Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China

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Abstract
Carbon dioxide emissions mitigation from road construction activities is one of potential pathways to deal with climate change. Aiming to estimate the magnitude of carbon dioxide emissions and identify the uncertainty from construction phase of real entire road projects including road structures and earthworks apart from pavement, this paper applied Life Cycle Assessment on 20 asphalt projects and 18 concrete road projects which were classified into high-grade road and low-grade road. The impact of uncertain data source and system boundary on results was checked, followed by discussion with previous studies. The findings show that average total emissions per kilometer per lane are variety but nearly 500 t for concrete and 1250 t for asphalt road. Carbon dioxide emissions comparison of asphalt road in this study with previous studies indicates that emissions of entire road project are 1.92 times higher than that of studies only considering pavement, 27% higher than that of studies without considering bridge and tunnel. Materials contribute to largest emissions in both asphalt road and concrete road, but off-road machinery even accounts for 45% of total emissions in concrete road. Emission of off-road machinery in asphalt road in this study is 13.6% higher than that of studies only considering pavement. Efforts should focus on earthworks and structures, and on improvement in off-road machinery performance not only on materials. Lack of consideration on phase of chemical reactions for cement in asphalt road and pre-consumption for fuel in concrete road could underestimate 15% of total emissions respectively. Recycling steel and electricity structure improvement play a weak role in road construction emissions reduction. For both concrete road and asphalt road, emissions of low-grade road are about 13% lower than that of high-grade road.

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1. Introduction
Carbon dioxide is the largest contributor to greenhouse gas that is contributing to recent climate change (EPA, 2016). Most of the countries have reached a consensus on reducing CO2 emissions, and some developed countries even make their low-carbon development strategies to reduce their domestic carbon emission to less than 60 percent until 2050. China has formulated CO2 emissions reduction target of CO2 emissions decrease by between 60% and 65% per GDP from 2005 to 2030 (Qi and Zhang, 2016).

It is reported that human activities are the primary carbon emissions source, accounting for about 90% of all carbon emissions in the world (IPCC, 2007), and among human activities, transportation activities is a key CO2 emitter. According to statistics, emissions from transportation sector take up about 27% of the total world energy-related emissions (IEA, 2012), and in China it accounts for 10.5% of total emissions in 2013 (Qi and Zhang, 2016). Accompanied with the pace of motorization, CO2 emissions from private vehicle has increased to 211 million metric tons in 2010 from 1.8 million metric tons in 1980 and has increasingly contributed to 24.2% of total transportation sector emissions from 3.3% (Qi and Zhang, 2016).

Apart from the tailpipe CO2 emissions during vehicle operation, transportation infrastructure, specifically road infrastructure, supporting for annual increasing automobile population in developing countries, show great potential to carbon emissions migration due to its higher use of materials, machinery energy consumption, and high quantity of vehicle and equipment fuels for transports and in-site construction activities (Muench, 2010). The emissions from road materials extraction and production, to-site transportation, on-site construction machinery and other phases during road life cycle including road construction, maintenance, recycling of road...
even make up 5%–25% of total CO₂ emissions from transport (Julienn et al., 2014), and among stages, construction phase was the biggest contributor to road project emissions (Barandica et al., 2013).

In China, 40% of total passenger volume (passenger-kilometers) and 33% of total goods volume (goods-kilometers) in 2014 was completed by highway (National Bureau of Statistics of China, 2016). Transportation infrastructure sector in China has undergone amazing development speed during the last three decades from 1978 to 2013, and during this time, highway mileage has increased by three-times from 0.89 million kilometers to 4.4 million kilometers and the total length of expressway increase remarkably to 104,400 km from 100 km within merely twenty years (National Bureau of Statistics of China, 2015). Aiming to meet the passenger and goods transportation demand, new road infrastructure construction or reconstruction and extension project in the next 20 years still is an important task. Quantity estimation and assessment on road project construction activities has received increasing attention from academia for understanding environmental effect and seeking the opportunities of CO₂ reduction. Life Cycle Assessment (LCA) is widely applied as a tool for assessing CO₂ emissions from the complicated process and large sources included into road project. The method of Life Cycle Assessment (LCA) has dramatically developed since 1980s, is a systematical method for assessing the environmental impact by identifying the flow of energy or material during a process or activity (ISO 14040, 2006).

The growing interest in the topic is reflected in the number of studies published recently. The first LCA on environmental effects of entire road construction project was conducted by (Stripple, 2001), calculating the CO₂ emissions from the complete life cycle of a road including the extraction of raw materials, the production of construction products, the construction process. Even the maintenance and operation of the road and finally the disposal/reuse of the road at the end of the life cycle were included. Majority of studies has evaluated the environmental impact from pavement. Park et al. (2003) and Treloar et al. (2004) have assessed the life cycle environmental impacts of different pavement structures including cement concrete pavement, composite pavement and asphalt pavement. On the basis of LCA application, other research organizations developed national or regional LCA road tool, including some focused on precise areas such as SimPro model for life-cycle environment and energy consumption analysis on road pavement materials, PaLATE model developing for environmental and economic impact assessment on road and PAS2050 designed for environmental and energy consumption on road project (Santero et al., 2011).

Huang et al. has estimated the emissions of an asphalt paving project using recycled materials including waste glass, incinerator bottom ash and recycled asphalt pavement (Huang et al., 2009a). Not like typical LCA frameworks of roads have put focus on recycled materials on pavement, Celauro et al. has considered the materials used in the embankment or in the subgrade during road construction based on PaLATE model (Celauro et al., 2015). Some studies expanded the system boundary to road structures such as bridge (Kendall, 2008; Wang et al., 2014), tunnel (Li et al., 2011). The LCA tool application on environmental impact also extended to specific areas such as importance of rolling resistance of different surface course (Araújo et al., 2014; Ghosh et al., 2015), carbonation of road surfaces and concrete structures (Galan Garcia et al., 2010), the disrupted traffic by road maintenance (Huang et al., 2009b; Galatioto et al., 2015) or construction (Kang et al., 2014) on the CO₂ emissions.

However, due to complexity and diversity of topography, layout and other factors, study cases on entire highway are less founded. Different road types in terms of highway (Park et al., 2003), intercity road (Wang et al., 2014; Santos et al., 2015), interstate road (Cass and Mukherjee, 2011), motorway (Fox et al., 2011), interurban road (Galatioto et al., 2015) and rural road (Celauro et al., 2015; Fox et al., 2011), are chose by studies, mainly because of the data accessibility, but no comparative analysis for environmental results of different road types in published studies. It is important for decision makers and constructor to understand CO₂ emissions level of different road types and make specific measures on CO₂ reduction.

Since the CO₂ emissions reduction has been introduced into world or national development targets, advanced technology and low-carbon strategies such as renewable energy, carbon capture technology on coal industry, electricity structure adjustment, and recycled materials are gradually introduced. All these new factors could affect certain phases in life-cycle inventory analysis on road infrastructure construction activities, thus have impact on CO₂ emissions of road infrastructure construction activities. There are more uncertainties existing in CO₂ emissions estimation on road constructions.

With the aim of making a contribution to estimate the magnitude of CO₂ emissions of entire road project including road structure and earthwork, identify significant factors and understand possibility of CO₂ emissions reduction from different categories of road construction, this study applied LCA on four categories of real road project. Following the analysis on total emissions of road project and emissions shares of each element, uncertainty analysis of the emissions results was conducted. At last, comparative discussions on emissions results in this study with other researches. This information, together with the national statistics regarding the quantity of road constructed annually in kilometers, contribute to the countrywide inventory of CO₂ emissions with validity and reliability and to provide reference for CO₂ reduction from road infrastructure. Also, this study broadens the number of case studies considerably to support and compare with different types of road projects.

2. Material and methods

2.1. System boundary definition

This study aims to quantify CO₂ emissions using an LCA methodology according to ISO 14040 (ISO 14040, 2006). The CO₂ emissions of a road project construction are estimated by the aggregation of impacts over its life cycle system boundary, as shown in Fig. 1. In this study, road structures including bridge and tunnel are enclosed into the system boundary. Off-road construction machinery, the main source of fuel and electricity consumption, not only covers conventional on-site equipment, but also includes machinery or equipment in asphalt mixing station and concrete mixing plant.

Functional unit is definite in this part and it is a physical unit. In this study, the emission values have been normalized to match the functional unit of one lane per kilometer, representing as t/lane-km.

2.2. Inventory analysis and CO₂ emissions calculation

Inventory analysis on emissions from materials production process begins with raw materials extraction, processing and transportation to the stock ground. Emissions from off-road machinery and transportation vehicle are measured practically by calculating the emissions produced from fuel consumption. Summing emissions of the three main sources can get the total emissions of a road project, then normalizing the total emissions into functional unit using length and number of lanes of the road project. Emissions per functional unit of each road category are
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