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Application of LCA in Expressway Energy Consumption Analysis in South China

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Abstract. In order to quantify the life cycle energy consumption of highways, life cycle assessment method is adopted to quantitatively analyze the energy consumption of a bridge-based expressway in South China. The total life cycle energy consumption was 1343967 tce, while the energy consumption per functional unit was 18733.86 tce/km. In addition, the proportion of the life cycle energy consumption for raw material production, construction and transportation was 71.90%, 13.64% and 14.47%, respectively. As data analysis shown, cement and steel bars have the greatest impact on energy consumption, the energy-saving measures during the construction phase should focus mainly on electricity and diesel, while during the operation phase should focus on controlling the power consumption. Based on the results, a series of energy-saving measures are proposed from the perspective of material-saving, energy-saving and management-strengthen.

1. Introduction

Expressway worked as a modern road transportation channel which is significant in social economy, however, the processing of its construction, utility and maintenance consumes a large amount of energy as well as emitting greenhouse gases, resulting in serious influence on environment. Life cycle assessment (LCA) is an important international tool for environmental management and product designation, which is included into ISO 14000 environmental management standard series[1]. To carry out assessments on energy consumption and CO2 emission of the whole process [3-5], scholars divided the period of road life cycle into several process, including raw material production, raw material transportation, construction, operation, maintenance, demolition and recycling phase based on the research of building life cycle energy consumption emissions [2].

In the field of pavement engineering, LCA theory has penetrated into the construction, repair and maintenance of pavement. The energy consumption and carbon emissions are various among different pavement structures, construction techniques, maintenance technologies [6-9]. Scholars have carried out research in the field of bridges, tunnels and subgrades, Liu and Ouyang used a bridge as an example to calculate the carbon emissions of bridge engineering life cycle, among which the carbon emissions were the largest in the raw material production phase, while the carbon emissions of automobile exhaust during operation phase is second, and the third is those during the on-site construction phase [10]. Taking a highway tunnel project in western China as an example, Li et al. [11] calculated the CO2 emissions during the construction process and found that 90% of the CO2 emissions came from...
diesel consumption. The energy consumption of highway engineering is related to the total energy consumption of the transportation industry, scholars have carried out research on life cycle energy consumption and carbon emissions of the whole road, but most of which are on roads with relatively low ratio of bridge and tunnel. Sun et al. [12] used carbon footprint theory to calculate the endogenous carbon emissions of expressways and conducted comparative analysis. Wang et al. [13] reviewed the estimation method of CO2 emissions from highway construction based on engineering budgetary table, and calculated the CO2 emissions of roadbed, pavement, bridge, culvert and tunnel construction during the construction period of a highway in southwest China, Liu et al. [14] calculated the CO2 emissions of different grades and pavement structure, and concluded the CO2 emissions of asphalt pavement construction were 2.5 times of concrete pavement highways, and the CO2 emissions of low-grade road were 13% lower than highways.

In recent years, China's expressway network has been continuously improved. Subgrade often replaced by bridges in road design to effectively balance the various contradictions between road construction and the surrounding environment. In the future, the proportion of bridges in highway construction will become larger and larger. The energy consumption level of highways with high proportion of bridges is still to be quantified. In this study, the total length of bridges accounted for 95.8% of the expressway in South China, and the life cycle assessment method will be used to quantitatively analyze the energy consumption of raw materials production phase, on-site construction phase and operation and maintenance phase, and energy-saving measures will be proposed to provide basic support to promote green road development.

2. Life cycle assessment method
The life cycle assessment method is to collect and evaluate the input, output and potential environmental impacts of the product life cycle. It is an effective measure to evaluate the energy consumption during the construction and operation of highway engineering [15], which can be divided into four steps: definitions of goal and scale, inventory analysis, impact assessments, and interpretation of results [16, 17].

The goal definition is to define the type of environment to be evaluated according to the environmental impact characteristics of the object; the scale of the study can be defined according to the research conditions and depth, including system boundaries, assumptions and constraints, and functional units. Inventory analysis is to collect energy and material flow information data, to establish input and output models of product systems, and to objectively quantify resources and energy consumption in the life cycle of the highway. There are two ways to collect data: one way is based on the estimated budget and quota of highway engineering, or on the survey and analysis of previous studies; and the other way is to conduct on-site investigations of construction companies. Impact analysis is to quantify different loads into the same form or dimension based on inventory analysis, to estimate the energy and resources used in the system, and to analyze its potential impact. The interpretation of results is mainly to identify major issues in the life cycle impact assessment, to form the main conclusions, and to make relevant recommendations.

3. Case study
This paper takes an expressway in South China as an example to calculate the life cycle energy consumption of highway engineering. The total length is 71.74km, the design speed is 100km/h, the roadbed width is 33.5m, the roadway has six lanes, and the asphalt concrete pavement structure is adopted. The total length of bridges is 68.76 km/34 and the length of tunnel is 820m/1. One service area, one management office, one parking area, two maintenance areas, and 46 toll stations are set up along the expressway.

3.1 Definitions of goal and scale
The goal of this paper is to analyze the energy consumption of highway construction, to support the formulation of energy conservation and emission reduction measures. The system boundary is defined
as raw material production phase, on-site construction phase and operational maintenance phase (Figure 1). The raw materials production phase includes raw material mining/extraction, transportation and the production of construction materials; the construction phase mainly includes the operation of on-site construction equipment and machinery; the operation and maintenance phase includes normal operation of service areas and tunnels, and maintenance of pavement. Considering data availability, the to-site transportation of materials and the demolition and recycling phases are not included.

![Figure 1. The definition of system boundary](image)

3.2 Inventory analysis

The environmental impact type of the life cycle inventory analysis is energy consumption. In this study, the life cycle of the expressway includes the raw material production phase, the construction phase, and the operation and maintenance phase. The total energy consumption of the three phases is summed to obtain the total energy consumption $Q$ of the life cycle. The formula is as follows:

$$Q = Q_1 + Q_2 + Q_3$$

Table 1. Production energy consumption of main building materials [1, 15, 18].

| Material     | Unit | Energy consumption/kg(tce) |
|--------------|------|---------------------------|
| Reinforcement| t    | 841.67                    |
| Steel        | t    | 852.01                    |
| Cement       | t    | 105                       |
| Sand         | m³   | 1.31                      |
| Gravel       | m³   | 6.2                       |
| Asphalt      | t    | 167.19                    |

3.2.1 Raw material production phase

The energy consumption load during the raw material production phase is expressed in terms of the energy consumption per material unit. The main raw materials for expressway construction include steel, cement, stone and asphalt. The energy consumption data of material units are mainly based on the existing research results (Table 1). $Q_1$ is calculated by the following formula.

$$Q_1 = \sum_{i=1}^{n} Q_{1i} = \sum_{i=1}^{n} (q_{1i} \times r_i)$$

$Q_{1i}$ is the energy consumption of the i-th raw material production phase; $q_{1i}$ is the i-th amount of raw material utility; $r_i$ is the i-th production energy consumption per raw material unit; $n$ is the number of raw material type.
3.2.2 On-site construction phase

The energy used in on-site construction machinery includes electricity, gasoline, diesel, heavy oil, coal and so on. In order to carry out analysis and comparison of different energy types during the construction phase, conversed standard coal unit is used to calculate the total energy consumption $Q_2$ of the site construction phase according to the following formula. The value of conversion coefficient refers to the General Rules for Comprehensive Energy Consumption Calculation (GB/T 2589) (Table 2).

$$Q_2 = \sum_{i=1}^{m} Q_{2i} = \sum_{i=1}^{m} (p_i \times u_i)$$  

$Q_{2j}$ is the i-th conversed energy consumption; $p_i$ is the consumption of the j-th energy; $u_j$ is the standard conversion factor of the j-th energy; $m$ is the number of energy type.

Table 2. The conversion coefficient of energy consumption.

| Energy type | Unit | Conversion coefficient of energy consumption /kg(tce) |
|-------------|------|------------------------------------------------------|
| Heavy oil   | kg   | 1.4286                                               |
| Gasoline    | kg   | 1.4714                                               |
| Diesel      | kg   | 1.4571                                               |
| Coal        | kg   | 0.7143                                               |
| Electricity | kw·h | 0.3300                                               |

3.2.3 Operation and maintenance phase

The operation of expressway mainly consumes electric energy, while maintenance, repair and reconstruction activities consume building materials, and maintenance and construction also generates a large amount of energy consumption. The energy consumption inventory analysis in the operation and maintenance phase can be carried out with reference to the raw material production phase and the on-site construction phase. Since the case in this study haven’t open to traffic yet, the energy consumption in the energy consumption of operation and maintenance phase was estimated by refer to other operating projects.

3.3 Impact assessment

The total energy consumption of raw material production was 966252 tce, and the energy consumption per unit of raw material production was 13469 tce/km. Among the various raw materials, steel and cement are the main energy-consuming materials, with contribution rates accounted for 52.42% and 31.17% of the total energy consumption of raw materials production phase, respectively. In addition, Rolled steel and steel strand accounted for more than 10%, asphalt accounted for 3.71%, sand and gravel only accounted for 2% (Figure 2).
The total energy consumption during the construction phase was 183279 tce, and the energy consumption for the functional unit (six-lane expressway per kilometer) was 2554.77 tce/km. The whole project is mainly composed of bridges and many kinds of machinery involved in bridge construction, most of which are electricity driven. The electric energy consumption accounted for 68.26% of the total energy consumption; diesel was also the main consumption target, accounting for 24.01%; the heavy oil energy consumption accounted for 6.89%, which was mainly used for asphalt pavement mixing. The amount of gasoline and coal used was less than 1% (Figure 3). In the implementation of energy conservation and emission reduction management during the construction phase, it is necessary to control the off-road machinery consuming electric energy and diesel. In addition, heavy oil consumption should also be controlled considering the severe environmental pollution caused.

The total energy consumption in the operational maintenance phase was 194436 tce. The annual electricity consumption of normal road operation was calculated based on the local average value. The annual energy consumption was 28.05 million kWh or 9257 tce. The operation period is calculated according to 20 years, consumed a total of 185140 tce. The energy consumption during the operation period mainly comes from toll stations, which should be the focus of energy conservation and emission reduction control. In addition, tunnel ventilation and lighting is a large energy-consuming household during the operation period. For mountain roads with long tunnel lengths, energy-saving and emission reduction measures for tunnel operations should be considered. Road maintenance and repairs include road repairs, structural repairs, and so on. According to the 7th and 12th years of road overhaul considerations, the energy consumption level of overhaul is mainly referred to the previous research. The energy consumption of the functional unit overhaul was 129.58 tce, and the total energy consumption of the overhaul in this case is 9296 tce. Comparing the previous energy consumption statistics research of highway engineering (Table 3), the energy consumption per kilometer per lane of this case is significantly higher. The energy consumption in the raw material production phase was 6 times of the non-bridge tunnel, and twice of
the mountain highway; the energy consumption during the construction phase is 31 times of the bridgeless tunnel, which is 1.6 times of the mountain highway. In the future, the proportion of bridge construction will become larger and larger, and the energy consumption of highway construction will also increase.

| Location        | Ratio of bridge and tunnel | Energy consumption per kilometer per lane (tce) | Reference          |
|-----------------|----------------------------|-----------------------------------------------|--------------------|
|                 |                            | Raw material production phase | On-site construction phase |
| Henan province  | 58.6% / 266.93             | /                                | 266.93             | Fu et al. [19] |
| Midwest China   | 0                          | 350.0                            | 13.76              | Shang et al. [18] |
| Guizhou province| 46.7% / 250.55             | /                                | 250.55             | Chen et al. [21] |
| South China     | 39.3% 97% (bridge 95.8%)   | 1121.9                           | 278.56             | Fei et al. [20] |
|                 |                            | 2244.8                           | 425.8              | This study      |

### Table 3. Comparison with previous studies.

#### 3.4 Results and Discussion

As the life cycle impact assessment results shown, the total energy consumption of the life cycle in this case was 1343967 tce, the largest was the raw material production energy consumption accounting for 71.90% (Figure 4), which should be the key point of energy saving and emission reduction of highway projects. Under the premise of the construction quality, it can reduce the energy consumption of raw material production, by using new materials and recycled materials instead of traditional building materials rationally. In addition, it is also an effective energy-saving and emission-reducing measure to prolong the service life of structures, avoid redundant construction and waste of resources.

The energy consumption in the construction and operation phases was similar, accounting for 13.64% and 14.47%, respectively (Figure 4). The construction and operation phases belong to the direct management process of the highway industry, as the key phase of energy conservation and emission reduction in the highway industry. For the construction phase, we should start with construction technology, select technical solutions with low energy consumption and advanced technology, and strengthen the management of key machinery and equipment, to avoid the construction of old equipment with high energy consumption and high pollution. For the operation phase, considering the life cycle, taking energy-saving equipment and intelligent control measures can reduce power consumption during the operation period. In addition, the prevention of road surface maintenance is also an effective energy-saving and emission-reducing measure. From the perspective of functional unit energy consumption, the energy consumption in the whole life cycle, raw material production, construction process and operation phase was 18733.8 tce/km, 13468.8 tce/km, 2554.8 tce/km, 2710.3 tce/km (Fig. 5), respectively, which could provides references for other bridge-based highway life cycle energy consumption analysis.

The construction of bridge is characterized by high-intensity energy input and material migration. The consumption of high-energy and high-contamination building materials such as cement and steel bars in the raw material production phase is quite large. The excavation, drainage, reinforcement, pouring, lifting and other processes in the construction phase require machinery with high energy consumption, which should be the focus of energy conservation and emission reduction for highway projects.
4. Results and Conclusions
This study applies life cycle assessment to establish the life cycle energy consumption calculation method based on typical highways in South China, and quantifies the life cycle including raw material production, on-site construction, operation and maintenance phases, and proposed the corresponding measures on energy conservation and emission reduction. The main research conclusions are as follows:

(1) The total life cycle energy consumption of a six-lane highway in South China was 1343967 tce, of which the energy consumption of raw materials accounts for more than 70%, and the energy consumption for construction and operation was similar. The life cycle energy consumption of the functional unit highway was 18733.8 tce/km, and the energy consumption per unit of raw material production, construction process, operation and maintenance phase was 13468.8 tce/km, 2554.8 tce/km, and 2710.3 tce/km, respectively.

(2) The energy consumption of steel and cement production in the raw material production phase of expressway exceeded 90%; the proportion of electric energy and diesel consumption in the construction phase exceeded 90%, of which the electric energy amounted to 68.26%. In addition, the heavy oil consumption has larger environmental pollution and energy consumption, and the proportion of heavy oil consumption accounted for 6.89%; the electricity consumption during the operation phase and the energy consumption of road overhaul are basically the same.

(3) Over 95.8% mileages of this case are bridges, and the total energy consumption was significantly higher than the previous research. Thus, it is necessary to guide the bridge structure design and construction technology shift to low carbon development. For different phases of the life
cycle, measures such as material saving, energy saving, and management enhancement can be adopted according to the characteristics of energy consumption.

Limited by the basic data, project management and other conditions, the conclusions of the energy consumption data obtained in this study need to be further refined. In particular, the next step in the operation phase is to calculate the maintenance, repair cycle and measures of the highway structure in detail. Moreover, more efforts should be taken in strengthening investment in monitoring statistics, operational power monitoring, maintenance plans, etc., and conducting effective evaluation of relevant energy conservation and emission reduction measures as well. For bridge-based expressways, comparative analysis of energy consumption in different bridge structures and different construction process life cycles should be carried out to provide support for green road construction.

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