Study on energy consumption evaluation of mountainous highway based on LCA

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Abstract. For the system to understand the road construction energy consumption process, this paper selects a typical mountainous highway in the south, using the theory and method of Life Cycle Assessment (LCA) to quantitatively study the energy consumption of the whole process of highway raw materials production, construction and operation. The results show that the energy consumption in the raw material production stage is the highest, followed by the highway operation and construction stage. The energy consumption per unit of tunnel engineering, bridge engineering, roadbed engineering and pavement engineering in the construction phase are 2279.00 tce, 1718.07 tce, 542.19 tce and 34.02 tce, and in operational phase, 85.44% of electricity consumption comes from tunnel ventilation and lighting. Therefore, in the bridge and tunnel construction process, we should promote energy-saving innovation of the construction technology and mechanical equipment, and further strengthen the research and development of tunnel ventilation, lighting energy-saving equipment and intelligent control technology, which will help significantly reduce the energy consumption and greenhouse gas emissions of the life cycle of highway.

1. Foreword
Highway as an important infrastructure of the country, in their own construction and operation process need to take up valuable land and line resources, consume a lot of energy, water and steel, cement, gravel and other building materials, and then pull the high energy consumption and high emissions of building materials, construction equipment and other related industries. In 2016, Ministry of Transport issued the document of "Guidance on the implementation of green road construction"[1], clearly put forward to "co-ordinate the use of resources to achieve intensive savings", which also marks the road construction from extensive to green development transformation. Therefore, it is important to reduce the energy consumption of highway construction and realize the goal of national energy saving and emission reduction. How to quantify the energy consumption of the life cycle of highway has become the basis of green highway construction.

Domestic and international research on energy consumption and greenhouse gas emissions attaches great importance, and formed a Life Cycle Assessment (LCA) theoretical system, which will be used for highway energy consumption research. Häkkinen[2] compared the life cycle of Finnish concrete pavement with asphalt mastic pavement. Park et al.[3] applied the Life Cycle Assessment method to the road, combined with the national energy balance schedule and the Korean economy's input-output model to assess the energy consumption and gas emissions during the road life cycle material mining and production stage. Chappat et al.[4] analyzed the energy consumption and emissions of 20 different types of pavement materials. The results show that cement pavement needs the most energy, followed
by hot mix asphalt pavement. At Tsinghua University, Shang Chunjing et al.\cite{5} using the bill of quantities and the highway project budget quota to carry out the evaluation study on the energy consumption and atmospheric emissions of the life cycle of highway. Wang Suiyuan et al.\cite{6} analyzed the raw material acquisition and construction energy consumption of three kinds of highway asphalt concrete pavement and two kinds of cement concrete pavement. Liu Muyu et al.\cite{7} calculated the carbon emissions of bridge engineering life cycle.

At present, the research on road energy consumption is different at home and abroad, due to the difference on construction technology, construction equipment and raw materials, and the variability of the basic data sources is relatively large, which leads to the lack of consistency between the evaluation results. Based on the basic information of highway engineering, this study makes a quantitative analysis on the energy consumption of raw material production, construction and operation, and provides a systematic method for highway energy consumption evaluation to support highway construction development of energy saving and emission reduction.

2. Research scope

For the quantitative analysis of the energy consumption of highway construction, taking into account the convenience of the relevant data collection, we have made some reasonable settings. From the energy consumption interface, this study considers only the energy consumption generated by processes or activities directly related to highway construction, regardless of the energy consumption such as plant infrastructure construction, construction equipment production and workers’ life. Highway construction is generally divided into roadbed, pavement, bridge, tunnel, housing construction, electromechanical engineering, traffic safety facilities and other units. The related research shows that the main energy consumption works of highway construction are roadbed, bridge and culvert, tunnel and pavement. In this paper, the above four is the main research object, temporarily not considering the housing construction, electromechanical engineering and traffic safety facilities. The transport of raw materials may vary widely depending on the distance, the equipment used and the conditions of the transport road, and the proportion is small, so it is not included in the study.

In order to better reflect the energy consumption of the life cycle of highway, we selected a typical mountainous highway in the south, and carried out the research on the total and unit energy consumption in the whole process of raw materials production, construction and operation. The project uses four-lane highway standard, the roadbed width is 26.0m, the design speed is 100 km/h. The route length is 130.035km, the toll station, tunnel and interchange ramp using cement concrete pavement, and the remaining sections are made of asphalt concrete pavement structure. This route has been set up 64 bridges, a total length of 33034.5 meters, 6 medium and small bridges with a total length of 314m; and there are 21 tunnels, total length of 17705m, including long tunnels 10735m / 5 seats, medium tunnel 3350m / 5 seats, short tunnel 3620m / 11 seats, the ratio of bridge to tunnel is 39.26%.

3. Research on energy consumption of life cycle

3.1. Energy consumption of raw material production

The main raw materials of highway construction include steel, cement, stone, asphalt and so on, the total energy consumption of these materials mining, manufacturing and other processes is collectively referred to as raw material production energy consumption. The energy consumption per unit of basic raw materials can be expressed by the coefficients given in table 1\cite{5,8,9}, the amount of raw materials can be obtained by means of design stage of the project or actual engineering data, and then calculate the energy consumption of various types of raw materials production.
Table 1. Raw materials energy consumption of highway construction

| raw materials | unit | energy consumption |
|---------------|------|--------------------|
| steel         | t    | 841.67             |
| cement        | t    | 105                |
| gravel        | m³   | 1.31               |
| crushed stone | m³   | 6.2                |
| asphalt       | t    | 167.19             |
| sand          | m³   | 27.63              |

The total energy consumption of raw materials of the selected highway is 583545.06 tce. The proportion of various raw materials energy consumption is shown in Figure 1, visible cement, steel and sand is the main source of raw material production energy consumption, total accounting for 95.69%. Therefore, under the premise of ensuring project quality and construction safety, we should save the use of cement, steel and sand. Under the situation of the supply-side structural reforms, reducing the energy consumption of materials through the process optimization will have a significant effect to reduce the energy consumption of highway construction.

3.2. Energy consumption during construction

The highway industry has limited measures to reduce energy consumption in raw materials, but we can take a lot of technical and management measures to reduce the energy consumption of highway construction process. Therefore, we should deal with the energy consumption of the construction process more detailed quantitative analysis.

3.2.1. Total energy consumption of construction. The energy used in the highway construction mainly includes electricity, diesel and petrol, etc., according to the roadbed, pavement, bridge, tunnel project division, on the basis of their respective projects, we have estimated the amount of energy required for construction, and multiplied by all kinds of energy standard coal conversion coefficient (see table 2[10]), finally summed to get the total energy consumption.
Table 2. Major energy standard coal conversion coefficient

| Energy type          | Unit       | Standard coal conversion coefficient |
|----------------------|------------|--------------------------------------|
| raw coal             | kgce/kg    | 0.7143                               |
| petrol               | kgce/kg    | 1.4714                               |
| diesel               | kgce/kg    | 1.4571                               |
| fuel oil             | kgce/kg    | 1.4286                               |
| liquified natural gas| kgce/kg    | 1.8620                               |
| electricity          | kgce/kw·h  | 0.3300                               |

It has been calculated that the total energy consumption of the selected highway construction is 144890.73 tce, and the various types of energy consumption of each professional engineering are shown in figure 2. It can be seen that the energy consumption of bridge engineering is the highest during the construction process, as 57295.05 tce, and mainly electricity energy consumption of 51163.2 tce; then the energy consumption of roadbed engineering, to 42822.76 tce, mainly for diesel, accounting for 99.6%; the energy consumption of tunnel engineering is not much different from roadbed engineering, for 40349.77 tce; and pavement construction energy consumption is only 4423.15 tce, for the lowest professional engineering.

Figure 2. Energy consumption of professional engineering in highway construction process

Figure 3. The proportion of various types of energy in the process of highway construction

3.2.2. Construction energy consumption types. Overall, the main types of energy consumption for highway construction are electricity and diesel, accounting for 56.91% and 42.74% respectively, and the proportion of petrol is very low, only 0.35% (see figure 3). Professional engineering due to different construction techniques and equipment, energy proportional relationship are also different. For example, in the tunnel engineering, electricity consumption accounted for 74.3%, and diesel consumption accounted for 24.82% (see figure 4), but in the pavement engineering, the main energy consumption come from the pavement material mixing paving, and diesel is the mainly energy consumption, accounting for 71.71%, electricity accounted for 25.89% (see figure 5).
3.2.3. Energy consumption of functional unit construction. The calculated total energy consumption and energy proportion of highway construction have a certain reference value for the calculation of highway energy consumption in similar areas. However, due to each highway mileage and the proportion of bridge and tunnel are quite different, therefore, the calculation of the professional engineering functional unit of various types of energy consumption, can greatly improve the application of research results. As shown in figure 6, the most energy consumption were tunnel engineering and bridge engineering, respectively 2279.00 tce and 1718.07 tce per functional unit (4-lane per km), accounting for 49.83% and 37.57%, the roadbed and pavement engineering respectively for 542.19 tce and 34.02 tce, the sum of only 12.60%.

![Figure 4. The proportion of various types of energy in tunnel construction](image)

![Figure 5. The proportion of various types of energy in pavement construction](image)

![Figure 6. Energy consumption per functional unit in the process of highway construction](image)

3.3. Energy consumption during operation
The energy consumption in the highway operation period is divided into two parts: the electric energy consumed by the normal operation of the road, and the electric energy consumed by the maintenance management equipment; the fuel savings generated by the operation of the vehicle due to the improvement of road traffic conditions.

3.3.1. Electric energy consumption during operation. As the selected highway yet to be completed, so we can estimate the electric energy consumption during highway operation period, including the electric energy required for toll stations, management centers, service areas and maintenance work areas. We only consider the length of more than 500 meters of tunnel’s electric energy consumption of independent lighting and ventilation (see table 3), the annual operating energy consumption of 67.3 million kw·h, converted to 22209 tce, so the total energy consumption during 20-year operating period
is 444180 tce. The electric energy consumption of tunnel ventilation and lighting accounted for 85.44% of the total, which should be the focus of energy saving and emission reduction.

**Table 3. Estimation of electricity consumption in highway operation**

| Place                | Quantity | Electric energy consumption (million kw·h /year) |
|----------------------|----------|-----------------------------------------------|
| toll station         | 12       | 5.4                                           |
| management center    | 1        | 0.4                                           |
| service area         | 3        | 1.2                                           |
| maintenance work area| 7        | 2.8                                           |
| >500m tunnel         | 10       | 57.5                                          |
| **Total**            |          | **67.3**                                      |

3.3.2. *Vehicle fuel saving*. Using the "With and Without methods" analysis of driving speed and fuel consumption changes on the highway and existing road. Using formula (1) to calculate the fuel saving year by year in the operating period of 20 years (figure 7), so the total fuel savings of 2304.4516 million liters, converted to 3292140 tce.

\[ Q = (E_0 - E) \times L \times Pt \times 365 \]  

In the formula:
- \( Q \) — the new road fuel savings (L/year)
- \( E_0 \) — without the project, the average fuel consumption of the old road (L/vehicle km)
- \( E \) — with project, the average fuel consumption of the new road (L/vehicle km)
- \( L \) — new road mileage (km)
- \( Pt \) — the average daily traffic volume of the new road in the \( t \) year (vehicle/day)

**Figure 7. Fuel saving in highway operational phase**

4. **Total energy consumption study**

From the full life cycle of highway construction, the total energy consumption should include the sum of the above, in view of the vehicle fuel savings mainly in highway operational phase, it is the road after the construction of indirect social benefits, do not count into the road itself life cycle absolute energy consumption. The total energy consumption of the selected highway is 1,172,600 tce, and the energy consumption of raw materials is the largest and close to 50%. Operation phase calculated by 20 years, the energy consumption accounting for 37.88%, we should be through a variety of energy-saving technologies and management measures to further reduce operational energy consumption,
especially tunnel ventilation, lighting electric consumption. Although the energy consumption of the construction process in the three years is only 12.36% (figure 8), however, it is entirely part of the road department direct management process, it is also the focus of energy saving and emission reduction control. From the energy consumption per functional unit, raw material production, construction and operation phase were 4487.60 tce/km, 1114.24 tce/km, 3415.85 tce/km, and provide reference for the analysis of energy consumption of highway full life cycle in other mountainous areas.

Figure 8. energy consumption of highway full life cycle in southern mountainous area

5. Results and discussion
This study has established a simple and feasible energy consumption calculation method system which covers the whole life cycle of raw material production, highway construction and operation, and selects the typical mountainous highway in the south to carry on the actual calculation, the result has important practical significance to reduce the energy consumption and greenhouse gas emissions:

(1) The total energy consumption of road raw materials production is 583545.06 tce, mainly for the cement, steel and sand, accounting for 95.69% of total energy consumption, so these three categories should be as the focus of energy consumption control.

(2) The total energy consumption of highway construction is 144890.73 tce, the professional engineering energy consumption from large to small is as follows: bridge engineering (57295.05 tce)> roadbed engineering (42822.76 tce)> tunnel engineering (40349.77 tce)> pavement engineering (4423.15 tce). The main energy types are electricity and diesel, accounting for 56.91% and 42.74% respectively. The energy consumption of tunnel engineering, bridge engineering, roadbed engineering and pavement engineering per functional unit were 2279.00 tce, 1718.07 tce, 542.19 tce and 34.02 tce respectively. Therefore, the use of advanced construction technology and mechanical equipment in the tunnel and bridge engineering will be able to achieve more significant energy saving effect.

(3) Highway in 20 years of operation to save the vehicle fuel consumption 3292140 tce, and the total power consumption of 444180 tce, of which 85.44% tunnel ventilation and lighting, so it is the key control area of energy saving and emission reduction in highway operation period.

(4) Without calculating the vehicle fuel saving, the total energy consumption of the life cycle of highway was 1,721,600 tce. The raw material production, construction process and operation phase accounted for 49.76%, 12.36% and 37.88% respectively, and the energy consumption per functional unit were 4487.60 tce/km, 1114.24 tce/km, 3415.85 tce/km respectively.

Due to the limitation of basic data, engineering management and other conditions, the energy consumption data calculated in this study need to be further accurate. In the future, we can strengthen the research in the aspects of traceability of construction raw materials, construction energy consumption monitoring statistics and operation electricity monitoring. And we should expand the scope of research to the highway whole life cycle, such as the raw materials, construction, operation and maintenance, etc., to study accurately the energy consumption of roadbed, pavement, bridges, tunnels, housing construction, electromechanical engineering, traffic safety facilities and so on, which finally will provide better decision-making proof for green highway construction.
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