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Estimation of carbon dioxide emission in highway construction: a case study in southwest region of China

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A B S T R A C T

The large-scale transportation infrastructure construction in developing countries such as China requires emission estimation method for better project design. This study proposed an empirical method to estimate carbon dioxide (CO_2) emission which was generated from highway construction based on four real projects in southwest region of China. The proposed method estimated the total emission from different steps of construction process (raw material production, material transportation and onsite construction) by different project types (e.g. subgrade, pavement, bridge, and tunnels). The results show that in general over 80 percent of the CO_2 emission was generated from raw material production; the onsite construction and material transportation only accounted for 10 and 3 percent of the whole CO_2 emission, respectively. Moreover, the CO_2 emission from bridge and tunnel constructions was much larger than subgrade and pavement construction. The total CO_2 emission from road, bridge and tunnel constructions was 5229 kg/m, 35,547 kg/m and 42,302 kg/m, respectively. The empirical estimation method of the CO_2 emission proposed in this study can be considered as references for CO_2 emission estimation in other regions which are similar as southwest region of China.

1. Introduction

Global warming has been a severe challenge to the human being in recent decades. It is widely known that the greenhouse gas, especially carbon dioxide (CO_2), blamed to be the main cause of global warming. According to U.S. Energy Information Administration (EIA), the total CO_2 emission from the energy consumption in the world was 32,578.645 million tons in 2011, among which 8715.307 million tons came from China (U.S. EIA, 2013). Such amount of CO_2 emission in China is believed to be generated by the large-scale transportation infrastructure construction. Since the first expressway built in 1988 in China, the total length has been 96,200 km by the end of 2012, and the length will be increased to 108,000 km in 2015 (National Bureau of Statistics of China, 2013; Ministry of Transport of the People's Republic of China, 2011). However, currently there are few empirical methods available which can be used to evaluate the CO_2 emission estimation from large-scale construction process in China.

Many studies have investigated the carbon emission issue in the world. Dixit et al. (2010) identified the parameters for embodied energy measurement for buildings, proposed the needs for an embodied energy measurement protocol for buildings (Dixit et al., 2012), and later proposed a conceptual model about system boundary for embodied energy (Dixit et al., 2013). Harmouche et al. (2012) developed a carbon footprint calculator for building construction, with the consideration of project characteristics (e.g. size, location, material choices). Han et al. (2013) also studied how to embody energy consumption in building construction, and selected a cluster of landmark commercial buildings in E-town, Beijing for case.

In the field of road engineering, some research frameworks and emission estimation methods have been proposed and used for environmental impact assessment. Park et al. (2003) assessed the environmental impacts of highways in life cycle. Fox et al. (2011) introduced a pilot result of carbon management system for road projects applied in Scotland. Tsai et al. (2012) proposed a framework for developing sustainable items for highway design. Avetisyan et al. (2012) proposed an optimization-based methodology to permit a construction firm to assess its equipment needs while accounting for the greenhouse gas emissions. Huang et al.

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(2013) outlined the common methodology of road carbon foot printing, and performed case studies in UK and India using CHANGER (the Calculator for Harmonized Assessment and Normalization of Greenhouse-gas Emissions for Roads). And Barandica et al. (2013) evaluated Greenhouse gases in road construction from a life cycle perspective, and analyzed four construction projects in Spain. Specifically, the life cycle assessment of road pavement has been the focus by many researchers (Kim et al., 2012; Cass and Mukherjee, 2011; Yu and Lu, 2012). Besides that, the University of California Pavement Research Center (UCPRC) has worked on recommending common practices for conducting LCA (Life Cycle Assessment) for pavements, and the UCPRC Pavement LCA Guideline intended for pavement LCA practitioners was presented, which includes a LCA framework for pavements, as well as some recommended data and models that have been used in California and other states in U.S. (Harvey et al., 2010). Michigan Department of Transportation (DOT) also studied on developing and implementing a project based life cycle framework which can be used to estimate the carbon footprint for typical construction work-items (Mukherjee and Cass, 2011). Moreover, Abolhasani et al. (2012) investigated the fuel use and emissions of non-road construction vehicles using real world data, and Frey et al. (2012) summarized the characterization of real-world activity, fuel use, and emissions of selected motor graders fueled with petroleum diesel and B20 biodiesel. Chang and Kendall (2011) made a life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system.

Although many studies attempted to estimate the carbon emission in different regions, their results were not quite consistent, and there is a need for local researchers in China to propose its own estimation method according to its own circumstances. Shang et al. (2010) analyzed the energy consumption and atmospheric emissions of highway roadbed earthwork, drainage, protection and pavement engineering in life cycle. Pan (2011) investigated the energy consumption and carbon emissions of asphalt and cement concrete pavement in life cycle. Ouyang and Liu (2011) studied the carbon emissions of bridge project in life cycle with a case study. Xu (2012) calculated bridge cases' carbon emissions of two structures (e.g. concrete beams and steel - concrete composite beams). Li et al. (2011) made a case study on the CO_2 emissions from working machinery during highway tunnel construction.

Recently, the government of China started to realize to reduce the large quantity of CO_2 emission from the large-scale transportation infrastructure construction. The first step of this work is to quantitatively estimate CO_2 emission by different types of transportation infrastructure construction (e.g. subgrade, pavement, bridge, and tunnels). While lots of work have been done worldwide in order to estimate of CO_2 emission, however, there is still not a widely accepted method available. Moreover, the previous studies usually focused on one type of road construction without considering subgrade, pavement, bridges and tunnels. Currently there is still a need for the method of CO_2 emission estimation that can be used in the real projects in China. Such method is potentially very helpful in the transportation infrastructure construction. For example, a short-distance bridge/tunnel or long-distance road, which is more environmental friendly based on the evaluation of CO_2 emission estimation?

This study proposed an empirical method to estimate CO_2 emission from highway construction in China. First, the whole transportation infrastructure construction process was divided into three steps: raw material production, material transportation and onsite construction. Then the CO_2 emission was calculated based on project budget sheet from four real highway projects in southwest region of China. After that the emissions from each phase and internal compositions were detailed analyzed for subgrade and pavement construction. Thanks to the large numbers of bridges and tunnels contained, general estimation results for these two structures were presented. In addition, the emission densities were compared from the perspective of these three structures: road, bridge and tunnel. At last, we validated our results through the comparison and discussion with similar researches and made final conclusion.

The paper is organized as follows. Section 2 proposes the empirical method in order to estimate CO_2 emission. Section 3 presents the case study of four real projects in southwest region of China. Section 4 is the sensitivity analysis of the case study. Section 5 is the results discussion, and Section 6 provides the conclusions.

2. The proposed method for CO_2 emission estimation

This study attempts to propose an empirical method to estimate CO_2 emission by using budget sheets, which record the detail consumptions of materials and energy. In the study scope, highway construction process is divided into three phases: raw material production, material transportation and onsite construction. The total emissions are the sum of each stage:

$$Q = Q_1 + Q_2 + Q_3 \tag{1}$$

Where, Q is the total amount of CO_2 emission from highway construction; Q_1, Q_2, and Q_3 is the amount of CO_2 emission from raw material production, material transportation and onsite construction, respectively. The unit of Q, Q_1, Q_2, and Q_3 is kg.

2.1. The CO_2 emission from raw material production

The CO_2 emission from raw material production refers to the CO_2 emissions of materials which are generated in the mining, processing and manufacturing factories and other production processes. The formula to record CO_2 emissions from raw material production can be defined as:

$$Q_1 = \sum_{i=1}^{n} Q_{1i} = \sum_{i=1}^{n} (q_i \times u_i) \tag{2}$$

Where, Q_1 is the total CO_2 emission from raw material production; Q_{1i} is the CO_2 emission from the production of material i; q_i represents the coefficient of CO_2 emission from the production of material i; u_i refers to the quantity of material i; $i = 1, 2, \ldots, n$, are the types of materials considered. The unit of Q_1 and Q_{1i} is kg.

The major materials for highway construction are steel, cement, asphalt and stone. The steel materialized process consists of two stages: raw material exploitation and steel production. Direct and indirect environmental impacts may exist in either stage. There are several studies investigated the emission from the two stages. Gong (2004) detailed analyzed the steel materialized system from exploitation to final product, in which direct environmental impacts from processing and transportation combined with the indirect impacts from energy production were considered. Luo et al. (2011) also calculated the emission factor of steel production, but the value obtained was less than Gong (2004)'s, because Luo et al. (2011) just considered the emission of material production processing part. He and Zhang (2013) built a model and discussed the carbon emissions and influencing factors of steel industry in China. They concluded that the energy consumption and emissions had increased a lot in developing countries with the economy development. The extensive development mode is still common at current stage, but the energy-saving technology has been improved. They found that the carbon emission density for steel production