Carbon emission calculation of construction machinery during the expressway construction period

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Abstract. Based on the emission coefficient method, this paper constructs the carbon emission calculation model of construction machinery during the construction period of the expressway, and carries out an example analysis of the concrete expressway according to the highway Engineering budget Quota and the bill of quantities. Under the background of green development, it provides a theoretical basis for highway construction to adopt corresponding energy-saving and emission reduction strategies, so as to achieve a win-win situation between economic and social development and ecological environment protection.

1. Introduction
Transportation infrastructure construction, especially highway construction, mechanized construction consumes a lot of energy[1-2] and produces a lot of carbon dioxide. According to the National Highway Network Plan (2013-2030) released by the Ministry of Transport in June 2014, the planned length of expressways in China is 118,000 kilometers, and the estimated investment on expressways is about 250 million yuan[3]. Under the requirements of green development, it is of great significance to study the carbon emission of construction machinery during the construction period of the expressway, so as to provide a reference for adopting corresponding energy-saving and emission reduction strategies.

In recent years, scholars at home and abroad have conducted a series of researches on the carbon emission of construction machinery during expressway construction period. Abolhasani (2008) studied the carbon emissions of construction machinery based on monitoring data from construction sites[4]; Cass (2011) calculated the energy consumption in the process of highway construction by collecting and sorting out the data on material transportation and construction in a certain highway construction process in the United States[5]; Wang Xianwei (2014) calculated the carbon emission equivalent of each stage of each project of a certain expressway, and concluded that the carbon emission produced by materials and construction machinery accounted for 89% of the carbon emission equivalent of the expressway[6]; Wang Chengwu (2016) estimated the construction project construction carbon emission quota based on carbon source consumption and carbon emission factor according to the construction project budget quota and relevant consumption quota[7]; Chen Yun (2019) analyzed the energy and fuel consumed by various construction machinery for asphalt pavement, and based on the calorimetric value of fuel and electricity and carbon emission factor, a theoretical method was used to construct a carbon emission calculation model for asphalt pavement construction machinery[8].
Based on this, this paper comprehensively considers the carbon emission of construction machinery during the construction period of the entire expressway, and makes a comparative analysis of the carbon emission of construction machinery in each sub-project.

2. Carbon emission calculation model of construction machinery during expressway construction period

Highway construction engineering generally includes subgrade engineering, pavement engineering, bridge engineering and tunnel engineering. According to "Highway Engineering Budget Quota", the mechanical construction of roadbed construction mainly involves the subgrade surface cleaning and excavation, excavation of earth and stone, transportation of earth and stone, compaction before filling, compaction of earth, treatment of soft soil foundation and other activities. The mechanical construction of pavement construction mainly involves the activities of foundation excavation, drilling, digging pile, expansion joint stage, building steel basin rubber bearing, split-stone concrete and so on. The mechanical construction of bridge construction mainly involves the activities of foundation excavation, drilling, digging pile, invert, backfill, positive tunnel ventilation, tunnel lighting, shaft support and lining, reinforcement and other links. The carbon emissions from the above activities come from the energy consumption of construction machinery, which is mainly gasoline, diesel and electricity.

There are three main calculation methods for carbon emission, namely, measurement method, mass balance method and emission coefficient method. Emission coefficient method is widely used in the world[9]. Discharge coefficient method[10] refers to the product of the carbon emission coefficient of a substance and the activity data.

According to the emission coefficient method, the carbon emission calculation model of construction machinery during the construction period of expressway is as follows:

\[ C = \sum_{i} (M_i \times \lambda_i) + P \times \eta \]

In the formula: \( C \) is the carbon emission produced by construction machinery; \( i \) is the type of energy; \( M_i \) is the consumption of energy \( i \) used for construction machinery; \( \lambda_i \) is the carbon emission coefficient of energy \( i \); \( P \) is power consumption; \( \eta \) is the average carbon emission coefficient of electricity.

Based on the calculation method of carbon emission coefficient based on fuel weight or volume proposed by World Resources Institute (WRI), the carbon emission coefficient of fossil fuels = average low calorific value * Carbon content per unit calorific value * Carbon oxidation rate * 44/12, the carbon emission coefficient of related fossil fuels is sorted out (Table 1), in which the average coefficient of electric energy in North China is adopted.

| Listing data | Gasoline (kg) | Diesel oil (kg) | Electricity (Kg/kw. H) |
|--------------|---------------|-----------------|------------------------|
| CO₂ (kg)     | 2.98          | 3.16            | 1.246                  |

3. Case Analysis

In this paper, a highway in Hebei Province is selected as an example. The mainline is 68.68 kilometers long. The road adopts the standard construction of two-way four-lane expressway, the design speed is 80Km/h, the width of the subgrade is 24.5 meters, the width of separated bridges and tunnels is 10.25m. There are two large Bridges of 3,256.5m. There are 36 Bridges of 15034.85m and 2 middle Bridges of 77m. Small bridges 18m, culvert 85. There are 1 3118m long tunnels, 2 1717m middle tunnels and 3 1060m short tunnels.
According to the project bill of quantities, the carbon emission of construction machinery during the construction period of roadbed engineering, road engineering, bridge engineering and tunnel engineering is calculated respectively.

3.1. The subgrade engineering

1. Cleaning and digging
   Crawler single-bucket excavator within 135KW is adopted, and the mechanical crew is as follows:
   \[
   \frac{2762888.90}{100} \times 6.42 = 177377.47 \text{(machine-team)}
   \]

2. Excavators dig earth and stone
   The crawler single-bucket excavator is used within 2.0m³, and the mechanical platform is as follows:
   \[
   \frac{12981340.30 + 278627}{100} \times \frac{1.15 + 1.77}{2} = 19359.55 \text{(machine-team)}
   \]

3. Compaction before filling
   12-15T light wheel roller is adopted, and the mechanical platform is:
   \[
   68.685 \times 24.5 \times 0.3 = 504.83 \text{(machine-team)}
   \]

4. Tamp earth fill
   In this stage, earth rammer is used for tamping. The mechanical platform team is as follows:
   \[
   (168.1 - 161.8) \times 10000 / 1000 \times 0.64 + (817.3 - 506.8) \times 10000 / 1000 \times 0.97 = 3052.17 \text{(machine-team)}
   \]
   According to formula Table 1 and Formula (1), the carbon emission of subgrade construction machinery is calculated as follows:
   \[
   \left(177377.47 \times 98.06 + 19359.55 \times 92.19 + 504.83 \times 40.46 + 3052.17 \times 61.72 + (14300874.89 + 3689032.06) \times 33.71 \right) \times 3.16 = 1977613194 \text{kg}
   \]

3.2. The pavement engineering

1. Road cushion
   12-15T roller with compacting thickness of 150mm is adopted. The mechanical platform is:
   \[
   \frac{465775.00}{1000} \times 0.66 = 307.41 \text{(machine-team)}
   \]

2. Cement stabilized macadam base
   It adopts wheel loader within 3m³ and stabilized soil mixing equipment within 300t/h. The compaction thickness is 180mm, 150mm and 170mm respectively. The mechanical platform is:
   1) Tyre loader within 3m³:
   \[
   2996151.00 \times (0.48 + 0.03 \times 3) + 1405/1000 \times 0.48 + 2848/1000 \times 0.48 + 2 \times 0.03 = 1710.02 \text{(machine-team)}
   \]
   2) Stable soil mixing equipment within 300t/h:
   \[
   2996151.00 \times (0.24 + 0.02 \times 3) + 1405/1000 \times 0.24 + 2848/1000 \times 0.24 + 2 \times 0.02 = 899.98 \text{(machine-team)}
   \]

3. Pc-2 emulsified asphalt penetration layer
   The asphalt spreader is used within 4000L, and the mechanical platform is:
   \[
   (1401009.00 / 1000) \times 0.11 = 154.11 \text{(machine-team)}
   \]

4. Rubber powder /SBS composite modified asphalt waterproof adhesive layer
   The asphalt spreader is used within 4000L, and the mechanical platform is:
   \[
   (2558772.00 / 1000) \times 0.04 = 102.35 \text{(machine-team)}
   \]

5. Concrete laying
   Paving machine is used, track type laying is used, laying thickness is 20cm, the mechanical platform is:
1) Track-type cement retaining soil pavers: \((68685 \times 24.5/1000) \times 0.47 = 790.91\) (machine-team)

2) Concrete sewing machine: \((68685 \times 24.5/1000) \times 3.38 = 5687.80\) (machine – team)

3) Concrete mixing truck within 6m³: \((68685 \times 24.5/1000) \times 2.74 = 4610.82\) (machine – team)

4) Concrete mixing station within 40m³/h: \((68685 \times 24.5/1000) \times 1 = 1682.78\) (machine – team)

According to formula Table 1 and formula (1), the carbon emission of pavement construction machinery can be calculated as follows:

\[
\begin{align*}
(307.41 \times 40.46 + 1710.02 \times 115.15 + 899.98 \times 539.56 + 790.91 \times 83.66 + 4610.82 \times 55.54) \\
+ [(154.11 + 102.35) \times 34.28 + 5687.80 \times 6.24] \times 2.98 + 1682.78 \times 394.31 \times 1.246 \\
= 4173059.02\text{kg}
\end{align*}
\]

3.3. The bridge engineering

1. For foundation excavation, a single foundation pit volume <= 1500m³ is set. A crawler single-bucket excavator is used within 1.0m³:

\[
\frac{489291.75}{1000} \times 3.14 = 1536.38\text{(machine – team)}
\]

2. In the case of drilling or digging the cast-in-place pile, the rotary drill is used to drill the hole, the pile diameter is less than 250cm, the hole depth is less than 40m, and the mechanical engineer is:

1) Crawler single-bucket excavator within 1.0m³:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 0.02 = 160.81\text{(machine-team)}
\]

2) Trucks within 15T:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 0.07 = 562.85\text{(machine-team)}
\]

3) Crawler crane within 15T:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 0.06 = 482.44\text{(machine-team)}
\]

4) Rotary drill within 2500mm diameter:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 2.36 = 18975.96\text{(machine-team)}
\]

5) Mud mixer:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 1.3 = 10452.86\text{(machine-team)}
\]

6) AC arc welder within 32KV.A:

\[
\frac{(364+4072+178+9568+4575+25895.99+17003.9+18299.7+450)}{10} \times 0.02 = 160.81\text{(machine-team)}
\]

3. In the stage of steel basin rubber bearing

1) Truck crane within 20T:

\[
\frac{(256+1758+398+11+885+12+56+4+7+416+536+4+162+232+4)}{1} \times 0.14 = 772.94\text{(machine-team)}
\]

2) AC arc welder within 32KV.A:

\[
\frac{(256+1758+398+11+885+12+56+4+7+416+536+4+162+232+4)}{1} \times 0.32 = 1766.72\text{(machine-team)}
\]

4. In the expansion joint stage

1) Modular expansion device:

Truck crane within 12T:

\[
(73.50+1790.12+128.34+1404.72+648.38+73.5)*0.05=205.928\text{(machine-team)}
\]

Ac arc welder within 32KV.A:

\[
(73.50+1790.12+128.34+1404.72+648.38+73.5)*0.23=947.27\text{(machine-team)}
\]

2) Comb tooth plate telescopic device:

Ac arc welder within 32KV.A:

\[
(19.20+244.48+28.5+24.44)*0.92=291.29\text{(machine – team)}
\]

5. Split-stone concrete

1) Concrete mixer within 250mL:

\[
\frac{(470.27+646.6)}{10} \times 0.37=41.32\text{(machine-team)}
\]

2) Truck crane within 8T:

\[
\frac{(470.27+646.6)}{10} \times 0.22=24.57\text{(machine-team)}
\]

According to formula Table 1 and Formula (1), the carbon emission of bridge construction machinery can be calculated as follows:

\[
\begin{align*}
((160.81+1536.38) \times 74.91+562.85 \times 61.72+482.44 \times 33.52+205.928 \times 44.95+24.57 \times 32.38) \times 3.16 + \\
(18975.96 \times 618.55+10452.86 \times 9.74 + \\
(160.81+947.27+291.29) \times 87.63+41.32 \times 52.74) \times 1.246 = 15501782.31\text{kg}
\end{align*}
\]
3.4. The tunnel engineering

1. Open hole excavation
   The length of the tunnel is less than 4000m, the surrounding rock has grade 1, and the mechanical platform is:
   1) Air-leg wall chisel machine: $(92415.34/100) \times 11.55 = 10673.97\text{ (machine/team)}$
   2) Electric air compressor within 20m$^3$/min:
      $\left((92415.34/100) \times 2.21\right) = 2042.38\text{ (machine/team)}$

2. Spray concrete
   1) Mechanical shift of the power air compressor within 9m$^3$/min is:
      $\left((90644.88/10) \times 1.22\right) = 11058.68\text{ (machine/team)}$
   2) The concrete jet mechanical platform is:
      $\left((90644.88/10) \times 1.42\right) = 12871.57\text{ (machine/team)}$

3. Invert backfill
   Within 60m$^3$/h, the concrete conveying pump machinery shift is:
   $\left((3149.4 + 3360.96 + 52778.78 + 81577.48)/10\right) \times 0.11 = 1549.53\text{ (machine/team)}$

4. Proper ventilation
   1) The 1000KW internal axial fan mechanical station is:
      $1717 \times 128.5 \times 2/100 + 1060 \times 128.5 \times 3/100 = 8498.99\text{ (machine/team)}$
   2) Mechanical platform shift of centrifugal fan within 2132m$^3$/min is:
      $3118 \times 87.4/100 = 2725.13\text{ (machine/team)}$

5. Lighting inside the cave
   1) The mechanical platform of the truck within 2T is:
      $\left((3118 + 1717 + 2 + 1060 + 3)/100\right) \times (1.12 + 1.12) = 218.00\text{ (machine/team)}$
   2) The mechanical station of AC ARC welder within 32KV.A is:
      $\left((3118 + 1717 + 2 + 1060 + 3)/100\right) \times (4.85 + 1.77) = 644.26\text{ (machine/team)}$

6. Shaft support and lining
   1) Shotcrete mechanical platform:
      Concrete jet:
      $\left((90644.88/10) \times 1.65\right) = 14956.41\text{ (machine/team)}$
      Single barrel slow-moving hoist within 200KN:
      $\left((90644.88/10) \times 0.16\right) = 1450.32\text{ (machine/team)}$
      Within 80KN, double barrel fast moving winch:
      $\left((90644.88/10) \times 0.49\right) = 444.16\text{ (machine/team)}$
      Electric multi-stage pump with a diameter of 100mm:
      $\left((90644.88/10) \times 0.42\right) = 3807.08\text{ (machine/team)}$
      Electric air compressor within 10m$^3$/min:
      $\left((90644.88/10) \times 1.42\right) = 12871.52\text{ (machine/team)}$

30KW internal axial fan:
   $\left((90644.88/10) \times 0.39\right) = 3535.15\text{ (machine/team)}$

2) Mechanical platform for steel reinforcement:
   Single barrel slow-moving hoist within 200KN: $1423.49 \times 0.12 = 170.82\text{ (machine/team)}$
   Ac arc welder within 32KV.A: $1423.49 \times 0.85 = 1209.97\text{ (machine/team)}$

30KW internal axial fan: $1423.49 \times 0.64 = 911.03\text{ (machine/team)}$

According to formula Table 1 and Formula (1), the carbon emission of tunnel construction machinery can be calculated as follows:

\[
\begin{align*}
&[2042.38 \times 601.24 + 12871.52 \times 346.87 + (12871.57 + 14956.41) \times 42.6 + 1549.53 \times \\
&365.11 + 8498.99 \times 531.33 + 2725.13 \times 660 + (644.26 + 1209.97) \times 87.63 + (1450.32 + \\
&170.82) \times 148.38 + 4441.60 \times 156.09 + 3807.08 \times 233.78 + (3535.15 + 911.03) \times 159.4] \times \\
&1.246 + 11058.68 \times 60.34 \times 3.16 + 218.00 \times 20.08 \times 2.98 = 22622513.86\text{ kg}
\end{align*}
\]
3.5. Comparison and analysis

As shown in Figure 1, carbon emissions from the subgrade engineering are 1977613194kg; carbon emissions from the pavement engineering are 4173059.02kg; carbon emissions from the bridge engineering are 4173059.02kg; carbon emissions from the tunnel engineering are 15501782.31kg, from the perspective of carbon emissions from construction machinery during the construction period of the above sub-projects. It can be clearly seen that construction machinery generated the most CARBON dioxide, accounting for 98%, during the construction period of the highway roadbed engineering, because of the large amount of excavating, transporting earthwork, tamping earth and filling in this stage, a large number of construction machinery is needed.

![Figure 1. Comparison of carbon emission of construction machinery in each division](image)

4. Summary

According to "highway project budget quota" define the highway subgrade engineering, road engineering, bridge engineering, tunnel engineering machinery construction activities, based on the discharge coefficient method to construct the highway construction is the construction mechanical calculation model of carbon emissions, case study on the highway, get the construction period of highway roadbed engineering construction machinery biggest conclusion carbon emissions. However, the concrete construction of the expressway is not carried out in strict accordance with the quota, and there is still room for further research.

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