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Study on the whole lifecycle energy consumption scenarios of expressway

Cui Peiqiang[1,a], Yu Qi[2,3,a], Liu Jie[2,3], Mao Ning[2,3,*], and WU Yizheng[4]

[1] Gezhouba Group Transportation Investment Co., Ltd., Qiaokou Road, Qiaokou District, Wuhan 430000, Hubei Province, China
[2] Transport Planning and Research Institute, Ministry of Transport, Shuguang Xili, Chaoyang District, Beijing 100028, China
[3] Laboratory of Transport Pollution Control and Monitoring Technology, Shuguang Xili, Chaoyang District, Beijing 100028, China
[4] Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, China

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Abstract. This paper constructs a set of energy consumption scenarios for typical expressway construction, operation and maintenance phases, and analyses the energy demand under each scenario. Firstly, a comprehensive lifecycle energy consumption framework for expressway is established, detailing the energy consumption scenarios during construction, operation, and maintenance phases. Secondly, based on literature review and scenario assumptions, the study examines the energy consumption levels under different scenarios and analyses the proportion of energy consumption in each scenario. The results show that the ratio of energy consumption during the construction, operation and maintenance phases of expressway is about 5:10:3. The energy consumption during the construction phase is the highest for the construction of expressway trunk lines, accounting for about 80.6% of the total energy consumption. During the operation phase, fuelling and refuelling stations consume the most energy, accounting for about 71.4%. The energy consumption of expressway trunk lines is the highest during maintenance phase, which accounting for about 70%. This analysis facilitates a deeper understanding of the characteristics of the integration between transportation and energy networks, and assists the transportation sector in achieving carbon peak and carbon neutrality goals in a scientifically sound manner.

1 Introduction

As an essential sector for pollution reduction and carbon emission reduction in China, the field of transportation has garnered increasing attention for its energy-saving and carbon-reduction initiatives. In recent years, with the profound integration of transportation and energy development, the clean energy supply system for expressway has become a significant measure for energy conservation and carbon reduction in the road sector. In 2023, the sales volume of new energy vehicles in China reached 9.5 million units, accounting for over 60% of the global share. A cumulative total of 20,000 charging piles have been constructed in the service areas of expressways. With the rapid development of new energy vehicles, the energy consumption performance during the operation of expressway has attracted widespread concern. The level of energy consumption on expressways has a profound impact on the construction of self-sufficient energy systems for expressway infrastructure. This study systematically categorizes and analyses the energy consumption scenarios throughout the entire lifecycle of expressway, providing a detailed breakdown of the distribution and proportion of energy use during the construction, operation, and maintenance phases. This analysis facilitates a deeper understanding of the characteristics of the integration between transportation and energy networks, and assists the transportation sector in achieving carbon peak and carbon neutrality goals in a scientifically sound manner.

The energy footprint of expressway is a multifaceted issue that encompasses their construction, operation, and maintenance phases. Understanding the energy dynamics at each stage is crucial for sustainable infrastructure planning and carbon emission reduction strategies. Various researchers have investigated energy consumption in transportation. Song *et al.* (2014) examined shifts in the transportation sector in Shanghai from 2000 to 2010 and their implications for transportation energy consumption and efficiency. Jia *et al.* (2010) developed a calculation model based on vehicle operation to analyse China's transportation energy consumption levels. Different methodologies

[a] These authors contributed equally to this work and should be considered co-first authors.
* Corresponding author: maoning@tpri.org.cn

have been employed to study energy consumption in highway systems, focusing on diverse aspects of highway construction, operation, and maintenance. Artificial Neural Networks (ANN) has been developed to predict highways energy consumption (Cansiz *et al.*, 2022). Life Cycle Assessment method has been adopted to quantitatively analyse the energy consumption of bridge-based expressways in South China (Lv *et al.*, 2018). The Analytic Hierarchy Process combined with fuzzy synthetic evaluation was applied to establish and calculate an energy consumption index system for highway transportation infrastructure, providing a rapid evaluation method (Qi *et al.*, 2020). A dynamic model of road transportation energy demand system in Beijing was built to analyze the relationship between urban road transportation energy demand and economy and passenger transportation (Zhang *et al.*, 2019). Principal Component Analysis was utilized to identify and analyze the main influencing factors of energy consumption in highway service areas, elucidating the relationship between energy consumption and factors such as building scale and traffic flow (Shi-Yong *et al.*, 2021). Additionally, real-world data collection and analysis were conducted to study the energy consumption patterns of electric vehicles on highways, examining the impact of driving conditions and operational scenarios (Liang *et al.*, 2023). Several studies have revealed energy consumption variations during different phases of expressway development. The energy consumption during the construction phase is primarily attributed to the building of trunk lines and tunnels. Lu (2011) developed a statistical model highlighting the energy-intensive nature of highway construction. Zou and Cheng (2019) provided empirical data on energy consumption during the construction of a specific highway segment, emphasizing the substantial energy draw from tunnel and trunk line projects. Mao *et al.* (2023) conducted a quantitative evaluation on the energy consumption and carbon emissions during the asphalt pavement regeneration process. During the operation phase, the energy landscape shifts towards the use of infrastructure and the vehicles themselves. Tang (2013) and Li (2016) explored the energy consumption of expressways during operation, including the energy required for traffic management systems, lighting, and other operational necessities. Guo *et al.* (2022) have proposed a new method for measuring energy consumption during the operational phase of highways, specifically within service areas. Their findings indicate significant energy consumption, primarily from electricity, which suggests areas for targeted energy efficiency improvements. The maintenance phase, often understated, is nonetheless substantial in terms of energy use. Pan (2011) and Shen (2017) conducted research on the energy consumption and carbon emissions associated with highway maintenance, revealing that routine upkeep and repairs contribute significantly to the overall lifecycle energy consumption.

This study expands the existing body of knowledge by constructing a set of energy consumption scenarios for a typical expressway, offering a thorough breakdown of energy use during construction, operation, and maintenance, while considering the impact of new energy vehicles on expressway energy consumption, thereby providing foundational support for research on expressway clean energy systems.

2 Methodology

2.1 Lifecycle-based energy consumption scenarios of expressway

According to the ISO 14044:2006 standard, Life Cycle Assessment (LCA) is a systematic framework employed to evaluate various aspects associated with product development and its potential impacts throughout the entire life cycle – from raw material acquisition and processing to manufacturing, use, and ultimately disposal (*i.e.*, cradle to grave) (ISO 2006). This paper utilizes a life cycle assessment approach to analyze energy consumption scenarios related to the entire life cycle of expressway. Within this framework, the life cycle of an expressway can be segmented into three distinct phases: construction, operation, and maintenance.

In terms of energy consumption characteristics of expressway, the construction phase is categorized into four primary scenarios: expressway trunk lines, tunnels, service areas, and toll stations. The operation phase consists of six main scenarios: tunnels, service areas, toll stations, expressway trunk lines, operation and management centers, and fuelling (LNG) stations/charging (battery swap) stations. Finally, the maintenance phase encompasses four scenarios: expressway trunk lines, tunnels, service areas, and toll stations.

2.1.1 *Energy consumption scenarios during the construction phase*

To conduct a comprehensive analysis of the energy consumption characteristics during the construction phase of expressway, this study establishes a set of energy consumption scenarios specific to this phase. The analysis takes into account the unique construction characteristics associated with various expressway contexts and delineates the energy consumption projects within each scenario. The specific classification of these projects is presented in Table 1.

2.1.2 *Energy consumption scenarios during the operation phase*

The operational phase of expressway constitutes the primary stage of energy consumption, primarily deriving from the energy consumption of infrastructure facilities and transportation equipment. This study establishes a scenario set for energy consumption during the operational phase of expressway, outlining the principal energy-consuming equipment within expressway infrastructure. The energy consumption of refuelling/LNG stations and charging (battery swap) stations reflects that of transportation equipment. Detailed specifics are provided in Table 2.

2.1.3 *Energy consumption scenarios during the maintenance phase*

The maintenance phase of expressway encompasses road maintenance as well as the maintenance of associated

Table 1. Energy consumption scenarios during expressway construction phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects
Expressway trunk lines	Road base engineering	Drainage engineering, road base earth-rock engineering, soft foundation treatment.
	Road surface engineering	Pavement structure and subgrade, pavement surface layer, pavement accessory engineering.
	Road intersection engineering, bridge and culvert engineering	Excavation, island construction, cofferdam installation, sinking wells, piling, grouting, masonry engineering, arch keystone, steel structure engineering.
	Traffic engineering and ancillary facilities engineering	Safety facilities and signage, communication system installation, power supply system installation, lighting system installation, optical cable and cable installation, grounding engineering, green engineering.
	Temporary engineering	Temporary access road, temporary bridge, dock, building construction, power line construction and demolition, communication line construction and demolition, water supply pipeline construction and demolition, pre-acceptance maintenance.
Tunnels	Tunnel engineering	Tunnel body engineering, tunnel door engineering, auxiliary tunnel engineering, facility installation.
Service areas	Vehicle service facilities engineering	Parking lot construction, gas station construction, charging pile installation, vehicle access road construction, repair shop construction.
	Personnel service facilities engineering	Toilet, canteen, restaurant, shop, hotel, lounge, and medical station construction, pedestrian plaza and walkway construction, other facility construction
	Management facilities engineering	Monitoring room, communication equipment room, management office, staff dormitory construction.
	Auxiliary facilities engineering	Electrical room construction, garbage classification facility construction, pumping station and other auxiliary room construction, sewage treatment facility construction.
	Emergency facilities engineering	Emergency rescue site construction toll station.
Toll stations	Toll area construction	Toll booth, toll island, and toll canopy construction.
	Toll plaza construction	Widening of roads before and after the toll station.
	Management building construction	Office, staff dormitory, and monitoring room construction.
	Auxiliary facilities construction	Garage and kitchen construction, and water, electricity, and gas facility installation.

facilities. This study constructs a scenario set for energy consumption during the maintenance phase of expressway, providing an overview of the primary energy consumption projects under different scenarios. Detailed information is presented in Table 3.

2.2 Expressway energy consumption analysis model

Based on the constructed scenario set of expressway energy consumption, and utilizing literature analysis and scenario assumptions, this study investigates energy consumption levels under different scenarios and analyzes the proportion of energy consumption in each scenario. A typical example (four lanes in both directions, 15% bridge-tunnel ratio, 50 km service area spacing, 12.5 km toll station spacing, 100 km management center spacing, 10,000 pcu/d traffic volume, 20% of which are new energy vehicles, 15 years operation phase) is proposed in this paper for calculating energy consumption levels.

3 Analysis of energy consumption scenarios for expressway

3.1 Analysis of energy consumption scenarios during expressway construction phase

The levels of energy consumption during the expressway construction phase are detailed in Table 4, while the corre-

Table 2. Energy consumption scenarios during expressway operation phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects
Infrastructure energy consumption	Tunnels	Lighting fixtures, ventilation systems, monitoring equipment, safety information equipment, emergency power facilities, etc.
	Service areas	Lighting fixtures, refrigeration and heating equipment, life service facilities, vehicle service facilities, office facilities, monitoring equipment, etc.
	Toll stations	Toll facilities, monitoring equipment, office lighting facilities, etc.
	Expressway trunk lines	Lighting fixtures, monitoring equipment, communication equipment, etc.
	Management centers	Life facilities, office facilities, etc.
Transportation equipment energy consumption	Refuelling /LNG stations	Gasoline vehicles, diesel vehicles, natural gas vehicles, etc.
	Charging (battery swap) stations	Electric vehicles, hydrogen fuel cell vehicles, etc.

Table 3. Energy consumption scenarios during expressway maintenance phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects
Expressway trunk lines	Road base maintenance and repair	Roadbed maintenance engineering, slope protection engineering, drainage engineering, etc.
	Road surface maintenance and repair	Daily pavement maintenance, pavement crack and pothole repair, etc.
	Ancillary facilities maintenance and repair	Signage and marking maintenance, roadside facility maintenance, etc.
	Green belts maintenance and repair	Watering, pruning, fertilizing, pesticide application, replanting, etc.
Tunnels	Tunnel maintenance	Daily cleaning, crack treatment, water leakage treatment, landslide treatment, cleaning and replacement of lighting facilities, drainage system maintenance, mechanical and electrical facilities maintenance, etc.
Service areas	Vehicle service facilities maintenance	Parking lot, gas station, charging station, vehicle traffic lanes, repair shop maintenance, etc.
	Personnel service facilities maintenance	Restaurants, shops, toilets, hotels, lounges, pharmacies, first aid stations, pedestrian squares, pedestrian walkways, other facility maintenance, etc.
	Management facilities maintenance	Monitoring room, communication equipment, management office building, employee dormitory maintenance, etc.
	Auxiliary facilities maintenance	Electrical room, garbage disposal facilities, pump room and other auxiliary construction maintenance, sewage treatment facility maintenance, etc.
	Emergency facilities maintenance	Emergency rescue site maintenance, etc.
Toll stations	Toll areas maintenance	Toll island, toll booth, toll canopy maintenance, etc.
	Toll plazas maintenance	Road pavement maintenance, etc.
	Management buildings maintenance	Office, staff dormitory, monitoring room maintenance, etc.
	Auxiliary facilities maintenance	Garages, kitchens, water/electricity/gas facilities maintenance, etc.

Table 4. Energy consumption scenarios during expressway construction phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects	Energy consumption intensity (tce/km)
Expressway trunk lines (80.6%)	Road base engineering	Drainage engineering, road base earth-rock engineering, and soft foundation treatment.	366.7
	Road surface engineering	Pavement structure and subgrade, pavement surface layer, and pavement accessory engineering.	131.8
	Road intersection engineering, bridge and culvert engineering	Excavation, island construction, cofferdam installation, sinking wells, piling, grouting, masonry engineering, arch keystone, and steel structure engineering.	81.1
	Traffic engineering and ancillary facilities engineering	Safety facilities and signage, communication system installation, power supply system installation, lighting system installation, optical cable and cable installation, grounding engineering, and green engineering.	11.2
	Temporary engineering	Temporary access road, temporary bridge, dock, building construction, power line construction and demolition, communication line construction and demolition, water supply pipeline construction and demolition, and pre-acceptance maintenance.	16.8
Tunnels (18.6%)	Tunnel engineering	Tunnel body engineering, tunnel door engineering, auxiliary tunnel engineering, and facility installation.	140.5
Service areas (0.4%)	Vehicle service facilities engineering	Parking lot construction, gas station construction, charging pile installation, vehicle access road construction, and repair shop construction.	0.56
	Personnel service facilities engineering	Toilet, canteen, restaurant, shop, hotel, lounge, and medical station construction, pedestrian plaza and walkway construction, and other facility construction	0.56
	Management facilities engineering	Monitoring room, communication equipment room, management office, and staff dormitory construction.	0.56
	Auxiliary facilities engineering	Electrical room construction, garbage classification facility construction, pumping station and other auxiliary room construction, and sewage treatment facility construction.	0.56
	Emergency facilities engineering	Emergency rescue site constructiontoll station.	0.56
Toll stations (0.4%)	Toll area construction	Toll booth, toll island, and toll canopy construction.	0.56
	Toll plaza construction	Widening of roads before and after the toll station.	0.56
	Management building construction	Office, staff dormitory, and monitoring room construction.	0.56
	Auxiliary facilities construction	Garage and kitchen construction, and water, electricity, and gas facility installation.	1.12

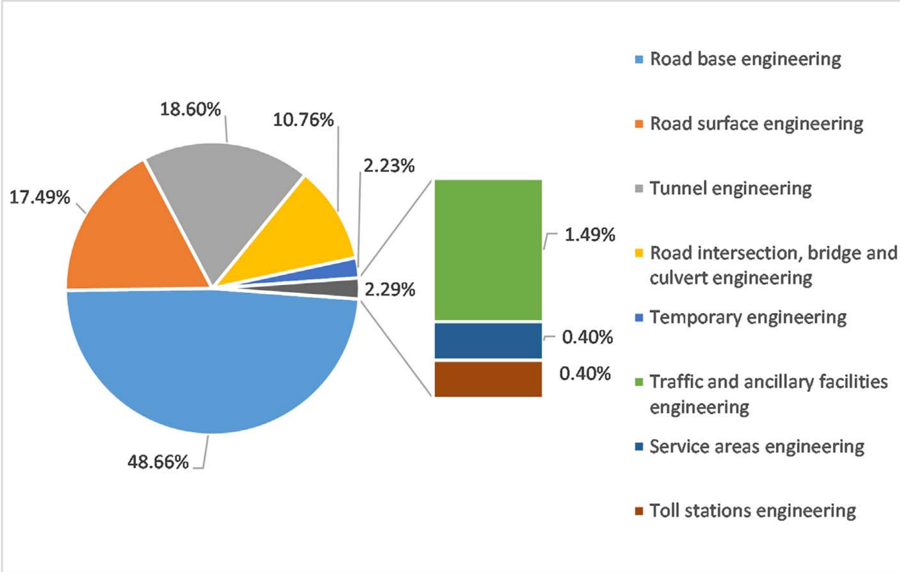

Fig. 1. Proportion of energy consumption during expressway construction phase.

sponding consumption proportions are illustrated in Figure 1.

3.1.1 Expressway trunk lines

The construction of expressway trunk lines mainly involves six major types of projects, which are road base engineering, road surface engineering, bridge and culvert engineering, ancillary facilities engineering, road intersection engineering and temporary engineering. The energy consumption of expressway trunk line projects accounts for about 80.6% of the total energy consumption during the construction phase (Lu, 2011), of which about 95% is consumed by mechanical equipment and mixing stations, and about 5% is consumed by on-site offices and life. For asphalt concrete pavement construction, energy consumption in the mixing stage accounts for about 90% of the total energy consumption during the construction phase, paving and compaction accounts for about 8%, and material transportation accounts for about 2%. For cement concrete pavement construction, the proportion of energy consumption in the mixing stage is higher, approximately 94%.

3.1.2 Tunnel

The tunnel engineering mainly includes tunnel body engineering, tunnel door engineering, auxiliary pit and facility installation works. The main energy consumption machinery for tunnel body engineering includes air compressor, rock drill, loader, dump truck, welding machine, bulldozer, etc. The main energy consumption machinery of the tunnel door engineering includes crane, welding machine, dump truck, etc. Auxiliary pit construction mainly uses winch, air compressor and ventilator. Facility installation works mainly use cranes, cargo trucks, winches, welding machines, forklifts, etc. According to the mainstream market equipment performance and engineering shift scheme, the energy consumption of tunnel engineering accounts for about 18.6% of the total energy consumption of the construction phase (Zou and Cheng, 2019).

3.1.3 Service area

The construction of service area includes: (1) Vehicle service facilities: parking lot, gas station, charging pile, vehicle access, repair workshop, etc. (2) Personnel service facilities: restaurants, toilets, stores, hotels, medical stations, pedestrian passages, etc. (3) Management facilities: monitoring rooms, communication equipment rooms, management office rooms, staff dormitories, etc. (4) Auxiliary facilities: electrical rooms, refuse collection points, sewage treatment facilities, etc. (5) Emergency rescue places, etc. According to statistics, the energy consumption for the construction of service areas accounts for about 0.4% of the total energy consumption during the construction phase. The overall energy consumption of the construction of the five types of facilities is comparable, accounting for about 20% respectively (Li, 2013).

3.1.4 Toll station

The construction of toll station mainly includes: (1) Toll area: toll island, toll booth, toll shed, etc. (2) Toll plaza: road widening project before and after the toll station. (3) Management building: toll staff offices, dormitories, monitoring rooms, etc. (4) Auxiliary facilities: including garage, kitchen, water, electricity and gas supply facilities, etc. According to statistics, the energy consumption of toll station construction accounts for about 0.4% of the total energy consumption during the construction phase. Among the four types of facilities, the energy consumption of the construction of ancillary facilities is higher, accounting for about 40% of the total energy consumption of the construction of toll stations, while the other three types of facilities each account for about 20% (Zou, 2015).

Table 5. Energy consumption scenarios during expressway operation phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects	Energy consumption intensity (tce/km · a)
Infrastructure energy consumption (20%)	Tunnels	Lighting fixtures, ventilation systems, monitoring equipment, safety information equipment, emergency power facilities, etc.	4.52
	Service areas	Lighting fixtures, refrigeration and heating equipment, life service facilities, vehicle service facilities, office facilities, monitoring equipment, etc.	3.12
	Toll stations	Toll facilities, monitoring equipment, office lighting facilities, etc.	3.12
	Expressway trunk lines	Lighting fixtures, monitoring equipment, communication equipment, etc.	1.87
	Management centers	Life facilities, office facilities, etc.	2.96
Transportation equipment energy consumption (80%)	Refuelling/LNG stations	Gasoline vehicles, diesel vehicles, natural gas vehicles, etc.	55.62
	Charging (battery swap) stations	Electric vehicles, hydrogen fuel cell vehicles, etc.	6.70

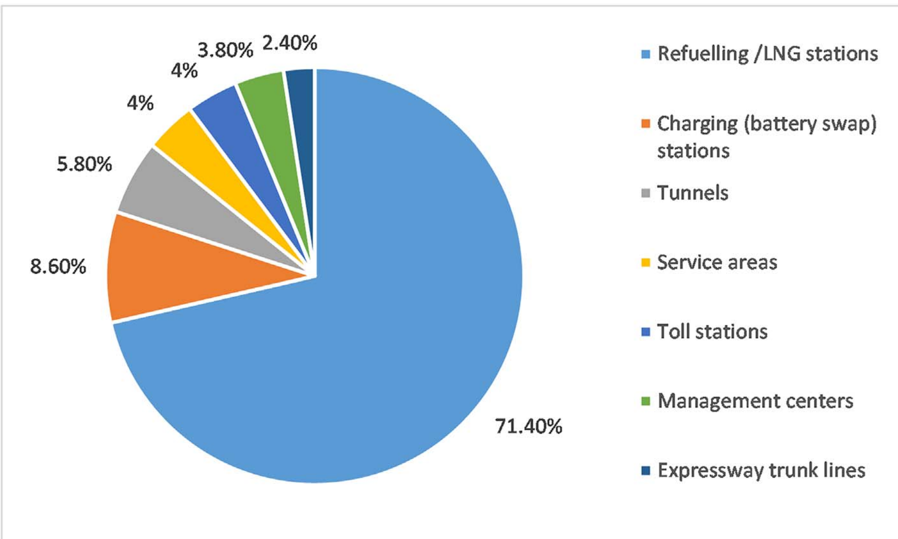

Fig. 2. Proportion of energy consumption during expressway operation phase.

3.2 Analysis of energy consumption scenarios during expressway operation phase

The levels of energy consumption during the expressway operation phase are detailed in Table 5, while the corresponding consumption proportions are illustrated in Figure 2.

3.2.1 Tunnel

In order to ensure the safety of traffic during expressway operation, tunnels need to be equipped with lighting, ventilation systems and other equipment, which are the main energy consumption facilities in the tunnel. Due to the complex traffic situation in the tunnel, the tunnel is equipped with a large number of monitoring equipment in and around the tunnel, mainly including: traffic flow video monitoring equipment, lighting brightness, light monitoring equipment, air quality monitoring system, wind speed/direction monitoring system, fire monitoring, alarm system, and its supporting data transmission and storage equipment. In addition, some tunnels will be equipped with safety information display equipment and emergency backup power system (UPS). According to statistics, the average energy consumption intensity of tunnels is about

4.52 tce/km · a, accounting for about 5.8% of the total energy consumption during the operation phase (Lu, 2011), which is the highest energy consumption infrastructure during the operation phase.

3.2.2 Service area

Service areas involve a variety of energy consumption equipment, and the energy consumption scenarios are complex, mainly including indoor and outdoor lighting, cooling and heating equipment, catering and entertainment living service equipment, vehicle service equipment, audio and video monitoring equipment, and office facilities and equipment (Lu, 2011). According to statistics, the average energy consumption intensity of service areas is about 3.12 tce/km · a (Tang, 2013), which accounts for about 4% of the total energy consumption during the operation phase.

3.2.3 Toll station

The energy consumption facilities of expressway toll stations mainly include toll collection facilities, monitoring facilities, lighting fixtures, and office facilities. At present, the main toll collection method of China's expressways is the fully automatic electronic toll collection method with the help of ETC (Electronic Toll Collection) and the semi-automatic method with manual toll collection and computer management. Toll collection facilities mainly include electric railing, ETC equipment, vehicle detector, lane control computer and its communication equipment, etc. Monitoring facilities mainly include toll booth cameras, lane cameras and their data storage and transmission equipment, etc. Lighting fixtures mainly include lighting fixtures around the toll station and special lamps and lanterns used to indicate toll station information, etc. Office facilities mainly include computers and air conditioners. According to statistics, the average energy consumption intensity of toll stations is about 3.12 tons of standard coal/km · years (Li, 2021), which accounts for about 4% of the total energy consumption during the operation phase of expressway.

3.2.4 Expressway trunk lines

Energy consumption equipment on expressway trunk lines mainly includes traffic signal equipment, information monitoring equipment and communication equipment. Due to the long mileage of expressway trunk lines, the equipment is generally set only in key sections or set in the form of equal spacing, and the total energy consumption is relatively small. Expressway trunk line energy equipment mainly includes bridges, ramps, curves and other key locations to ensure the safety of vehicles and set up special signals, display real-time road information such as variable message boards and other traffic signal equipment, as well as set up in key sections of traffic and meteorological information monitoring and collection equipment, information transmission and communication equipment set up at equal intervals along the expressway. According to statistics, the average energy consumption intensity of expressway trunk lines is about 1.87 tce/km · a (Lu, 2011), which accounts for about 2.4% of the total energy consumption during the operation phase.

3.2.5 Operation and management center

The energy consumption of operation and management center mainly includes office energy and living energy. Office energy refers to the energy used by management personnel to ensure the normal operation of the expressway management, command and control work, involving information management equipment, communication equipment, traffic engineering facilities along the route and other energy consumption equipment. Living energy mainly refers to the energy used to meet the daily needs of staff, involving lighting, kitchen and bathroom and air conditionings. According to statistics, the average energy consumption intensity of the operation and management center is about 2.96 tce/km · a (Li, 2021), which accounts for about 3.8% of the total energy consumption during the operation phase.

3.2.6 Fueling (LNG) stations/charging (battery swap) stations

The energy consumption equipment of fuelling stations mainly includes fuel dispensers, transformers, distribution cabinets, protection equipment, and sewage treatment equipment. At present, China's electric vehicle sales have ranked first in the world for eight consecutive years. It is expected that the charging and switching facilities along the expressway will become important energy consumption equipment of the expressway in the future. The energy consumption equipment of expressway charging (battery swap) stations mainly includes charging modules, relays, monitoring and measuring equipment, charging guns, communication modules, battery exchange equipment, static charging equipment, etc. According to statistics, the energy used for vehicles during the operation phase accounts for about 80%, and the energy used for infrastructures accounts for about 20% (Liang, 2020).

3.3 Analysis of energy consumption scenarios during expressway maintenance phase

The levels of energy consumption during the expressway maintenance phase are detailed in Table 6, while the corresponding consumption proportions are illustrated in Figure 3.

3.3.1 Expressway trunk lines

The maintenance of expressway trunk lines mainly involves the maintenance of road base, road surface, ancillary facilities and green belts. Road base maintenance includes road shoulder maintenance, road slope maintenance, etc. Road surface maintenance includes daily maintenance, road diseases maintenance, etc. Maintenance of ancillary facilities includes facility scrubbing, replacement, signage maintenance, etc. Greening maintenance includes vegetation watering, pruning, fertilization, replanting, etc. According to statistics, the energy consumption of expressway trunk

Table 6. Energy consumption scenarios during expressway maintenance phase.

Scenario sets	Energy consumption scenarios	Energy consumption facilities/projects	Energy consumption intensity (tce/km · a)
Expressway trunk lines (70%)	Road base maintenance and repair	Roadbed maintenance engineering, slope protection engineering, drainage engineering, etc.	12.52
	Road surface maintenance and repair	Daily pavement maintenance, pavement crack and pothole repair, etc.	12.52
	Ancillary facilities maintenance and repair	Signage and marking maintenance, roadside facility maintenance, etc.	2.09
	Green belts maintenance and repair	Watering, pruning, fertilizing, pesticide application, replanting, etc.	2.09
Tunnels (20%)	Tunnel maintenance	Daily cleaning, crack treatment, water leakage treatment, landslide treatment, cleaning and replacement of lighting facilities, drainage system maintenance, mechanical and electrical facilities maintenance, etc.	8.35
Service areas (5%)	Vehicle service facilities maintenance	Parking lot, gas station, charging station, vehicle traffic lanes, repair shop maintenance, etc.	0.42
	Personnel service facilities maintenance	Restaurants, shops, toilets, hotels, lounges, pharmacies, first aid stations, pedestrian squares, pedestrian walkways, other facility maintenance, etc.	0.42
	Management facilities maintenance	Monitoring room, communication equipment, management office building, employee dormitory maintenance, etc.	0.42
	Auxiliary facilities maintenance	Electrical room, garbage disposal facilities, pump room and other auxiliary construction maintenance, sewage treatment facility maintenance, etc.	0.42
	Emergency facilities maintenance	Emergency rescue site maintenance, etc.	0.42
Toll stations (5%)	Toll areas maintenance	Toll island, toll booth, toll canopy maintenance, etc.	0.42
	Toll plazas maintenance	Road pavement maintenance, etc.	0.42
	Management buildings maintenance	Office, staff dormitory, monitoring room maintenance, etc.	0.42
	Auxiliary facilities maintenance	Garages, kitchens, water/electricity/gas facilities maintenance, etc.	0.83

lines maintenance accounts for about 70% of the total energy consumption during the maintenance phase, of which about 30% is used for road base and road surface maintenance, and about 5% is used for ancillary facilities and greening maintenance (Lu, 2011).

3.3.2 Tunnel

Tunnel maintenance is specifically divided into major maintenance and slight repair. Major maintenance is mainly daily inspection, tunnel cleaning, shaft maintenance, etc. Slight repair is mainly for the frequent repair of minor damage in the tunnel. Tunnel maintenance energy consumption accounts for about 20% of the total energy consumption during the maintenance phase (Pan, 2011).

3.3.3 Service area

Service area maintenance refers to the maintenance of the facilities and equipment, mainly including the maintenance of vehicle service facilities, personnel service facilities, management facilities, ancillary facilities and emergency facilities. The energy consumption of service area maintenance accounts for about 5% of the maintenance phase (Pan, 2011), of which the five kinds of facilities above account for 1% respectively (Shen, 2017).

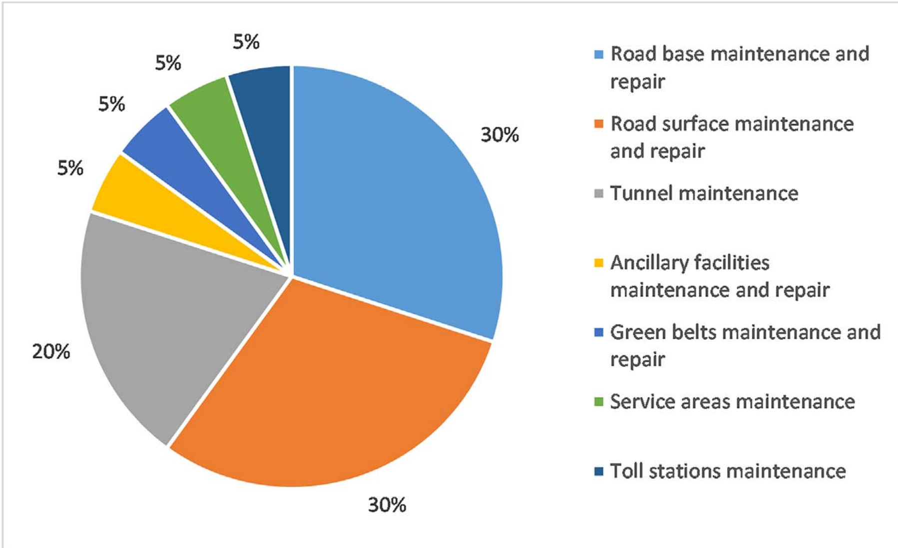

Fig. 3. Proportion of energy consumption during expressway maintenance phase.

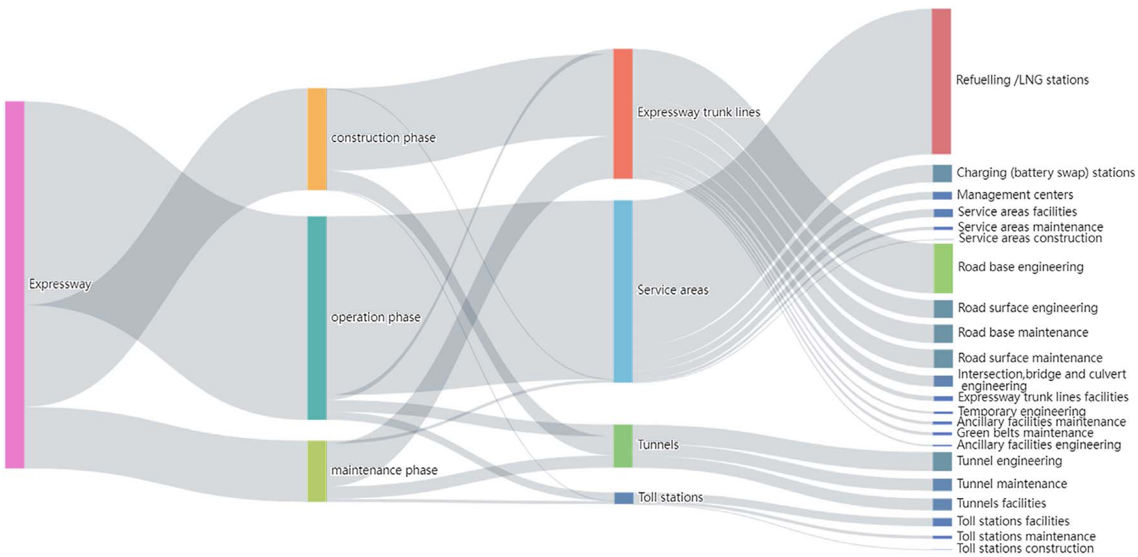

Fig. 4. Energy consumption analysis of expressway life cycle scenarios.

3.3.4 Toll station

Toll station maintenance mainly includes the maintenance of toll area, toll plaza, management building and ancillary facilities. The energy consumption of toll station maintenance accounts for about 5% of the maintenance phase, of which the ancillary facilities accounts for about 2% (Díaz *et al.*, 2017)

4 Conclusion

To delve into the energy consumption characteristics of expressway under various scenarios, a comprehensive lifecycle energy scenario set for expressway has been established. This paper, through literature analysis and hypothetical scenario studies, concludes as follows:

1. The proportion of energy consumption during the construction, operation and maintenance phase of the expressway is about 5:10:3. The comprehensive analysis of energy consumption throughout the entire lifecycle is graphically represented in Figure 4.
2. During the construction of expressway, particular attention should be given to energy conservation in the trunk lines construction, accounting for about 80.6% of the total energy consumption during the construction phase. Measures such as reducing fossil fuel

consumption, improving energy efficiency and utilizing clean energy sources should be adopted to decrease energy consumption and greenhouse gas emissions during this phase.

3. During the operational phase of expressway, the primary energy consumption is attributed to fuelling and refuelling stations and charging (battery swap) stations. It is suggested that the integration of photovoltaic-charging-electricity systems be promoted through design and construction to increase the utilization of green energy and reduce the energy consumption of expressway.
4. During the maintenance phase, the energy consumption of expressway trunk lines is the highest, accounting for about 70% of the maintenance phase. It is recommended that during the maintenance phase, energy consumption should be reduced by employing measures such as the use of recycled asphalt materials and the adoption of clean energy machinery.

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