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Life cycle assessment for carbon dioxide emissions from freeway construction in mountainous area: Primary source, cut-off determination of system boundary

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ABSTRACT

Carbon dioxide (CO_2) emissions mitigation from transportation infrastructure construction activities is regarded as one of the potential pathways to deal with climate change. Aiming to assess the magnitude of CO_2 emissions associated with freeway infrastructure construction activities and identify primary emissions sources in mountainous area, this study firstly assessed life cycle CO_2 emissions of an entire freeway project in mountainous area in China, including pavement, bridge, tunnel, intersection, traffic safety facilities and temporary works into the system boundary. The results show that CO_2 emissions related to road segment are one magnitude lower than that of bridge and tunnel. In addition, negligence of intersection, traffic safety facilities and temporary works could underestimate 4% of total CO_2 emissions of the freeway project. CO_2 emissions distribution of the different types of materials and equipment distribute as the similar Pareto Principle, which reminds that definition of system boundary could focus on the few of inputs that matter on the aspects of data limited, rough estimation and comprehensive understanding of environmental impact. Findings of this study could offer transport agencies more comprehensive references to understand the contribution of freeway infrastructure construction activities in the mountainous area to climate change, and provide decision makers insights to take measures in the planning phase, particularly in the construction phase in terms of equipment selection, construction design, and construction materials design.

1. Introduction

Carbon dioxide (CO_2) gases associated with the transportation sector has become a global concern as its dominant impact on climate change. The sector contributes to 27% of global energy-related CO_2 emissions and 13% of total global GHGs, and it will be the main growth point of CO_2 emissions in future (Climate Change 2014: Mitigation of Climate Change, 2014). CO_2 emissions saving from transportation become a key way to release the pressure for many countries to carry out the global commitment to controlling and reducing national carbon emissions (Intergovernmental Panel on Climate Change, 2015).

CO_2 emissions from exhaust pipes during vehicle operation has attracted scholars and managers more attention, and abundant research achievements on quantitative mathematical calculation model and assessment tool have been obtained, such as CMEM (Scora and Barth, 2006) and MOVE (Koupal et al., 2002). In fact, apart from the CO_2 emissions associated with vehicle operation, the phase of road construction and maintenance has witnessed a broad margin for environmental improvement. It is a phase that a large amount of materials consumption is needed and a great deal of fuel and energy used in the operation of construction equipment, transportation vehicle, and machinery. Large quantities of indirect CO_2 emissions are emitted during the acquisition and manufacturing process of materials and fuels (Celauro et al., 2015; Huang et al., 2015). Researches claimed that the CO_2 emissions associated with road infrastructure construction and maintenance could contribute to roughly 10% higher greenhouse gas emissions (GHG) of on-road vehicles than that one only estimates the emissions from vehicle operation (Chester and Horvath, 2009). Furthermore, results of life-cycle GHG of a highway reconstruction in a New Jersey case study indicates that GHG associated with the reconstruction project could account for 20% of the total emissions from traffic over a 50-year lifetime (Noland and Hanson, 2015). Notably, different from urban road serving for a large quantity of traffic volume, for roads with smaller traffic volume in periphery area, their CO_2 emissions during the phase of the operation has a relative less responsibility for total emissions during the whole life time of the road project.

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Instead, the CO_2 environmental impact of road construction should be subject to greater attention (Huang et al., 2015).

Those research on early CO_2 emissions impacts on road construction have mostly focused on components of a road project not an entire road project, especially on comparison analysis on different surface structures (Park et al., 2003; Treloar et al., 2004 Santero et al., 2013) and pavement material use (Horvath and Hendrickson, 1998; Stripple, 2001; Huang et al., 2009). Later, the research highlights extend to recycled materials, waste materials reuse and new materials used on the pavement (Huang et al., 2009; Chowdhury et al., 2010; Anastasiou et al., 2015) and on earthwork (Celauro et al., 2015; Barandica et al., 2013). Recently, some researches are not limited to assessment emissions of road segment including pavement and earthwork. Instead, they have expanded the road life cycle assessment system boundary to single specific road structures of the bridge (Kendall et al., 2008) and tunnel (Li et al., 2011; Huang et al., 2015). Exceptional studies by Wang et al. (2014) and Liu et al. (2017), integrating both the bridge and tunnel into life cycle assessment system and comparing CO_2 assessment results between the road and the two structures, concluded that the emissions associated with bridge and tunnel construction are obviously higher than that of road pavement and earthwork. Santos et al. developed a comprehensive pavement life-cycle assessment model by considering GHGs emissions but minor components of road project were not considered (Santos et al., 2017). Some scholars reviewed the application of LCA in road construction to quantify the potential impacts from the use of materials (Balaguera et al., 2018; Xu and Shi, 2018). However, rare researches claimed that minor components of traffic safety facilities, drainage works and temporary works for an entire road project also should be considered as their contribution to total emissions (Noland and Hanson, 2015). Nevertheless, they are usually omitted, owing to data limitation, simplifying assumptions in most researches.

Conclusions from previous studies on emissions source identification present that materials manufacturing has dominate contribution to total emissions, accounting for between 53% to 97%, and emissions from fuels and energy consumption by equipment and transportation vehicle makes up a less proportion (Wang et al., 2014; Fox et al., 2011; Park et al., 2003). Except for a study on four newly construction project in Spain, emissions associated with earthwork construction are much higher, accounting for between 60% to 85%, are mainly from construction equipment for earthwork construction (Barandica et al., 2013). In fact, emissions associated with road construction are emitted from direct construction activities and indirect construction activities. Direct construction activities contain construction and transportation activities on site, materials mixing activities off the construction site, and transporting the construction materials to a construction site or mixing plant directly from factory or supplier and transporting materials mixture to the construction site from mixing plant. Indirect construction activities include materials acquisition, manufacturing, and transportation to the factory, even allocation to the supplier. CO_2 emissions associated with indirect activities, especially for materials manufacturing, are mainly responsible for the manufacturing sector. For transportation management agency, it can be used as a basis for construction materials selection during the phase of road design and construction, but they could not make changes fundamentally. However, they can make efforts to minimize CO_2 emissions from on-, to- and off- site road construction activities.

Over the last 15 years, China has witnessed a rapid development in expressway construction, enjoying an increase of total expressway mileage to more than 12.35 ten thousand km in 2015 (China-Highway, 2016) from 16,300 km in 2000 (National Bureau of Statistics of China, 2015). The freeway density is up to 1.3 km per hundred square kilometers in 2015. Even though, the coverage of national expressway planning and construction is still uneven. Lower than the national average in 2015, the expressway density in the underdeveloped northwestern area in China is 0.54 km per hundred square kilometers, with 17,001 km of total expressway mileage (China-Highway, 2016). According to national highway planning, about 25,000 km of the expressway will be built during the period 2013–2030, and expressway construction in the western area is emphasized (National Development and Reform Commission, 2013). In China, the area of mountain and hills cover two-thirds of the total land area and are mainly distributed in the western area (Wu et al., 2015). This means that fairly long length of the expressway would be constructed in the mountainous area in future. To meet requirements of technical standards, the complicated terrain in the mountainous area makes expressway construction more difficult, causing deep-cutting and high-filling subgrades and generating many slope protection works. Besides, the construction of a road project in the mountainous area would lead to the time-consuming and materials-intensive construction of bridge and tunnel. In addition, the impact of topography on construction schedule, equipment, and materials selection could react on CO_2 emissions assessment results of a road project (Barandica et al., 2013; Cass and Mukherjee, 2011).

The national road network planning has emphasized the environmental impact assessment during road construction to promote the harmonious development of highway construction. However, lack of estimation of CO_2 emissions in a project level in mountainous area limits the environmental impact assessment in the network planning phase. In addition, the large amount types of materials, equipment, vehicle, and machinery are involved into the construction activities that make it difficult to take targeted and effective measures on CO_2 emissions control and saving in the phase of design and construction phase.

With the aiming of making a support for the comprehensive understanding of the CO_2 emissions impact for transport agency and providing a system boundary for developing a manageable, reliable and not-misleading estimation model for designers, contractors, constructors and environmental protectors, this study firstly applied life cycle assessment on construction phase of an entire freeway project in mountainous area in China, including six subprojects by four stages related to direct or indirect activities, the magnitude and composition of CO_2 emissions by subprojects and stages were calculated. Then the primary sources of CO_2 emissions and the contributions of these primary sources were further explored. Moreover, the cut-off determination of life cycle assessment system boundary was proposed based on the primary sources and their contributions on CO_2 emissions. In this way,

the level of CO_2 emissions associated with the freeway construction activities that the transport agency could control was discussed and policies were suggested in the final section of the context.

2. Methods and material

2.1. Scope and system boundary

An entire freeway road project is composed of six main subprojects including road segment (pavement and subgrade), bridge, tunnel, intersection, traffic safety facilities and temporary works. In this paper, pavement and subgrade refer to the road segment not including the works on bridge, tunnel, and interchange. Subgrade works include clearing topsoil, earth works, subgrade compaction and the subgrade construction for slope protection. Pavement construction works refer to basement and surface layer paving and rolling. Bridge construction comprises construction activities of four parts including foundation, substructure, superstructure, and sidewalk. Tunnel constructions include activities of tunnel excavation, transportation, concrete ejection and bolting support and lining. The context of traffic safety facilities construction activities is associated with guard rails, fence, road marking and sign board, delineator, hectometer stake, and bus stop. Temporary works are associated with service haul road, and temporary residence houses for the workers.

In this paper, the scope of CO_2 emissions life cycle assessment on entire road project not only focuses on each subproject, but also considers stages and related elements in each subproject during road