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Analysis and Discussion on the Current State and Demand of Energy Supply for Highway Transportation Facilities

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Abstract: Energy supply is a crucial factor in realizing the future transformation of highway transportation. Determining a comprehensive and sustainable energy supply network that aligns with the demands of future highway transportation facilities - ensuring they are "safe, reliable, environmentally friendly, efficient, and sustainable" - poses a key challenge for current highway developers and operational managers. This study examines the types and energy consumption of significant energy-consuming facilities along expressways. It delves into the current state of power supply and distribution technologies for highway transportation facilities, including low-voltage, medium-voltage, and complementary wind and solar power systems. Additionally, the research analyzes existing issues within power supply and distribution systems for highway transportation facilities. The study investigates the load characteristics and spatial distribution of electricity-consuming facilities along expressways, concluding with an analysis of the future trends in energy demand for highway transportation facilities. This comprehensive exploration encompasses aspects such as the scale of energy demand, the diversification of energy supply, and the need for a secure, efficient, and intelligent energy supply. The findings aim to provide valuable insights for developing innovative, diverse energy supply, and control technologies for safe, efficient, and interconnected highway transportation facilities.

1. Introduction

As transportation demands rapidly increase, the scale of transportation infrastructure construction in China remains consistently high. The total energy consumption and its proportion in the overall societal energy consumption of the transportation industry show a year-on-year upward trend. Highways, being the largest energy-consuming transportation mode on the demand side, have a vast distribution of energy-consuming facilities (primarily electrical) along their routes. These facilities exhibit large energy consumption, diverse types of energy loads, and high reliability requirements for some primary load equipment. With the development of intelligent highway construction, the future demand for energy will be even more substantial. The energy supply and service models for highway transportation facilities are facing a disruptive transformation, representing the most crucial and urgent area for the integrated development of transportation and energy.[1-3]

2. Analysis of Types and Energy Consumption of Important Energy-consuming Facilities along Expressways

Large-scale energy-consuming facilities set up along expressways are crucial for ensuring safe and reliable operation. According to their functional types, these important energy-consuming facilities can be classified into the following six categories:

(1) Monitoring System Type Energy-consuming Facilities

Electrical facilities for monitoring systems are mainly deployed in outdoor areas along the highway, such as gantry and cantilever variable message signs, signal lights, vehicle detectors, weather monitoring stations, cameras, monitors, etc. Along sections with continuous monitoring, cameras are generally set up every 2km or every 1km, resulting in a large quantity of cameras. Additionally, some electrical equipment units have relatively high energy consumption, such as gantry and F-type (single-pillar) variable message signs, which typically have power ranging from several hundred watts to several kilowatts. According to the "Technical Requirements for Expressway Monitoring Technology" and the "Interim Technical Requirements for Highway Network Operation Monitoring and Services," an average of 2 to 4 variable message signs is set up every 50 kilometers on expressways, including gantry variable message signs, cantilever variable message signs, pillar variable message signs, and variable speed limit signs, mainly located at expressway interchanges, toll plazas, tunnel entrances/bridge approaches, and sections with heavy traffic flow, adverse weather conditions, or frequent accidents.

(2) Communication System Type Energy-consuming Facilities

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Compared to other electromechanical systems, the number of electrical facilities for communication systems is relatively fewer. Currently, the main power-consuming devices include optical transmission equipment, optical fiber digital transmission systems, digital program-controlled exchange systems, emergency telephone systems, wireless mobile communication systems, and communication power supplies. Although there is a large quantity of electrical equipment, most of them have relatively low energy consumption per unit, with power generally ranging from several tens of watts to several hundred watts.

(3) Toll System Type Energy-consuming Facilities

Toll booths, toll lanes (entrance, exit), toll gantries for free-flowing traffic, and toll management centers are equipped with a large number of electrical facilities. Main components include toll canopy signal lights, lane control machines, automatic barrier machines, lane traffic lights, lane control signs, license plate recognition, video cameras, etc.

(4) Toll Station, Toll Plaza, Service Area, and Interchange Area Energy-consuming Facilities

This section of energy-consuming facilities is relatively concentrated in the entire highway system, with a considerable scale of energy consumption. For toll stations and toll plazas, the main power-consuming equipment is high pole lights used for nighttime illumination. Additionally, there are other auxiliary toll hardware electrical devices. The main energy-consuming facilities in service areas are lighting facilities, ventilation facilities, air conditioning facilities, household electrical facilities, and other gas-consuming facilities.

(5) Tunnel (Bridge) Lighting and Ventilation Type Energy-consuming Facilities

Expressways tunnels with a length exceeding 200 meters are equipped with tunnel lighting fixtures, ventilation fans (some very long tunnels over 3 km have axial flow fans), and a large number of energy-consuming devices for monitoring and surveillance inside the tunnel, such as surveillance cameras, vehicle detectors, lane control signs, and CO/VI detection equipment. The power of tunnel lighting fixtures is generally in the range of tens of watts to several hundred watts, and the power of jet fans is typically in the range of hundreds of watts. Large axial flow fans usually have a power range from several kilowatts to tens of kilowatts. Similar to highway management centers and service areas, tunnels are also highly concentrated energy-consuming facilities for expressway transportation, with a relatively large individual energy consumption.

(6) Power Supply and Distribution System Type Energy-consuming Facilities

The expressway power supply and distribution system are composed of many electrical equipment modules, providing stable and reliable electrical energy support for other electrical facilities along the expressway. Main components include:

1. AC Power Distribution System. High-voltage electricity (10kV or 35kV) is brought in from nearby high-voltage power grids to expressway substations; Transformers generate power supply voltage of 380V/220V; Low-voltage distribution panels and distribution lines then deliver power to various electrical facilities.

2. Diesel Generator Sets. Emergency backup power source to ensure uninterrupted power in case of a regular power supply interruption.

3. UPS Uninterrupted Power Supply System. Comprises rectifiers and charging devices converting AC mains to DC, and inverters converting DC back to AC, providing voltage stabilization.

4. DC Power Supply System. Primarily meets the power needs of certain DC devices in the communication system, such as vehicle detectors and emergency phones; DC power supply systems are typically derived from AC power sources through rectifiers, and uninterrupted power supplies may include batteries.

3. Current Status of Power Supply and Distribution Technology for Expressway Traffic Facilities

Given the current division of management responsibilities between the transportation and power supply industries in the transportation sector, the construction of power supply systems for highway users typically involves establishing the energy supply system based on the distribution circuit output end of the local power supply department's substation and low-voltage distribution cabinet. Currently, in China, the technical solution for power supply and distribution for traffic facilities along expressways is derived from the nearby 10/6kV public power grid. The public high-voltage transmission grid is usually constructed by the local power supply department and is generally located in concentrated areas of electrical facilities along expressways, such as tunnels, toll booths, service areas, monitoring centers, and management centers. Through the installation of 10kV/0.4kV substations in areas such as tunnels, toll booths, service areas, monitoring centers, and management centers, power is supplied to the electrical facilities within the effective supply radius, meeting the normal operational requirements with 220/380V electrical energy.[4]

Currently, various provinces and cities in China adopt four different power supply schemes for power supply systems along expressways based on different power supply distances and load characteristics:

(1) Low Voltage 380V Power Supply Scheme

In this scheme, the low-voltage distribution cabinet of the substation directly supplies power to the outdoor equipment along the highway, commonly used for loads close to the substation. See Figure 1 for the low-voltage cabinet circuit.

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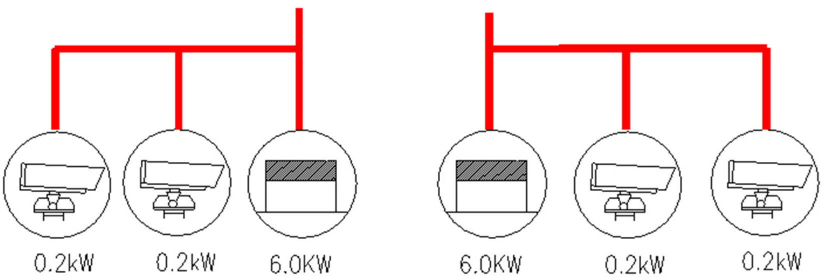

Figure 1 Direct 380V Low Voltage Power Supply Scheme for Outdoor Equipment

The low-voltage 380V power supply scheme provides three-phase power. Since expressway electrical facilities mostly use single-phase power, ensuring a roughly equal three-phase load is essential when connecting to a three-phase system. The voltage drop at the end of the power supply line is not allowed to exceed 5%. To meet the voltage drop requirements at the end of the line for distant or high-load electrical facilities, larger-diameter power cables are often used.

(2) 660V Voltage Boost and Reduction Power Supply Scheme

The 660V voltage boost and reduction power supply scheme have gradually gained application in recent years as an outdoor equipment power supply solution. If electrical facilities are within the range of 4km to 10km, a three-phase 660V power supply is employed. In the substation, three-phase 380V is boosted to three-phase 660V, and at the terminal of the electrical facility, the voltage is reduced back to three-phase 380V. The cables used have a voltage rating of 1kV. The power supply scheme is illustrated in Figure 2.

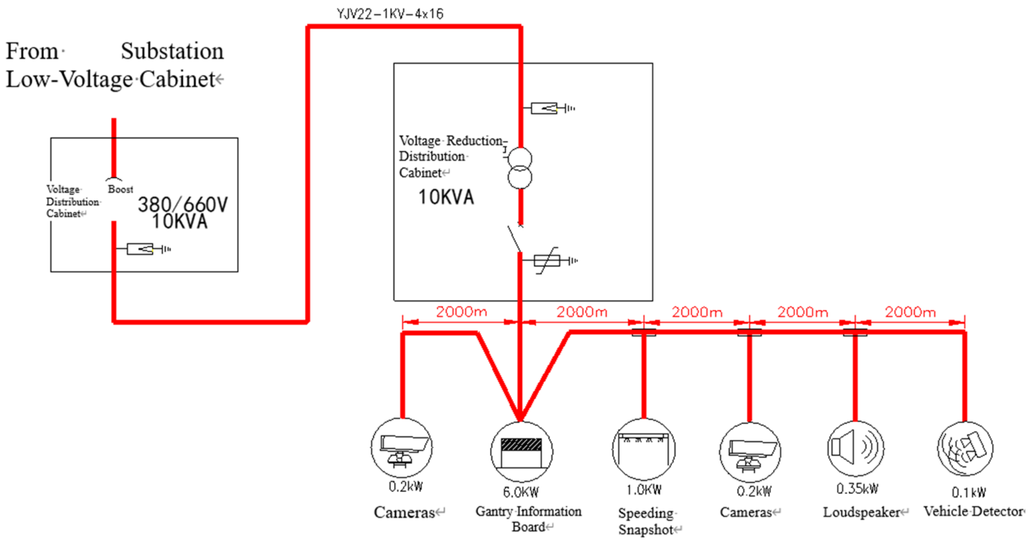

Figure 2 660V Voltage Boost and Reduction Power Supply Scheme

This scheme represents an enhancement over the low-voltage 380V power supply scheme in terms of both power supply distance and capacity. However, it has limitations for loads beyond 10km and for larger loads such as continuous monitoring and lighting throughout the entire distance. The system provides three-phase power, necessitating the balance of three-phase loads. As the system transmits 660V electricity to a centralized point of use and then reduces it to 380V using a step-down transformer to supply equipment within a certain range, there is a need for repeated cable laying.

(3) Medium Voltage 10kV Power Supply Scheme

The choice of voltage level for transmitting electrical energy is a balance between load capacity, power supply distance, and economic considerations. In theory, with a constant load, higher transmission voltage results in lower transmission current, reducing voltage drop within the cable and allowing for longer transmission distances. However, higher voltage levels demand greater insulation capabilities in power supply equipment, leading to increased insulation costs and overall equipment and cable expenses. The medium voltage 10kV power supply scheme is depicted in Figure 3.

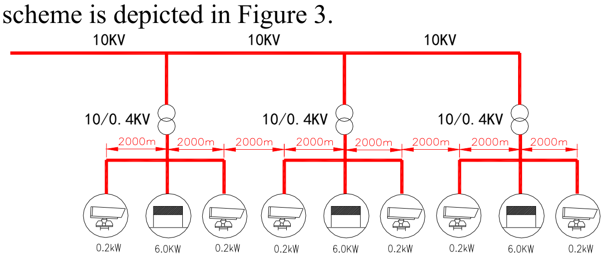

Figure 3 Indirect 10kV Power Supply Scheme for Outdoor Equipment

In expressway full-length monitoring projects, the electrical load mainly consists of devices such as cameras and variable message signs, with a relatively dispersed load. Powering these devices with a 10kV system involves placing a 10/0.4kV transformer at a location where the load is relatively concentrated, and then supplying power to electrical devices within a 4km radius. While 10kV voltage allows for longer transmission distances, the cost of 10kV cables and underground transformers is higher. Additionally, there is a secondary distribution issue in indirect power supply, leading to a high proportion of cable redundancy and increased costs.

(4) Wind-Solar Hybrid Power Supply Scheme

In some parts of China's expressways, small loads located far from substations are powered by solar or wind-solar hybrid systems. However, large loads such as information boards cannot be powered by these systems. The primary characteristics of solar-powered outdoor supply are its reliance on solar and wind energy, eliminating the need for traditional wiring. Moreover, the system is pollution-free, easy to maintain, has a long lifespan, and benefits from abundant energy sources. The system components are as illustrated in Figure 4:

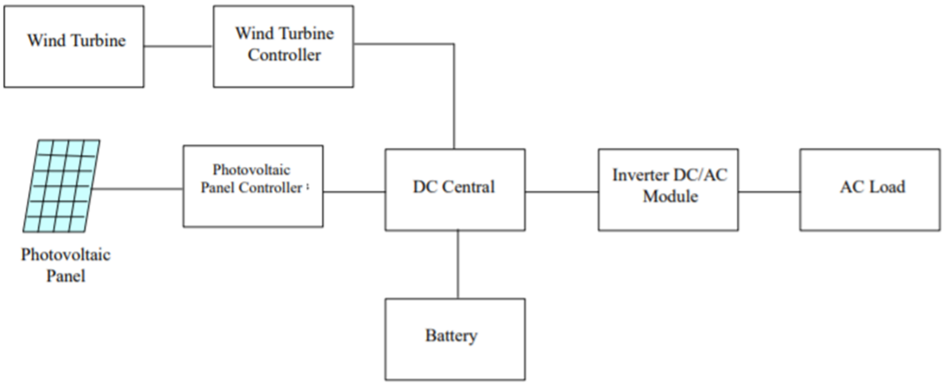

Figure 4 Wind-Solar Hybrid Power Supply Scheme

Currently, in our country, the supply and distribution of electricity along expressways are solely based on the perspective of meeting the power supply demand, mainly addressing issues related to low-voltage distribution and supply. Whether it is high-voltage or low-voltage supply, there are several problems existing: Weak load-bearing capacity and large cable usage: A significant amount of high and low-voltage cables are required, leading to high engineering costs, especially with the rise in raw material prices; Low power factor and high reactive power loss in the power transmission system: The level of energy interconnection and smart control is relatively low; Due to the open geographical terrain of expressways, power lines are vulnerable to lightning strikes and operational overvoltages in the power supply system, resulting in poor power quality; Expressways are located in remote areas, making high and low-voltage cables prone to theft, necessitating the installation of cable anti-theft systems. Therefore, the provision of safe, reliable, economical, and rational highway transportation facilities and low-voltage distribution systems is one of the fundamental conditions for ensuring the safety of electricity use and the quality of power along highways.

4. Analysis of Electrical Facility Characteristics along Expressways

(1) Analysis of Load Characteristics

The load characteristics of electrical facilities along highway transportation can be divided into two major categories: linear loads and nonlinear loads. Linear loads refer to loads where the impedance parameters (Z) remain constant as a function of the applied variable sinusoidal voltage, and the current is sinusoidal. High-pressure sodium lamps commonly used on expressways fall under this category of linear loads.

1) Linear loads can be further divided into inductive loads and capacitive loads. The common linear loads on expressways are mostly inductive loads. To improve the power factor during the operation of inductive loads and reduce the electrical energy loss caused by a low power factor, it is necessary to install capacitor compensation cabinets. Capacitor compensation cabinets can offset a portion of the inductive current, reducing the total current and the phase difference between current and voltage, thereby increasing the power factor. This compensation method is more effective for inductive loads.

2) Nonlinear loads refer to loads where the impedance parameters (Z) are not always constant but vary with other parameters such as voltage or time. An important characteristic of nonlinear loads is that when sinusoidal voltage is applied to the load, the current is not sinusoidal. Such loads include soft starters, switch-mode power supplies, variable frequency drives, electronic data imaging equipment, etc. The commonly used computers, network devices, toll booth equipment, cameras, variable message signs, detectors, and LED lighting fixtures on expressways all belong to the category of nonlinear loads.

Nonlinear loads also suffer from a low power factor due to mismatched current and voltage waveforms. If capacitor compensation cabinets are used for power factor compensation, it only shifts the phase of the current, which not only fails to improve the power factor but also causes an impact on the power grid when electrical devices are used during non-voltage peaks.

(2) Characteristics of Load Spatial Distribution

As mentioned earlier, apart from high-power electrical facilities such as lighting equipment, ventilation systems, and gantry-mounted highway LED variable signs along the expressway, most facilities have small individual loads that are spatially dispersed. They exhibit a belt-like distribution with a large supply radius. Additionally, on both sides of the road segment, there is a belt-like distribution of low-power electrical devices. For instance, the challenge of supplying power over long distances with low power consumption for numerous video surveillance cameras, weather detectors, vehicle detectors, and other devices with only a few watts of power along the highway is representative. The technical reliability and economic feasibility of the power supply system are particularly prominent.

Moreover, with the continuous increase in the mileage of expressways and the rapid development of smart highways, collaborative development of vehicles and roads, and the electrification of vehicles, there will be a significant addition of low-power electrical (charging) devices along the route. This necessitates that future power supply systems must cover the entire road network, and key technical indicators such as construction cost, power factor, harmonic currents, and voltage regulation accuracy will become increasingly stringent.

5. Analysis of Energy Demand for Highway Transportation Facilities

(1) The Scale of Energy Demand Shows a Dramatic Increase

Firstly, there has been significant development in the highway network over the past few decades, leading to an increasing number of facilities and equipment for traffic operation and management, resulting in a growing scale of energy consumption. According to data from the "Strategic Report on the Integrated Development of Transportation Energy," the annual electricity consumption of China's highway transportation infrastructure is 11.48 billion kWh, equivalent to 1.409 million tons of standard coal. Among these, the electricity consumption of highway tunnel facilities accounts for the largest proportion, approximately 97.6% of the total electricity consumption, while the electricity consumption of other facilities along highways accounts for about 2.4% of the total electricity consumption.

Secondly, as the smart highway initiative gradually advances, the demand for new formats such as vehicle-road collaboration, autonomous driving, vehicle electrification, and electrification of highway transportation facilities increases. In the future, highways will serve as the most important application scenario, inevitably leading to a significant increase in the number of intelligent and connected traffic operation information collection, monitoring, analysis and processing, communication transmission (5G), information dissemination, charging facilities, and auxiliary autonomous driving sensor devices along the route. It can be foreseen that the scale of electricity consumption and energy demand for facilities along highway transportation routes will increase by orders of magnitude compared to the current level. [5-9]

(2) Diversification Trend in Energy Supply

In recent years, the Ministry of Transport has successively issued documents such as the Implementation Plan for Promoting Ecological Civilization Construction in Transportation, the Opinions on Comprehensively and Thoroughly Promoting the Development of Green Transportation, and the Implementation Plan for Controlling Greenhouse Gas Emissions in the Transportation Industry during the 13th Five-Year Plan Period. It has also issued the "Green Transportation Standard System (2016)" and the General Specifications for Solar Power Supply System for Highway Facilities (GB/T 24716-2009), vigorously promoting the adjustment and optimization of the energy supply structure in the industry and the construction of green highway infrastructure. It promotes the application of energy-saving and emission-reduction technologies, promotes the deep and wide integration of clean energy with transportation equipment and transportation infrastructure, enhances the cleanliness and energy efficiency of transportation equipment and energy-consuming facilities, and assists in achieving the goals of our country.

From this perspective, transportation is no longer limited to conventional fossil energy as the sole energy source. The energy consumption of highway transportation facilities is gradually shifting towards a development trajectory dominated by conventional energy sources and utilizing various clean energy sources such as photovoltaics, wind energy, hydropower, geothermal energy, and hydrogen energy. The deep exploration of the potential and resources for the development and utilization of clean energy in highway transportation facilities transforms these facilities from mere energy consumers to a new model where energy consumption and energy supply coexist. This shift effectively alleviates the increasingly tight constraints on resources in China and supports the steady development of our country's ecological environment. [10-13]

(3) Urgent Demand for Safe, Efficient, and Intelligent Energy Supply

Currently, there are several issues with the electricity supply channels along China's highway transportation routes that need to be addressed: weak carrying capacity, low power factor, high reactive power loss, low electricity quality, unstable power supply, and low level of energy interconnection and smart control. Furthermore, it is well known that there is a geographical overlap between highway transportation facilities and solar photovoltaic resources. The energy supply for highway transportation will follow a trend of diversification. In the future, a significant amount of clean solar energy along highways will undoubtedly be deeply integrated into and fully utilized by transportation facilities.

As the energy dynamics of highway transportation facilities shift from being mere consumers of electricity to having the capability of clean energy generation, the energy systems of these facilities are transitioning from a singular "load" state to a coexistent "source-load" state. This means that with the integration of highway transportation facilities and distributed photovoltaic (PV) generation, these facilities are gradually transforming from energy consumers to providers of clean electric power. Distributed PV generation exhibits noticeable fluctuations due to variations in solar radiation intensity and day-night cycles, making it an intermittent and unstable power source. Looking ahead, with the rapid development of distributed PV energy technology along highway corridors, the widespread integration of clean PV energy into the highway supply and distribution systems raises crucial questions about effectively controlling, storing, absorbing, and utilizing PV clean energy. Therefore, the development of a secure, efficient, and intelligent energy supply and management technology system for highway transportation is a key technical challenge that needs immediate attention. Considering the global trends in technological development, the integration of information and communication technologies (ICT) such as the Internet of Things (IoT), big data, cloud computing, and cyber-physical systems with energy systems becomes essential. Establishing an energy internet through this integration proves to be a crucial technological approach to breaking away from dependence on fossil fuels in industrial and economic development models. Against this backdrop, the basic concept and vision of the energy internet have been proposed, regarded as a solid foundation and core driving force for the Third Industrial Revolution.[14-17]

6. Conclusion

(1) In order to adapt to the future development trend of expressways, energy-saving operation of expressways has become a trend in the industry. Facing the scale of electricity consumption and energy demand of facilities along future highways, by adopting intelligent and energy-efficient diversified power supply technologies, a distributed energy network utilizing various clean energy sources such as conventional energy, photovoltaics, wind power, hydropower, geothermal energy, and hydrogen energy is being constructed. This approach aims to address the issues faced by traditional power distribution systems, such as high construction costs and energy losses.

(2) This paper analyzes the current status of power supply and distribution technologies for highway transportation facilities. Addressing the application scenarios and demands for energy supply to distributed, long-distance, multi-single-point, and low-load electrical equipment along highways, a novel, safe, efficient, and intelligent interconnected diversified energy supply and control technology based on the characteristics of the energy internet is proposed. This technology enables the coexistence of "source-load," multi-point interconnection, online monitoring, intelligent distribution, and diversified complementarity in highway transportation energy systems, providing a safe, efficient, and intelligent energy supply network for highway transportation facilities.

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References

1. Chen Yanbo, Liu Zhihui, Wu Shicun et al. Preliminary Study on Highway Green Energy System Architecture [J]. New Type Power Systems, 2024, (01): 94-114.
2. Lu Xudong, Yu Xiongfei, Zhang Xiaofeng et al. Distributed renewable energy in highway tunnels application status and prospects[J]. Highway, 2024, (03): 379-385.
3. Tang Hongwei, Lu Chuanjie, Chen Mengjie. Intelligent comprehensive energy management system for highways [J]. China ITSJournal, 2024, (S1): 208-211.
4. Chen Yanbo, Liu Zhenxiang, Tian Haoxin et al. A Review and Prospect of Expressway Green Energy System[J]. Proceedings of the CSEE, 2024, (03): 1-18.
5. Huang Ying, Guo Hongxu, Liao Cuiping, Zhao Daiqing. Research on Low-carbon Development Path of Urban Transportation Based on LEAP Model: A Case Study of Guangzhou [J]. Advances in Climate Change Research, 2019, v.15; No.88(06): 670-683.
6. Ma Huiqiang, Liu Jiale, Gong Zhigang. Measurement and Evolution Mechanism of Carbon Emissions from Tourism Transportation in Shanxi Province [J]. Economic Geography, 2019, v.39; No.254 (04): 223-231.
7. Pei Jianzhong. Progress of Highway Engineering and Generation Upgrading of Highway Transportation System [J]. China Journal of Highway and Transport, 2018, v.31; No.183 (11): 1-10.
8. Tang Hao, Kuai Haidong, Huang Xiaoming. Highway Maintenance Energy Consumption Model Based on Life Cycle Analysis [J]. Journal of Southeast University (Natural Science Edition), 2016, v.46(03): 629-634.
9. Ouyang Bin, Feng Zhenhua, Li Zhongkui, Bi Qinghua, Zhou Aiyan. Calculation and Evaluation Method of Transportation Energy Consumption and Carbon Emissions: A Case Study of Jiangsu Province [J]. Soft Science, 2015, v.29; No.181(01): 139-144.
10. Jiang Haibing, Zhang Wenzhong, Qi Yi, Zhou Liang. Spatial Spillover Effects of Expressway Investment Based on Accessibility Analysis[J]. Geographical Research, 2014, v.33(01): 71-82.
11. Wang Fumin. Practice and Exploration of Financing Methods for Highway Construction Market [J]. Journal of Highway and Transportation Research and Development, 2000, (04): 67-69.
12. Kang Yanmin. Discussion on the Characteristics and Issues to be Noticed in the Development of China's Expressway Construction [J]. Journal of Highway and Transportation Research and Development, 2000, (06): 92-95.

13. Zhen Zhanhong, Jia Xuemin. Current Situation of Expressway Development [J]. Economic Forum, 2000, (18): 38.
14. Hong Juhua, Liu Junyong, et al. Preliminary Understanding and Research Outlook on Urban Energy Internet[J]. Electric Power Automation Equipment, 2017, 37(6): 15-25.
15. Chen Jinbin. Research on the Application of Intelligent and Energy-efficient Power Distribution Scheme for Expressway.Traffic Engineering,2019,5: 308-310.
16. Ding Rongjun, Zhang Zhixue, Li Hongbo. Reflections on Energy Internet in Rail Transit [J]. Electric Drive for Locomotives, 2016 (1): 1-5.
17. Khayyam S,Ponci F,Goikoetxea J,et al. Railway energy management system: centralized–decentralized automation architecture[J]. IEEE Transactions on Smart Grid, 2016, 7(2): 1164-1175.