon" goals, which has increased pressure on the transportation sector to accelerate carbon peak and carbon neutrality. Researching energy-saving technologies for urban rail vehicles is important for reducing energy consumption and carbon emissions.

As shown in Figure 1 urban rail vehicle energy consumption mainly includes traction energy consumption and Energy consumption of on-board auxiliary equipment. Extensive research has been conducted by domestic and international scholars to reduce energy consumption in urban rail vehicles. Milroy [2] and Albrecht et al. [3] focused on training automatic control systems, reducing energy consumption through optimizing acceleration and braking processes. Zhang et al. [4] considered aspects such as train traction, slope, and speed limits, thereby effectively reducing train energy consumption by optimizing the automatic running curve using the Grey Wolf Algorithm. Cong [5] examined the relationship between tracking running interval time and the maximum running speed of the tracking train section, providing parameters to formulate operational diagrams that meet energy-saving needs. Wang [6] studied the correlation between the composition of energy consumption in urban rail transport and its influencing factors, and the main factors affecting vehicle energy consumption were identified.

Furthermore, some scholars have investigated energy-saving technologies that use regenerative braking energy storage. Li and Gao [7] conducted a benefit analysis of the regenerative braking energy storage technology. They determined the relationship between energy recovery rates and rail lines through simulation research. However, they also stated that the application scope of the technology is limited.

This paper takes inspiration from these works and concentrates on energy-saving technologies for each urban rail transit vehicle system device. Specifically, the paper addresses the traction system and auxiliary inverter system of urban rail vehicles. This paper aims to reduce vehicle energy consumption and enhance the competitiveness of rail transport through these technical measures.

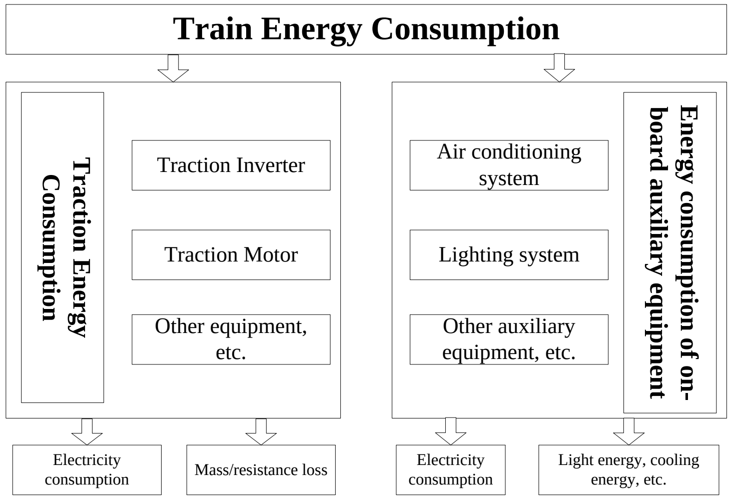

Fig. 1 Composition of vehicle energy consumption

2. Analysis of Vehicle Energy Saving Flow

Figure 2 shows a typical traction energy flow chart for urban rail, Derived from statistics and analyses of energy consumption data of rail transit systems in different European cities [8]. In Figure 2, infrastructure losses refer to the electric losses occurring from the point of common coupling to the pantograph (or collector shoes). Infrastructure losses principally depend on the voltage level of the rail system and its traffic load, being more important for low-voltage networks with heavy traffic. Typical values for infrastructure energy losses can be as high as 22%, 18%, 10%, and 6% for 600 V, 750 V, 1500 V, and 3000V-DC networks, respectively [9,10].

As seen in Figure 2, auxiliary systems consume an important share of the total energy entering the rolling stock. HVAC equipment is generally responsible for most of this consumption and is strongly influenced by climate conditions [11]. For instance, it has been reported that heating systems account for 28% of the total traction energy in Metro Oslo [12]. Based on Empirical Data Analysis, the auxiliary equipment energy consumption accounts for 9% to 20% of total train energy consumption [13].

Another major share of the traction energy is dedicated to overcoming the motion resistance of the rolling stock. It can be concluded from the available literature that, on average, motion resistance is responsible for approximately 16% of the traction energy use in urban rail services [8].

The most significant portion of traction energy is wasted in braking processes, see Figure 2. The amount of energy dissipated in braking strongly depends on the kind of urban rail system.

Electric motors can also act as generators while braking, so it is possible to recover and reuse a significant proportion of the braking energy [14]. In contrast, about one-third of the braking energy is irreversibly lost because of friction brakes and the losses occurring in motors, converters, and transmission systems during dynamic braking.

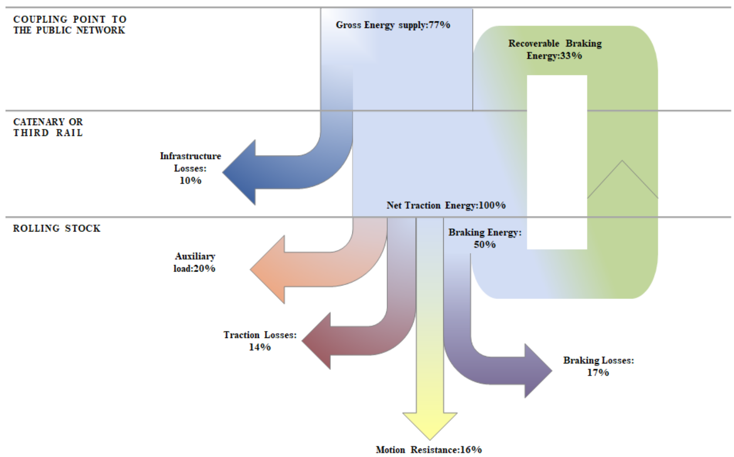

Fig. 2 Typical traction energy flow in urban rail systems

3. Energy-Saving Technologies for Vehicle Traction Systems

3.1 Lightweight Technology in Rail Transit

Carruthers et al. [15] analyzed the weight components of metro vehicles sourced from leading manufacturers such as Siemens, Alstom, and Bombardier. Applying the energy model conceived during the MODURBAN project, a quantitative correlation was delineated between the reduction in metro vehicle weight and operational energy conservation. Under specific circumstances, a decline of 10% in a vehicle's weight can culminate in a 7% reduction in traction energy consumption. Empirical data from the prolonged operations of the Hong Kong MTR indicates that an annual energy saving of 8,000 kWh can be achieved for every 1 ton reduction in train weight [16].

Mistry et al. [17, 18] led projects anchored on Advanced Composite Integrated Structures (ACIS) to pursue research on rail vehicle lightweighting. The study ascertained those specific components, namely, the vehicle cantilever seat supports, luggage racks, intermediate end wall structures, car body sidewalls, and roof structures, are prime candidates for a Fiber-Reinforced Polymer (FRP) composite redesign. The investigation also introduced a hollow axle design and endorsed the substitution of traditional materials with "bismaleimide matrix plus carbon fiber composite." The outcomes revealed substantial weight reductions: cantilever seat bracket (73%), luggage rack (50%), intermediate end wall (57%), car body sidewall (47%), roof structure (51%), and axles (50% and 64%), respectively. Such reductions promise a significant decrement in carbon dioxide emissions during train operations.

It can be seen that A lightweight construction strategy for rail vehicles facilitates diminished traction and braking forces during train acceleration and deceleration phases. One can effectively curtail traction energy demands by optimizing the vehicle's internal architecture, space layout, body constituents, and bogie materials and integrating innovative processes and modularization.

3.2 Permanent Magnet Motor Traction Technology

Khare and Shriwastava [19] studied the traction drive field weakening control algorithm of traction permanent magnet synchronous motor (PMSM) and analyzed the influence of various modes of low speed/high speed on the network from the perspective of EMC through simulation experiments. Liu et al. [20] carried out a line simulation of the energy consumption of the permanent magnet synchronous traction system and conducted a detailed comparison and analysis of the efficiency and energy consumption with the asynchronous traction system and the comprehensive energy saving rate of the permanent magnet traction system was 6.6%~36.9%. Zhang et al. [21] introduced the advantages and disadvantages of a permanent magnet synchronous motor as a traction motor in the field of rail transit and the application of permanent magnet synchronous traction systems at home and abroad. The paper shows that permanent magnet synchronous traction motor has the characteristics of high efficiency, high power factor, small size, lightweight, as well as fully enclosed and low noise, and its efficiency is 3%~5% higher than that of asynchronous motor of the same specification; Volume and mass can be reduced by 20%~30%.

Figure 3 shows an efficiency comparison between a permanent magnet synchronous traction motor and an asynchronous traction motor. Compared with the asynchronous traction motor, the efficiency of the permanent magnet synchronous traction motor is increased by about 5% in the full speed range under the maximum traction characteristic envelope. In the low-speed region, the efficiency improvement is even more significant, with more than 10%.

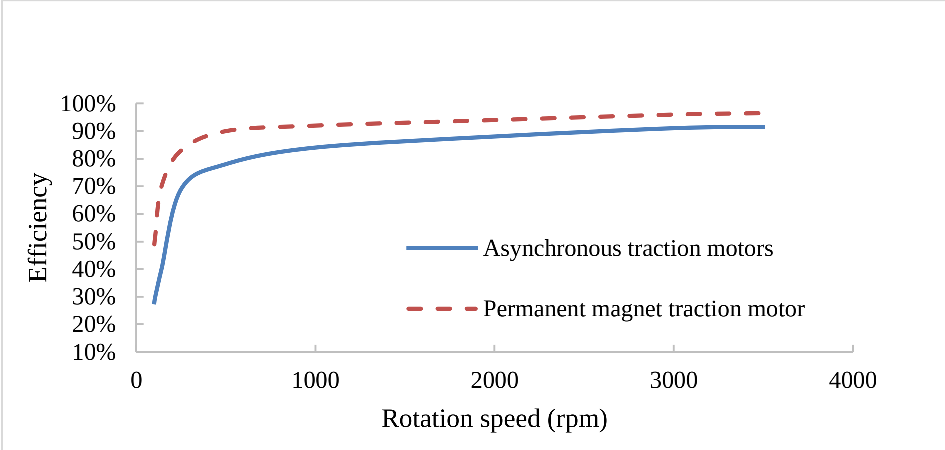

Fig. 3 Schematic diagram for efficiency comparison

Table 1 presents the traction energy consumption statistics of permanent magnet synchronous motor technology and asynchronous traction motor over 7 months [22]. According to the data, the average traction energy consumption per vehicle kilometer for permanent magnet synchronous motor technology is 13.54 kWh, whereas, for the asynchronous traction motor, it is 16.44 kWh. Compared to the latter, permanent magnet synchronous motor technology can save 2.90 kWh/km, reducing energy consumption by about 22%.

3.3 Silicon Carbide Technology

Silicon carbide (SiC) is a third-generation semiconductor material with high voltage resistance, high temperature, high frequency and high efficiency, which is suitable for traction inverters and auxiliary inverters in rail transit.

Table 2 enumerates the usage of SiC in the railway sector across specific nations globally until 2022. Japan can be considered the pioneer of SiC in rail transport, having implemented hybrid SiC power modules on the Ginza line of the Tokyo Metro in 2012 [24]. Experimental outcomes indicated that the optimized main circuit system operates with stable control, achieving a power consumption rate per vehicle kilometer that is 13.7% more efficient than the conventional silicon power module system.

Table.1 Comparison of average traction energy consumption per kilometer (kWh)

Time	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7
Asynchronous traction motors	16.34	16.19	16.28	16.25	16.54	16.48	16.97
Permanent magnet traction motors	13.77	13.85	13.52	13.49	13.41	13.32	13.42
Energy saving	2.57	2.34	2.76	2.76	3.13	3.16	3.55

Then in 2014, Europe was also actively exploring the application of SiC in the field of rail transport.

In recent years, China has made breakthroughs in the development and application of SiC devices. Currently, 8 rail transit lines have adopted SiC technology. A comprehensive study conducted by Fu et al. [23] presented a comparative analysis of the primary technical parameters between SiC devices and IGBT power modules. Under equivalent conditions, the turn-on, turn-off, and reverse recovery losses of the four-switch vehicle-controlled IGBT at 450A were found to be diminished by 40%, 71%, and 91%, respectively, in contrast to the corresponding losses of the single-switch vehicle-controlled IGBT operating at 1500A. In a parallel research venture, Wan et al. [25] retrofitted the diode in reverse parallel within the native IGBT inverter with a SiC material (SiC-SBD). Preliminary findings affirmed that its switching and conduction losses outperformed those of conventional silicon diodes. When utilizing silicon carbide in traction inverters, there was an average energy consumption reduction of approximately 3.22% compared to silicon-based traction inverters.

The integration of SiC technology in rail transit across China was meticulously examined. Distinctive outcomes were observed in various metro lines and tram systems. On the Suzhou Rail Transit Line 3, the incorporation of silicon carbide devices led to an energy conservation of 5%. In the case of Wuhan Donghu trams, when these devices were employed, the converter's power capacity surged beyond 20kW. This implementation was accompanied by a remarkable 40% reduction in energy consumption and a 30% diminution in both weight and volume. Similarly, for Guangzhou Metro Line 8, the utilization of silicon carbide devices resulted in a 13% weight reduction and an overall energy savings of 15%. Meanwhile, Xi'an Metro Line 4 experienced a comprehensive energy saving of 15% upon adopting silicon carbide technology.

Table.2 Application of SiC rail transit in some countries around the world

Country	Year	Line/Project	System
China	2018.12	Xi'an Metro Line 4	SiC + Permanent Magnet Motor
China	2019.11	Guangzhou Metro Line 8	SiC + Permanent Magnet Motor
China	2020.07	Wuhan East Lake Tram	SiC + Permanent Magnet Motor
China	2020.07	Zhuhai Line 1	SiC + Permanent Magnet Motor
China	2020.10	Shanghai Metro Line 8	SiC + Permanent Magnet Motor
China	2020.10	Shanghai Metro Line 6	SiC + Permanent Magnet Motor
China	2021.03	Suzhou Metro Line 3	All-SiC permanent magnet direct-drive trains
China	2021.05	Shenzhen Metro Line 1	All-SiC traction inverters
Japan	2012.02	Ginza line of the Tokyo Metro	SiC-VVVF Inverters
Japan	2014	Odakyu Electric Railway Train 1000	SiC Power Module Inverter
Japan	2015	N7005 train, JR Tokai	SiC Power Module Inverter
Japan	2019.02	2101 train, Tokyo Metro Marunouchi Line	SiC Power Module Inverter

Table.2 Application of SiC rail transit in some countries around the world (continue)

Country	Year	Line/Project	System
Japan	2019	E235 train, Yamanote Line	SiC Power Module Inverter
Japan	2021.11	E131 Series 500 trains, JR East Sagami Line	SiC-VVVF Inverters
Japan	2022.02	6500 trains on the Toei Mita Subway Line	SiC Power Module Inverter
Japan	2022.03	315 trains, JR Central Chuo Main Line	SiC-VVVF Inverters
Japan	2022.03	E131-600 trainsets, Omiya	SiC-VVVF Inverters
Japan	2022.05	Toei 6500 trains on the Tokyu Nikkoku Line	SiC Power Module Inverter
Europe	2014	Shif2Rail project, EU	SiC Power Module Inverter
Europe	2018.03	C20 metro in Stockholm, Sweden	SiC Power Module Inverter
Europe	2021.03	rail innovation program Horizon Europe 2021-2027, EU	SiC Power Module Inverter
Europe	2021.08	Arsenio tram in Munich, Germany	SiC Power Module Inverter
Europe	2021.12	UK's High Speed 2 (HS2)	SiC Power Module Inverter
Europe	2022.02	Renfe Operadora, Spain	SiC Traction Systems
Europe	2022.02	SNCF Voyageurs' AMLD long-distance electric trains	SiC Power Module Inverter

*Source: 2022 Silicon Carbide (SiC) Industry Research White Paper.

In summary, the energy-saving potential of SIC technology is relatively considerable.

3.4 Regenerative Braking Energy Storage Technology

Regenerative braking operates on the motor's reversibility principle. Under braking conditions, the motor switches to generator mode. The motor's rotor is driven to rotate by the inertia of the vehicle, producing a counter torque. This action converts a portion of the vehicle's kinetic or potential energy into electrical energy during energy recuperation. On-board energy storage systems aid in train traction and facilitate the recovery of this regenerated braking energy.

In Figure 4, the schematic depicts the on-board Hybrid ESS electric model. Key components include the supercapacitor (Vsc) serving as an energy storage unit, and the Power Flow Controller that manages current direction, regulating power delivery to the load and enabling feedback when necessary. ITRAIN represents the current to or from the vehicle, its magnitude adjusted by the controller to meet dynamic power demands. VLINE is the DC voltage from the overhead contact line. The system also features a battery (VBatt) for supplying extra energy or storing regenerative braking energy. This integrated configuration ensures efficient power management, facilitating optimal energy utilization and exchange between the supercapacitor and the battery based on operational requirements.

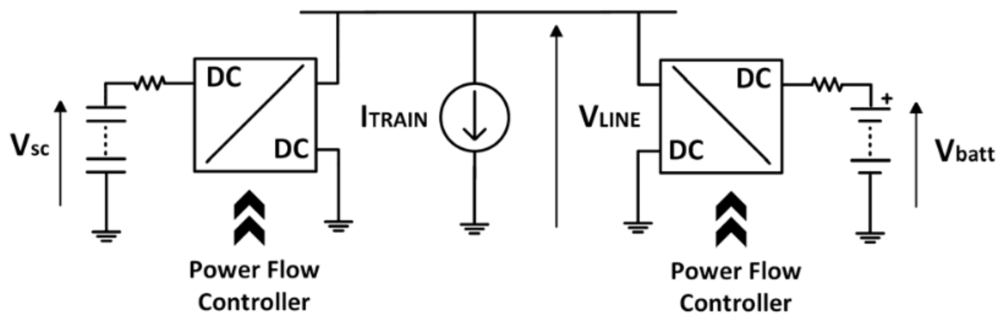

Fig. 4 On-board Hybrid ESS electric model

Graber et al. [26] undertook a comprehensive study on the sizing and energy management of on-board hybrid energy storage systems (H-ESS) tailored for urban rail transit. Their design integrated a lithium battery with a supercapacitor, creating a hybrid system for urban rail transit vehicles. Real-world case studies verified the performance of this on-board H-ESS, noting a significant reduction in line loss and SSE peak current by 43% and 32%, respectively. Building on this, Zhu and Wang [27], Zhang et al. [28] explored the utilization of the vehicle-mounted hybrid energy storage system (HESD) in electric locomotives. They introduced a power distribution scheme that harmonized the static power output of the battery with the dynamic output of the supercapacitor. Moreover, they proposed an optimal sizing for the HESD and utilized a bidirectional three-level DC/DC converter to manage the current and power control of the supercapacitor bank. Analytical and experimental data revealed that, compared to trains without the on-board HESD, there's a potential long-term operational energy saving rate of up to 27.39%.

4. Energy-saving technologies for a vehicle's auxiliary inverter system

A vehicle's auxiliary inverter system mainly consists of medium-voltage and low-voltage loads powered by the auxiliary inverter. There are two main ways to achieve energy savings: Firstly, by optimizing the efficiency of the auxiliary inverter to enhance its operational efficiency; Secondly, by reducing the power consumption of medium and low-voltage loads on the auxiliary inverter side to achieve energy-saving goals.

4.1 Improving efficiency of the auxiliary inverter

Apart from the silicon carbide technology mentioned earlier, there are two other focus areas to enhance the efficiency of the vehicle's auxiliary inverter: three-level power frequency auxiliary conversion technology and high-frequency auxiliary conversion technology.

The optimization to enhance the three-level power frequency auxiliary conversion technology is done by utilizing its structural characteristics, which involves introducing an intermediate level, thus increasing control freedom. The Hefei University of Technology research team proposed a segmented zero-voltage turn-on (ZVS) optimization method for Dual Active Bridge converters (DAB). They selected a T-type three-level dual active bridge converter as the research object and used phase-shift control to flexibly control the direction of the inductance current. This allowed them to achieve ZVS across the full power range [29]. This optimization method can significantly enhance the auxiliary inverter's efficiency by enabling zero-voltage turn-on across the full power range. This results in reduced switch losses and improved operational efficiency.

It is crucial to focus on designing and developing effective control algorithms to achieve the best results in high-frequency auxiliary conversion technology. An article published in the International Journal of Circuit Theory and Applications highlights the usefulness of a control algorithm known as Leakage Least Mean Fourth (LLMF). This algorithm enables the manipulation of a 5-level series H bridge multilevel inverter (5L SCHB-MLI) [30]. This algorithm uses refined control to regulate the voltages on the two DC links of the H bridge to approximately equal values, which is crucial for high-frequency auxiliary inverters as it ensures system stability during high-frequency operation, improving the efficiency of the auxiliary inverter.

4.2 Energy-saving technology for air conditioning systems

(1) Technology for Frequency Conversion Control

Variable-frequency air conditioning adjusts its capacity continuously by regulating the compressor motor's speed. The compressor motor's speed can be modulated continuously by the inverter, with variations proportional to the indoor air conditioning load. Thus, the variable frequency cooling system can achieve a balance between cooling capacity and heat load by adapting the compressor speed to changes in the indoor heat load.

At the beginning of the operational stage, the variable-frequency air conditioning system operates at a high-frequency state. The compressor runs at maximum speed, rapidly reducing the room temperature. When the temperature in the room approaches the set value, the control program adjusts the compressor's speed and cooling capacity to balance the indoor heat load. The whole adjustment process doesn't require the compressor to stop, thus reducing the loss of available energy. Such a process achieves the purpose of energy saving [31, 32]. During low-frequency operation, the compressor discharges less refrigerant per unit time. This relatively increases the area of the condenser and evaporator, leading to improved efficiency in air conditioning refrigeration and reduced power consumption. Urban rail transit vehicle variable-frequency air conditioning application projects measure an average refrigeration energy-saving rate of 30%.

(2) Technology for High-Efficiency Compressors with Permanent Magnet Synchronous Motors and DC Variable Frequency Control

The ventilation fan, condensing fan, and compressor in the air conditioning system have a substantial power output. Consequently, the compressor has a significant share of energy consumption. References 19-21 demonstrate the energy-saving benefits of using permanent magnet synchronous motors. Therefore, high-efficiency permanent magnet synchronous motors are approximately 4% more efficient than three-phase asynchronous motors under the same operating conditions. (3) Heat Pump Heating Technology

Heat pump heating technology uses electric energy to drive the compressor, following the reverse Carnot cycle principle to extract low-temperature heat energy with minimum energy consumption from the air. The compressor converts the absorbed heat energy into high-temperature heat, which heats the cabin [33]. Theoretically, heat pump heating technology can save about 60% of electricity compared to electric heating.

4.3 Intelligent Lighting Technology

According to Wang [34], using LED lighting in rail transit vehicles can reduce energy consumption by approximately 50%, thus serving as energy-saving technology. LED's centralized power supply technology replaces the separate power supply for each lamp, reducing energy consumption through limited LED drivers. Such technology is a possible method for increasing energy efficiency. The adaptive dimming control technology can be achieved by installing a photosensitive sensor in the carriage. The LED dimming controller adjusts the output power of LED lighting based on external illumination changes. The advantage of dimming with LED is that it keeps the luminance in the car at its optimal range. This method significantly enhances energy efficiency compared to the traditional fixed output power supply mode. An analysis carried out by Duan [35] compared the energy-saving effects of LED centralized power supply and adaptive dimming technology with three other lighting solutions using software simulation calculations and physical tests. The findings demonstrate that LED centralized power supply and adaptive dimming control provide the highest degree of energy savings. The simulation data indicates a potential reduction of approximately 30% in energy consumption compared to the non-adaptive dimming scheme of LED. The test results confirmed this point, showing an energy efficiency ratio of about 1.53:1 between the two schemes. The energy-saving effect of the LED centralized power supply dimming scheme is up to 1.8 times greater than traditional fluorescent lamps.

Although adaptive dimming technology is effective, its application range is limited and only suitable for elevated and ground line sections. This article suggests reducing lighting power during non-peak hours or when carriages are unoccupied, implementing segmented lighting modes, and installing passenger sensors. If carriages become unoccupied, lighting will automatically turn off or adjust to low brightness with other management measures in place. Further research is necessary to improve the energy-saving effects of these measures.

5. Conclusions and future research

This study critically examines the energy transfer and dissipation pathways within urban rail transit vehicles. Predominantly, the energy consumption is attributed to the traction system, followed by the air conditioning and lighting system apparatus, and losses due to braking. As shown in Table 3, The paper delves into vehicular energy conservation techniques from two perspectives: diminishing the energy expenditure of the vehicle's traction system and its auxiliary inverter system. Adopting permanent magnet motors, silicon carbide devices, and advanced control strategies can markedly curtail traction-related energy usage for traction systems. Concerning the auxiliary inverter system, enhancing conversion efficiency through implementing a three-level or high-frequency auxiliary inverter, coupled with reducing load energy intake via technologies such as frequency-variable air conditioning and LED lighting, can drastically minimize the overall energy consumption of the auxiliary system. The holistic integration of these technical interventions holds the potential to considerably decrease the energy consumption spanning the entire life cycle of the vehicle, thereby offering a robust technical framework for curtailing the energy demands of urban rail vehicles.

Table.3 Summary of energy-efficient technologies for urban rail vehicles

Classification	Points	Energy saving potential
Vehicle Lightweighting	Cantilevered seat supports, luggage racks, center end wall structures, body side wall and roof structures, axles	large
Traction Systems	Permanent magnet synchronous traction motors	Larger
	Silicon carbide devices	Larger
Auxiliary Reversing Systems	Three-level frequency-assisted converter technology	Medium
	High-frequency auxiliary converter technology	Medium
Regenerative Braking Energy Storage Technology	On-board energy storage devices	Larger
Vehicle Air Conditioning Systems	Inverter, high-efficiency permanent magnet synchronous motor DC inverter compressor technology, heat pumps	Larger
Vehicle Lighting Systems	LED intelligent lighting	Smaller
Based on the energy consumption share of each subsystem of the vehicle, and by combining the data from the above studies, the energy saving potential is classified into four levels: Large, Larger, Medium, and Smaller.		

The current study provides valuable insights into energy consumption patterns in urban rail transit vehicles and proposes effective measures for energy conservation. However, to further advance this field, future research should delve into a more granular analysis of the selected technology combination.

REFERENCES

[1] China Urban Rail Transit Association. “Annual Statistics and Analysis Report on Urban Rail Transit in China,” 2023.

https://www.camet.org.cn/tjxx/11944 (in Chinese).

[2] I. P. Milroy, “Aspects of automatic train control,” Ph.D. Dissertation, Diss. Loughborough Univ., 1980.

[3] A. Albrecht, P. Howlett, P. Pudney, and X Vu, “Optimal train control: analysis of a new local optimization principle.” American Control Conference, USA, 29 Jun-1 Jul. 2011, pp. 1928-1933, 2011

[4] C. Zhang, B. Wang, and S. M. Xie, “ Research on energy saving technology of train traction,” Modern Urban Rail Transit, Vol. 6, pp. 13-18, 2021. (in Chinese, translated abstract).

[5] J. S. Cong, “Analysis of Urban Rail Transit Train Operation Chart Parameters for Energy Saving.” M.S. thesis, Beijing Jiaotong Univ., 2015. (in Chinese).

[6] Y. M. Wang, “Quantitative Analysis on the Energy Factors of the Urban Rail Transit System.” Ph.D. Dissertation, Beijing Jiaotong University, 2011. (in Chinese, translated abstract).

[7] X. Li, and Z. Gao, “Cost-benefit analysis for regenerative energy storage in metro.” Chinese Manage. Stud. vol. 11, no. 1, pp. 19-34, 2017.

[8] A. González-Gil, R. Palacin, P. Batty, and J. P. Powell, “A systems approach to reduce urban rail energy consumption.” Energy Convers. Manage. vol. 80, pp. 509-524, 2014.

[9] E. Pilo de la Fuente, J. I. Pérez Arriaga, et al. E. P. de la Fuente, J. I. P. Arriaga, I. L. H. Ausín, and J. Jiménez, “Electricity energy flows for transportation Electricity flows for transport,” Technological Research Institute (IIT) of the Comillas Pontifical University of Madrid, Monografía vol. 9, 2008. ISBN: 978-84-89649-42-2 (in Spanish).

[10] R. Takagi, “Energy saving techniques for the power feeding network of electric railways.,” IEEJ Trans. Elec. Electron. Eng. vol. 5, pp. 312-316, 2010.

[11] J. M. Ortega, H. Ibaiondo, and A. Romo, "Kinetic energy recovery on railway systems with feedback to the grid,” 9th World Congress on Railway Research, France, 2011.

[12] J. P. Powell, A. González-Gil, and R. Palacin, “Experimental assessment of the energy consumption of urban rail vehicles during stabling hours: Influence of ambient temperature,” Applied Thermal Eng. vol. 66, pp. 541-547. 2014.

[13] X. B. Zheng, Y. Bai and S. S. Zhou, “Metro Train Energy Consumption Characteristics Based on Empirical Data Analysis,” J. Transport. Syst. Eng. Inform. Tech., vol. 21, no. 6, pp. 264-271, 2021.

[14] A. González-Gil, R. Palacin, and P. Batty, “Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy,” Energy conversion and management, Vol. 75, pp. 374-388, 2013.

[15] J. J. Carruthers, M. Calomfirescu, P. Ghys, and J. Prockat, “The application of a systematic approach to material selection for the lightweighting of metro vehicles,” Proc. IMechE Vol. 223 Part F: J. Rail and Rapid Transit, vol. 223, no. 5, pp. 427-437, 2009.

[16] F. Qi, Z. Wang, and Q. F. Jiang. "Research on Energy Saving Measures for Urban Rail Transit." Rolling Stock (1002-7602) vol. 61, no. 3, pp. 102–108. 2023. (in Chinese, translated abstract).

[17] P. J Mistry, M. S. Johnson, and U. Galappaththi, “Selection and ranking of rail vehicle components for optimal lightweighting using composite materials,” Proc IMechE Part F: J Rail and Rapid Transit, Vol. 235, no. 3) 390-402, 2021.

[18] P. J. Mistry, and M. S. Johnson. “Lightweighting of railway axles for the reduction of unsprung mass and track access charges,” Proc. Inst. Mech. Eng. Part F: J. Rail and Rapid Transit, Vol. 234, no. 9, pp. 958-968, 2020.

[19] A. Khare, and D. S. Shriwastava, “A Survey of Traction Permanent Magnet Synchronous Motor,” Int. J. Sci. Tech. Eng. Vol. 1, no. 10, pp. 149-152, 2015.

[20] L. J. Liu, W. G. Chen, X. Liu, and T. He, “Research on energy saving technology of metro permanent magnet synchronous traction system,” Elec. Drive Locomot. Vol. 6, pp. 23-25, 2018. (in Chinese, translated abstract).

[21] J. M. Zhang, H, Su, Q. Ren, W. Li, and H. Zhou, “Review on development and key technologies of permanent magnet Synchronous traction system for rail transit,” J. Traffic Trans. Eng. Vol. 21, no. 6, pp. 63-77, 2021. (in Chinese, translated abstract).

[22] H. H. Deng, and B. Y. Zhong, “Train energy consumption analysis of permanent magnet synchronous traction system for Changsha metro line 1,” Modern Urban Transit, Vol. 9, pp. 10-13, 2017. (in Chinese, translated abstract).

[23] Y. L. Fu, F. Xu, B. Zhang, Y. Zhu, and Y. M. Ma, “Research on the new generation traction system characterized by silicon carbide power modules and permanent magnet motors,” Modern Urban Transit, Vol. 11, pp. 33-38, 2019. (in Chinese, translated abstract).

[24] H. M. Peng, “Test Report of Ginza Line 01 Series Subway Train SiC Power Module Main Circuit System,” Foreign Railway Locomotives and Motor Cars, Vol. 6, pp. 29-34, 2013. (in Chinese).

[25] J. Wan, J. H. Shi, and Q. Dai, “Research on Traction Energy-saving of Urban Rail Transit Vehicle Based on Hybrid Silicon Carbide Devices,” Urban Rail Transit Research, Vol. 03, pp. 253-257, 2023. (in Chinese, translated abstract).

[26] G. Graber, V. Galdi, V. Calderaro, and A. Piccolo, “Sizing and energy management of on-board hybrid energy storage systems in urban rail transit,” Inter. Conf. Electrical Syst. Aircraft, Railway, Ship Propulsion and Road Vehicles & Inter. Trans. Electrification, November 2016 France. 2016.

[27] L. Zhu, and X. Wang, “Hybrid energy storage system of storage battery/super capacitor for mine electric locomotive,” J. Phys. Conf. Series 1633, no. 012081, pp. 1-8, 2020.

[28] B. Zhang, C. Wu, G. Meng, F. Xue, and S. Lu, “Optimal Sizing of Onboard Hybrid Energy Storage Devices Considering the Long-Term Train Operation,” IEEE Access, Vol. 10, pp. 1-12, 2022.

[29] X. J. Yang, L. H. Kong, Y. Du, J. W. Su, and X. J. B. Zhang, “ZVS Optimization Strategy of T-type Three-level Dual Active Bridge Converter,” High Voltage Eng., Vol. 48 no. 5 pp. 1913 – 1923, 2022. (in Chinese).
[30] S. Mittal, A. Singh, and P. Chittora. "Design and development of leaky least mean fourth control algorithm for single-phase grid-connected multilevel inverter," Int. J Circ Theory Appl, pp. 1-18, 2023.
[31] W. Ma, and Z. G. Cheng, “Discussion on Energy-saving Methods of Shanghai Rail Transit Train Air Conditioning System,” Urban Rail Transit Research, Vol. 17, no. 11, pp. 54-58, 2014. (in Chinese).
[32] J. Li, M. T. Liu, and F. X. Gao, “Energy-saving and Comfort Analysis of Urban Rail Transit Vehicle Variable Frequency Air Conditioning System,” Urban Rail Transit, Vol. 5, no. 18, pp. 99-103, 2015. (in Chinese).
[33] Z. S. Jin, “Research and Application Practice of Air Source Heat Pump Heating Technology,” Eng. Construct., Vol. 5, no. 12, pp. 50-52, 2022. (in Chinese).
[34] Q. F. Wang, “Application of LED Lighting in Subway Vehicles,” Energy Conservation, Vol. 32, no. 5, pp. 57-59, 2013. (in Chinese).
[35] H. L. Duan, “Research on Energy-saving Scheme of Urban Rail Transit Vehicle Lighting System,” Urban Rail Transit Research, Vol. 21, no. 2, pp. 34-37, 2018. (in Chinese).

Author's Biography:

Jingjie Yan Graduated from Southwest Jiaotong University, majoring in Vehicle Engineering (Urban Railway Transportation Direction) in 2016. He works at Shanghai Municipal Complete Equipment (Group) Co. Ltd., Railway Transportation Research Center as an Engineer, Electrician Technician. He is currently pursuing a master’s degree in engineering management at the Graduate School of Southeast Asian University, with a focus on urban rail transit vehicle technology.

Asst. Prof. Dr. Wirogana Ruengphrathuengsuka received his Ph.D. (Chemical Engineering) from Texas A&M University, USA, in 1992. At present, he is a director of the Master of Engineering Program in Engineering Management at SAU. His current research interests are in the areas of multi-phase equilibrium and transport in associated with interfacial science and renewable or alternative energy materials, and engineering