Modeling and Analysis of Carbon Emission in Life Cycle of Wave Beam Steel Guardrail

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Abstract. To refine the calculation of carbon emissions from the entire life cycle dimension of highways and provide theoretical support for the emission reduction of traffic safety facilities, life cycle assessment and carbon emission calculation methods are used to explore the carbon emission characteristics of corrugated beam steel guardrails throughout the entire process, clarify the accounting system boundary and analysis process, and construct emission models. In order to effectively reduce the carbon emissions generated by the construction of corrugated beam steel guardrails during highway construction, carbon emissions analysis and comparison were conducted based on field research and official data for commonly used double row double wave guardrails and three wave guardrails. The establishment of a carbon emission model for corrugated beam steel guardrails provides a foundation for "bottom-up" carbon emission statistics in the field of highways, improving the level of refined management in the process of highway construction and maintenance.

Keywords: Life cycle assessment · expressway · Corrugated beam steel guardrail · Carbon emission accounting · Model building

1 Introduction

Global warming is caused by greenhouse gas emissions such as carbon dioxide generated by human activities, which leads to frequent calamities related to heat waves, mountain fires, floods and waterlogging equal to extreme weather, causing high attention to carbon emission issues at home and abroad [1]. With the "carbon peak in 2030" and "carbon neutralization in 2060" goals proposed, the construction and research work of green highways in China has developed rapidly[2]. Carbon emission of highway facilities in the whole life cycle is an important part of the study of green highway. At present, there are many studies on carbon emission accounting in the process of highway construction at home and abroad, but pay less attention to traffic engineering facilities. Since the reform and opening up, China's highways have made considerable progress. By the end of 2021, China's total highway mileage reached 528.07 million kilometers, of which 169.1 million kilometers, forming a road network system with different levels of highways. As the last lifeline of highway traffic safety, corrugated beam steel fence is

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widely used in all levels of highways. Theoretically, it needs to be maintained or replaced every 3–5 years. Therefore, the production, construction, maintenance and recycling of corrugated beam steel fence are in great demand whether it is a new road or a maintenance operation. However, there are few detailed studies on Transportation Engineering facilities. Based on the life cycle evaluation method and the carbon emission calculation method, this study will build the life cycle carbon emission calculation model of wavy beam steel guardrail, and select two types of guardrail with similar protection level for example analysis.

2 Life Cycle Carbon Emission Assessment Methods

2.1 Life Cycle Assessment Methods

According to Environmental management-Life cycle assessment-Principles and frameworks (GB/T 24040–2008), life cycle assessment theory is divided into four stages: goal and scope definition, inventory analysis, impact assessment, and result introduction [3]. The goal and scope are defined as the goal and scope for understanding, organizing, and associating LCA results. Inventory analysis is part of a project's quantitative research. Lifecycle inventory identifies and quantifies resources, energy inputs, products, and waste discharges throughout the life cycle. Impact Assessment calculates data, analyses its impact, and evaluates it to make it easy for the audience to understand, that is, to identify potential environmental and human health impacts related to the product life cycle. Life cycle interpretation is the result of identifying, quantifying, reviewing and evaluating inventory analysis and impact assessment.

2.2 Carbon Emission Calculation Method

The commonly used methods for calculating carbon emission include the emission factor method, input-output method, quality balance method and actual measurement method. The emission factor method is a statistical method that focuses on calculation, and is also the most widely used and finer method to calculate carbon emission statistics. The input-output method is a mathematical analysis tool commonly used from the top to the bottom in economic activities. It analyzes complex input-output relations through the correlation between rows and columns in the input-output table, mainly analyzing the composition of industry, macroeconomic proportion and the correlation among various economic departments. Mass balance method is based on the law of mass conservation in chemistry. It has a very long history and is universal. For the calculation of carbon emissions, it is the only accurate standard calculation method for the calculation of carbon dioxide emissions [4]. The calculation results are accurate and reliable, which can provide reference for project design, environmental supervision and management departments, etc. [5]. However, the quality balance method is prone to system errors, and the data is difficult to obtain, and the authority is not high at present. Actual measurement is the only method of carbon emission statistics that emphasizes measurement. It can effectively measure direct emissions, but it is difficult to measure indirect emissions, and the implementation cost is high and difficult.

It can be found that the emission factor method has the advantages of easy operation and strong credibility of calculation results. Therefore,based on the life cycle assessment theory and emission factor method, this study proposed a method for carbon emission accounting of corrugated beam steel guardrail for Expressway in the whole life cycle.

3 Life Cycle Carbon Emission Assessment Of Wave Beam Steel Guardrail Product

3.1 Research Object and Scope

The object of this study is wavy beam steel fence, which is divided into two and three wave types. It is mainly composed of fence board, anti-blocking, post and bolt. The application scenarios are usually on both sides of highway, and can be divided into six levels according to the level of anti-collision. For the convenience of research and other researchers referencing data, the functional unit of this study is defined as the common functional unit of highway carbon emission accounting. The length of the highway is 1 km. The proportion of the end of the hesitant fence is very small. Therefore, the end of the fence is approximated to an equal-length fence. This study does not consider the effect of the end of the fence on the carbon emission of the overall roadside fence.

3.2 System Boundary

Direct emissions

At present, the corrugated beam steel guardrail used on highway is generally coated with zinc on the surface of Q235 steel base, and a few of the surface coatings are zinc epoxy-based polyester composite coatings. There is little direct discharge during the whole life cycle of production, storage, transportation and use. Therefore, the direct discharge of corrugated beam steel guardrail products in the whole life cycle is not considered.

Indirect Emissions

The life cycle of corrugated beam steel guardrail products mainly includes four stages: production, construction, maintenance and waste.

(1) Production stage

The production of fence panel mainly includes the production of fence panel, fence pillar, anti-blocking block, bolt group and other components, and the covering coating.

(2) Construction stage.

During the construction phase, the guardrail members need to be transported from the manufacturer to the construction site for setting. The main equipment used in the construction process is the pile driver. Therefore, the carbon emission during construction phase is mainly affected by transportation vehicle type, transportation distance, transportation frequency and pile driving frequency.

(3) Maintenance stage.

Common maintenance work of corrugated beam steel guardrail mainly includes replacement and cleaning. The replacement process is similar to construction. It can be calculated according to phase pipe method in construction stage, cleaning common special vehicles and calculating carbon emission through energy consumption in cleaning process.

(4) Abandonment stage.

Due to the fact that the corrugated beam steel guardrail is a metal product with high usage and significant environmental impact after disposal, it has high recycling value. Generally, it is recycled after the guardrail is abandoned. Due to the small difference in material quality before and after recycling, it becomes a new steel product after recycling, and the economic value of the products before and after recycling is similar. Therefore, the carbon emission distribution coefficient during the waste process is $\varepsilon = 0.5$.

3.3 Model Building

The construction of a life cycle carbon emission model for corrugated beam steel guardrails requires the selection of a data collection checklist, which mainly considers two factors: data availability and process refinement. The development of a data list directly affects the selection of unit processes in life cycle assessment. Through research on multiple manufacturers, users, and recyclers of corrugated beam steel guardrails, a logical diagram of the carbon emission model for the lifecycle of corrugated beam steel guardrails has been formed, as shown in Fig. 1.

The calculation of carbon emissions during the life cycle of corrugated beam steel guardrails, and the specific formula for calculating the carbon emissions generated by resource consumption from production to disposal stages (1).

$$C = (C1 + C2 + C3 + C4) \quad (1)$$

C_1——Carbon emissions generated during the production phase,$kgCO_2$;

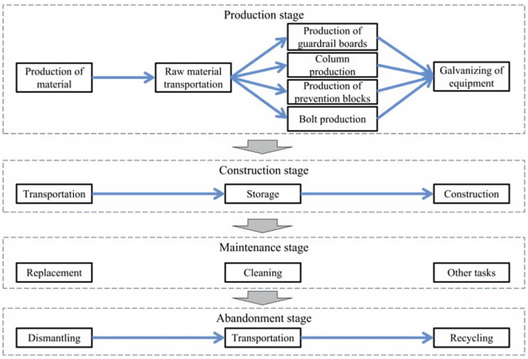

Fig. 1. Logic diagram of carbon emission model for the life cycle of corrugated beam steel guardrail

C_2——Carbon emissions generated during the construction phase,$kgCO_2$;
C_3——Carbon emissions generated during the maintenance phase,$kgCO_2$;
C_4——Carbon emissions generated during the abandonment stage,$kgCO_2$;

(1) Production stage.

The carbon emissions during the production stage are determined by the sum of the carbon emissions generated by the consumption of materials in each unit of the process and the carbon emissions generated by energy consumption, as shown in formula (2).

$$C_1 = E_{W1i} \times \beta_{W1i} + \sum E_{N1i} \times \beta_{N1i} \tag{2}$$

E_{W1i}——Material usage upstream of unit process i in production phase,kg;
β_{W1i}——Carbon emission factor for material of the i-th unit process in production stage,$kgCO_2/kg$;
E_{N1i}——Energy consumption of the i-th unit process in the production stage,kW h;
β_{N1i}——The i-th unit process energy carbon emission factor in the production stage,$kgCO_2$/kW h;

(2) Construction stage.

The carbon emissions during the construction phase are mainly composed of indirect emissions caused by energy consumption during transportation, storage, and equipment use during construction. According to JTG/T 3833–2018 [6], the carbon emissions during material transportation can be calculated, as shown in formula (3) [7]. The carbon emissions of all equipment in other unit processes are influenced by energy consumption and emission factors, as shown in formula (4).

$$C_{21} = \sum_{j=1,t=1}^{n} Q_j \times L_j / Q_t / V_t \times \beta_{2jt} \times (1 + \theta) \tag{3}$$

C_{21}——Carbon emission consumption during transportation process,$kgCO_2$.
Q_j——The transportation volume of the jth construction,kg;
L_j——The distance for transporting the jth type of material,km;
Q_t——Rated load capacity of the t-th type of transportation equipment,kg;
V_t——Speed of transportation equipment,km/Number of units;
β_{2jt}——Carbon emission coefficient generated per unit shift time when transporting Class i materials using Class t transport vehicles,$kgCO_2$/Number of units;
θ——No-load rate.

$$C_2 = C_{21} + \sum E_{N2i} \times \beta_{N2i} \tag{4}$$

EN_{1i}——Energy consumption of the i-th unit process in the production stage,unit of measurement;
βN_{1i}——The i-th unit process energy carbon emission factor in the production stage,CO_2/unit of measurement;

(3) Maintenance stage.

The carbon emission model for the replacement of corrugated beam steel guardrails during the maintenance phase refers to the carbon emission model during the construction phase. Due to the high consumption of water during the cleaning process of guardrails, the carbon emissions from obtaining water cannot be ignored Referring to relevant research and regulations, the carbon emission factor for water extraction is 0.168kgCO_2/t[8]. The carbon emissions generated by other processes during the maintenance phase are mainly determined by material and energy consumption, as shown in formula (5).

$$C_3 = C_{31} + E_{W3i} \times \beta_{W3i} + \sum E_{N3i} \times \beta_{N3i} \tag{5}$$

C_{31}——Carbon emissions generated by guardrail replacement during the maintenance phase, kgCO_2;

E_{W3i}——The i-th unit process material usage during the maintenance phase,kg;

β_{W3i}——Carbon emission factors for upstream materials used in the i-th unit process during the maintenance phase, kgCO_2/kg;

E_{N3i}——Energy consumption of the i-th unit process in the maintenance phase,unit of measurement;

β_{N3i}——The i-th unit process energy carbon emission factor in the maintenance phase, CO_2/unit of measurement;

(4) Abandonment stage.

The abandonment stage mainly consists of three stages: demolition, transportation, and recycling.The carbon emissions generated during the waste process are included in the waste process and the production process of new products based on the recovery rate and distribution coefficient. The parts that cannot be recovered are all included in the waste stage based on the non recyclable rate, Please refer to the simplified formula (6) for details.

$$C_4 = \left(C_{41} + E_{W4i} \times \beta_{W4i} + \sum E_{N4i} \times \beta_{N4i}\right) \times [1 + \lambda \times (\varepsilon - 1)] \tag{6}$$

C_{41}——Carbon emissions generated during transportation and replacement during the abandonment phase, kgCO_2;

E_{W4i}——Material usage in the i-th unit process of the abandonment stage,kg;

β_{W4i}——Carbon emission factors for upstream materials used in the i-th unit process of the abandonment stage, kgCO_2/kg;

E_{N4i}——Energy consumption of the i-th unit process in the abandonment stage,unit of measurement;

β_{N4i}——The i-th unit process energy carbon emission factor in the abandonment stage, CO_2/unit of measurement;

λ——Recovery rate of abandoned guardrails;

ε——Carbon emission distribution coefficient during the abandonment stage.

4 Carbon Emission Calculation and Analysis

In the process of highway construction, the carbon emissions during construction, maintenance, and disposal are influenced by different transportation routes and equipment used. Local conditions make it difficult to better understand the sensitivity of each process. Therefore, in order to effectively guide the selection of corrugated beam steel guardrails for highways from the perspective of carbon reduction, this section only calculates and analyzes the carbon emissions during the production stage of two commonly used guardrails for highways. The following is a data analysis of the carbon emissions of the two types of guardrails during the production stage, based on the functional unit of one kilometer road and referring to standards such as GB/T 31439.1 and GB/T 31439.2. The specific data for the construction quantity is shown in Table 1[9, 10].

Material used in production of corrugated beam steel guardrail is generally cold rolled carbon steel coil and cold drawn carbon steel seamless steel pipe. GB/T 51366–2019 is for carbon emission factors. See Table 2 for details [8].

The production of various components of the guardrail mainly consumes electrical energy, and the emission coefficient of electricity is calculated based on the average emission factor of 0.5703t CO_2/MWh of the national power grid in 2022. The data related to production equipment is based on the production line used by a certain factory in field research. The data related to the main equipment is detailed in Table 3 below.

According to calculation, if double-row two-wave beam steel guardrail is selected for 1km highway, the carbon emission is about 32002.4309kgCO_2e in production stage, and if three-wave beam steel guardrail is selected for production stage, the carbon emission is about 23660.8296kgCO_2e, in which the carbon emission generated by processing is less than 1%. Therefore, from the perspective of carbon emission, in highway construction, the carbon emission generated by three-wave beam steel guardrail is less in order to achieve better protection effect.

Table 1. Types and quantities of guardrail components

Double row and two waveform beam steel guardrail			Triple waveform beam steel guardrail		
Component	Model	Number	Name	Model	Number
Corrugated beam plate (4mm thick)	DB01	100	Corrugated beam plate (4mm thick)	RTB01	50
Column	G-F	102	Back plate	RTSB02	102
Splice bolt	JI-2、4、5	384	Column	Steel Pipe	102
Connecting bolt	JII-1、2、4、5、6	204	Splice bolt	JI-2、4、5	288
prevention block	F	204	Connecting bolt	JII-1、2、4、5、6	102
			prevention block	BG	102

Table 2. Logistics carbon emission factors

Material category	Carbon emission factor(kgCO_2e/t)
Cold rolled carbon steel plate coil	2530
Cold rolled and cold drawn carbon steel seamless steel pipes	3680

Table 3. Main Production Equipment for Guardrails

Equipment category	power	Production speed
Guardrail board production line	45kW	18m/min
prevention block production line	25kW	15m/min
Bolt blank production equipment	7.5kW	60pcs/min
Tapping equipment	2.2kW	120pcs/min

5 Conclusion

Life cycle assessment theory provides a scientific analysis method for carbon emission accounting. Based on the life cycle assessment theory, this study proposed a method for carbon emission accounting of corrugated beam steel guardrail for Expressway in the whole life cycle. Through examples, the comparative analysis of two road corrugated beam steel guardrails with similar degree of protection is carried out from the angle of carbon emission. It provides reference basis for energy saving and emission reduction in upstream and downstream industries.

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