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Greenhouse gas emissions from road construction in China: A province-level analysis

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A B S T R A C T

Road construction is a major contributor of greenhouse gas emissions in the transport sector. In this study, by using the life cycle assessment method, the greenhouse gas emissions from road construction in China are calculated on both the national and provincial levels. The results show that the equivalent cumulative carbon emissions from road construction in China were 1104 Mt CO_2e by 2013. Cement production accounts for the major emission, responsible for 87% of all emissions. The per-kilometer greenhouse gas emissions of cement-paved roads were over 60% higher than asphalt-paved roads. On the provincial level, the per square kilometer greenhouse gas emissions ranged from 10.6 t CO_2e/km^2 in Tibet to 823.0 t CO_2e/km^2 in Shanghai. The emissions level in coastal provinces was significantly higher than those in central and western provinces. This implies a huge growth potential of greenhouse gas emissions in the underdeveloped regions. Based on the analyses, it is suggested that greenhouse gas emissions associated with road construction should be paid more attention. A holistic approach should be employed to realize environmental-friendly road construction. Especially, the planning of road network expansion and the choice of road pavement materials should be determined with a strong consideration on their greenhouse gas emissions impacts.

1. Introduction

Road infrastructure emits large quantities of greenhouse gas (GHG) over their entire life cycle, including the production of raw materials, construction, operation, maintenance, and rehabilitation of the roads (Fernández-Sánchez et al., 2015; Santero and Horvath, 2009). Over the past decades, global economic development and population growth have driven substantial expansion of the road network, especially in the developing countries (Fan and Chan-Kang, 2005). Globally, more than 25 million kilometers of new roads are expected to be built by 2050, implying a 60% increase over the 2010 level (Laurance et al., 2014). Around 90% of all new roads are expected to be constructed in developing countries. According to the World Bank study, the transport sector accounts for nearly 14% of global GHG emissions and in which approximately 72% is caused by road construction, rehabilitation, maintenance, and usage (The World Bank, 2011). The large-scale road construction brings massive of GHG emissions. In the U.S., construction, maintenance, and rehabilitation of highways are responsible for around 28% of GHG emissions from the transportation sector (Melanta et al., 2013) and 13.22% from the construction sector (Mukherjee and Cass, 2012). In the European countries, road construction is one of the main drivers of resource use (Huang et al., 2007) and contributes highly to global warming (Barandica et al., 2013). As the report showed, Asia is responsible for approximately 37% of total GHG emissions, with China accountable for nearly 19% of the world's total or over 50% of Asia's contribution (The World Bank, 2011). The extensive road networks in developing countries such as China caused a continuous increase of GHG emissions (Schweikert et al., 2014).

During the past several decades, China is very representative in terms of the rapid growth of road network and the massive GHG emissions from road construction. Fig. 1 shows the rapid growth of China's road network from 1988 to 2013 (National Bureau of Statistics, 1988–2013). In the early years, China did not put high

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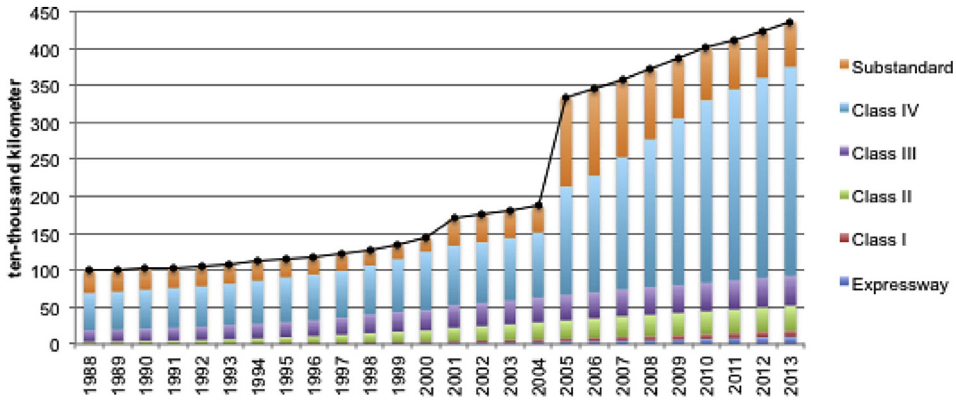


Fig. 1. Historical road length in China (Fan and Chan-Kang, 2005; National Bureau of Statistics, 1988–2013). Note: The 2004–2005 surge in road length is caused by the change of the statistical scope.

priority on the construction of transportation infrastructure (Li and Li, 2013). The road intensity, measured by the length of road per square kilometer, was only 97 km/km^2 in 1980, compared with the level of 230 km/km^2 in India (Fan and Chan-Kang, 2005). After the reform and open policy began, the demand for road transport soared and consequently transportation shortages and congestion problems surfaced with rapid economic growth. Besides, China has long pursued a biased development policy with the largest portion of public investment being concentrated in the coastal regions and in urban areas (Fan and Chan-Kang, 2005). It is not surprised therefore that the difference in economic growth rates and the regional inequality in China. Since 1985, the government started to gear up its investment in road network expansion, especially the construction of high quality roads such as highways connecting industrial centers in coastal regions (Xu et al., 2015). In the 1990s, the development of infrastructure became a national priority. Varieties of policies were implemented to promote the highway construction and maintenance (Démurger, 2001). The length of expressways increased from 147 km in 1988–104438 km in 2013, implying a 700-fold increase in 25 years (Xu et al., 2015). The improvement of the road quality and density in recent decades propelled the economic growth in China. With the robust increase of road network, the GHG emissions and environmental impacts soared at the same time. Calculating the GHG emissions from road construction in China has become a more pressing issue.

Life-cycle assessment (LCA) is a commonly-used method for systematically evaluating the environmental impacts of products, processes or service systems through their life cycle (Nisbet et al., 2002). The LCA method is widely used to calculate GHG emissions associated with transportation infrastructure (Cass and Mukherjee, 2011).

A large number of studies have been conducted to investigate the carbon footprint of road network and the measures have been taken to reduce the GHG emissions. In the early years, the studies were mostly conducted in developed countries. Stripple from Sweden estimated the NO_x, SO_2 and CO_2 emissions of road construction, road maintenance and road operation by using LCA method for the first time (Stripple, 2001). This work calculated the emissions throughout the whole life cycle, including raw materials extraction and production, transportation, construction, operation, maintenance, rehabilitation and end of life treatment. And their research showed that the dominating activity for the GHG emissions is the construction of the road. The maintenance of the road is the second largest source of the emissions. The operation of the road accounts only a small part of the total emissions. Horvath et al. compared the environmental impacts of asphalt and steel-reinforced concrete pavements in the U.S. (Horvath and Hendrickson, 1998). The results showed that asphalt-paved roads were recycled in large quantities compared with steel-reinforced concrete roads. It helps to save resource and avoid pollution. Based on the research, asphalt pavement was considered to be a better choice from a sustainable development perspective. White et al. analyzed the impacts of raw material production and road construction of different pavement types by considering the local resources, climate conditions, traffic volumes, and energy needs in the U.S. (White et al., 2010). Their study revealed that more efforts should be made to lower GHG emissions in pavement production and construction. Based on numerous studies on road pavement, the University of California Pavement Research Center (UCPRC) and the University of California Institute of Transportation Studies (UCITS) recommended common practices for conducting environmental LCA for pavement. Their efforts answered the key questions regarding LCA practice and its application (Harvey et al., 2010). Loijos et al. demonstrated that the main contributor of GHG emissions within the road life cycle is cement production (Loijos et al., 2013).

Santos et al. from Portugal applied the LCA model to explore the impacts of in-place recycling practices on pavement construction and rehabilitation (Santos et al., 2014). Compared with traditional reconstruction activity, in-place recycling-based activity was proved to reduce 75% of GHG emissions. Huang et al. in the UK developed a LCA model for asphalt-paved road construction and maintenance that accommodated a recycling practice (Huang et al., 2009). Their study suggested that more efforts should be put on the asphalt surface recycling projects rather than aggregates. The Athena Institute in Canada presented a comparison of energy consumption and environment burdens from the construction and maintenance of flexible hot-mixed asphalt-paved roads and rigid cement-paved roads (Athena sustaninable materials institute, 2006). The cement pavement showed a significant energy advantage over asphalt pavement, but an increase in global warming potential. Based on sensitivity analyses, material production and construction activities have the most significant environmental impacts on road life cycle (AzariJafari et al., 2016; Nisbet et al., 2002). In Denmark, Birgisdottir developed a LCA model, ROAD-RES, to estimate the environmental impacts from road construction and recycling of residues (Birgisdottir et al., 2007; Birgisdóttir et al., 2006). The assessment suggested that the combustion of fossil fuels is the major contributor of emissions. Barandica et al. evaluated the GHG emissions of Spanish road projects from a life cycle perspective (Barandica et al., 2013). The calculation indicated that 60%–85% of emissions in the construction stage were from the earthworks. Kim et al. estimated the GHG emissions from material production for road construction in Korea (Kim et al., 2012).

Meanwhile, several platforms and software tools have been developed to estimate GHG emissions of road construction, such as CHANGER developed by International Road Federation (IRF) (Huang et al., 2013), PaLATE developed by the University of California, Berkeley (Cross et al., 2011) and asPECT developed by UK Transport Research Laboratory (Huang et al., 2012). Other tools like Green Star and DGNB are available in Australia and Germany (Miliutenko, 2012). These existing tools are used to evaluate GHG emissions throughout the whole life cycle of road construction.

Initial works have also been done in China's context. Pan et al. investigated energy consumption and CO_2 emissions of highway network by using life cycle method and established a China-specific calculation model (Pan, 2011). Wang et al. showed that the majority of CO_2 emissions in highway construction were generated from raw material production (Wang et al., 2015). The impacts from material transportation and onsite construction were less important. Ma et al. (2016a) and Peng et al. (2015) estimated the GHG emissions from asphalt-paved highways by using a process-based LCA method. Their results suggested that the focus should be put on the raw material production and asphalt mixing phases to reduce GHG emissions. Based on the life cycle inventory method, Ma et al. divided cement-paved highway construction into three phases, raw material production, concrete manufacture, and pavement onsite construction (Ma et al., 2016b). According to their study, the main GHG emissions are generated from the raw material production phase, accounting for 92.7% of total emissions.

Existing studies have laid a solid foundation for analyzing the GHG emissions of several road projects in China. However, the cumulative GHG emissions of the road network in China is still unclear. Besides, regional disparities are difficult to be captured under the existing framework. There is a need to establish a method to investigate the GHG emissions from road construction at the national and provincial levels. With the aim of filling such a gap, this study establishes a LCA framework to investigate the GHG emissions from road construction in China both on the national and provincial levels. Methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases are normalized into units of CO_2e. This study contributes to (1) theoretically establishing a process-based LCA framework to estimate the GHG emissions of different materials during road construction; (2) empirically quantifying the GHG emissions of paved road construction in China, based on which policy recommendations with region-specific implications can be developed; (3) arousing the attention of government and industries on green construction of the road.

2. Methods and data

2.1. Road classification

There are two common standards of road classification in China, i.e., quality-based classification and pavement-based classification (National Bureau of Statistics, 1988–2013). Table 1 shows the quality-based classification standard. Under such a standard, roads are classified into Expressways, Class I Highways, Class II Highways, Class III Roads, Class IV Roads and Substandard Roads. Fig. 2 (a) shows the breakdown of total road length by road classes. It can be found that high quality roads/Asphalt-paved roads (Expressways, Class I and Class II Highways) accounted for 12% of the total length, while low quality roads/cement-paved road (Class III Roads, Class IV Roads and Substandard Roads) accounted for almost 88% of the total length. In particular, Class IV Roads and Substandard Roads accounted for more than 79% of the total road length.

The other road classification standard is based on pavement, including paved roads, roughly paved roads and unpaved roads. There are two main kinds of paved roads, asphalt-paved roads and cement-paved roads. Fig. 2 (b) shows that paved roads represent the major part of China's highway length. Pavement construction process causes a large amount of GHG emissions. The structure layers of paved roads are asphalt or cement concrete pavement, cement-stabilized gravel base and graded gravel subgrade. Accumulated length of paved roads in China was nearly 2.5 million kilometers until 2013 (National Bureau of Statistics, 1988–2013). The length of asphalt-paved roads was 688092 km, accounting for 16% of total road length. The length of cement-paved roads accounted for 41% of total road length. In China, asphalt pavement is predominantly used in Expressways, Class I Highways and Class II Highways. Class III Roads and half of Class IV Roads are paved with cement concrete (the other part of the Class IV road is mainly roughly paved road) based on the China Statistical Yearbook.

2.2. System boundary

The system boundary of this study is shown in Fig. 3. GHG emissions from road construction in China are calculated in this study through a LCA framework. This study is focus on paved roads in China mainland from Expressway to Class IV roads which caused the majority GHG emissions on road construction. The roads which are unpaved or roughly paved by sand or gravel was minor impact on environment, therefore the calculation of them is excluded. As suggested in the literature review, the GHG emissions from road construction are mainly from three phases: raw material production, pavement construction and cement-stabilized gravel construction. As graded gravel subgrade construction has small contribution to the GHG emissions, this phase is neglected in this study.

In this study, Expressways, Class I Highways and Class II Highways are all assumed to be asphalt-paved roads. Class III and half of Class IV roads are regarded as cement-paved roads. The main raw materials used in road construction are asphalt, cement, aggregates, and mineral powder. The aggregates are composed of crushed stone, sand and gravel. Various additives are added to asphalt mixture and cement concrete to improve the quality of the road pavement. The additive agents usually have high emission factors in their production phases. But the dosages of these agents are very small, for which they are not considered in this study. According to the construction process of hot mixture asphalt, the

Table 1
Quality-based road classification standard in China (Chen, 2011).

Name	Average Daily Traffic	Total lanes	Major pavement	Service life	Speed
Expressway	≥25000	4/6/8	Asphalt	20 years	120 km/h
Class I Highway	10000-25000	4	Asphalt	20 years	60/80/100 km/h
Class II Highway	2000–10000	2	Asphalt	15 years	60/80 km/h
Class III Road	200–2000	2	Concrete	10 years	
Class IV Road	<200	2	Concrete	10 years	
Substandard Road	Roads that are not up to standard				

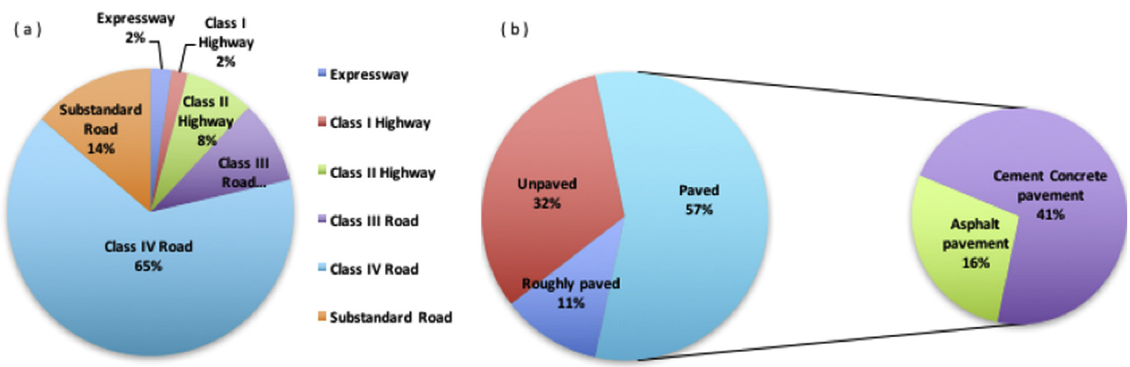


Fig. 2. Breakdown of total road length by road classes (a) Road classes (b) Type of pavement (Ministry of Transport, 2013).

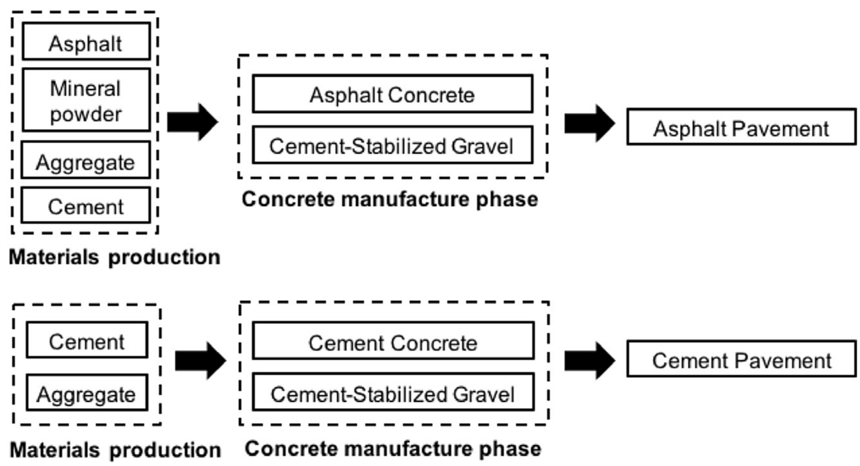


Fig. 3. System boundary for the calculation of GHG emissions from road construction.

main GHG emissions come from raw material production phase and asphalt mixture mixing and heating phase. For cement concrete construction and cement-stabilized gravel construction, the primary GHG emissions are from raw material production phase. The emissions from mixing plant are minor in these processes. The calculations also consider the lane width, scope ratio and cement emission factors in different types of the roads and different provinces. The transportation of raw materials is insignificant, which are neglected in this study.

GHG emissions are measured by using the unit of CO_2 equivalents (CO_2e) (Ma et al., 2016b). GHG emissions considered in this study include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These three gases account for 98.9% of the GHG emissions from road construction (Cross et al., 2011). The spatial boundary is China mainland. Taiwan, Hong Kong, Macau and other islands are not included due to data availability.

2.3. Model and calculations

GHG emissions from road construction in each province are obtained by multiplying the GHG emissions factor of each type of the road by its length. Cumulative GHG emissions are obtained by summing all provinces up, as Eq. (1) shows.

$$GE = \sum_i \sum_j (EF_j \cdot RL_{i,j}) \tag{1}$$

where,

GE is the cumulative GHG emissions from road construction (t CO_2e);
EF_j is the GHG emissions factor of Class j road (t CO_2e/km);
RL_{ij} is the length of Class j road in province i (km);

Based on literature review, the emissions from cement production had the most significant influence on the environment. In this study, the GHG emissions factor of cement production phase is calculated by using Eq. (2). The calcination of limestone, combustion of fuels and electricity consumption are all considered.

$$EF_{Cement,i} = EF_{Calcination,i} + EF_{Fuel,i} + EF_{Electricity,i} \tag{2}$$

where,

$EFCement, j$ is the GHG emissions factor of cement production in province i (t CO_2e/kg);
$EFCalcination, i$, $EFFuel, i$ and $EFElectricity, i$ are the GHG emissions factors of the calcination process of limestone, combustion of fuels in the kiln and power generation in province i (t CO_2e/kg).

2.4. Data

2.4.1. Road length and structure

Fig. 4 shows the length of the roads at the provincial level (detailed data provided in Supplementary Table 1) (Ministry of

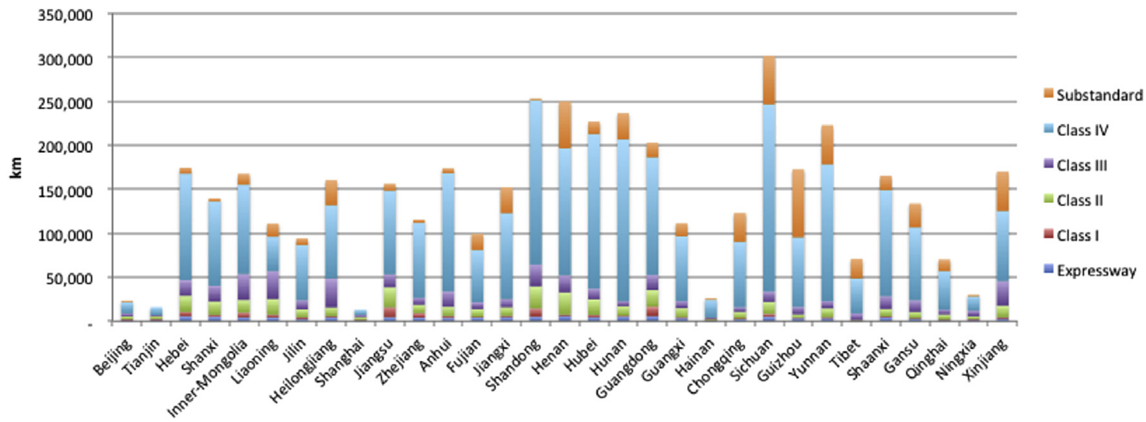


Fig. 4. Province-level road lengths in China (Ministry of Transport, 2013).

Transport, 2013). Table 2 summarizes the lane and path width of different classes of roads and the basic dimensional information of pavements in road design (Zhang and Liu, 2015). The road consists of three layers. The topmost layer is the asphalt or cement pavement surface. The purpose of this layer is to provide a smooth, abrasion resistant and strong surface. The cement-stabilized gravel base is the middle layer, which helps to distribute the stress. The subgrade is the complicated natural earth. The GHG emissions caused by hot mixture asphalt or cement concrete pavement, cement-stabilized gravel base are carefully analyzed in this study. The slope ratio is 1:1.5 as shown in Fig. 5 (Zhang and Liu, 2015).

2.4.2. GHG emissions factors of raw materials

The primary materials for road construction are asphalt, cement, aggregate and mineral powder. By referring to China-specific emissions factors, the GHG emissions factors of asphalt, aggregate and mineral powder are assumed to be 439.8 kg/t (Zhang and Liu, 2015), 3.12 kg/t (Wang and Wei, 2015), and 133.4 kg/t (Wang and Wei, 2015; Zhang and Liu, 2015). The GHG emissions factor of cement production is calculated based on actual situation in China. Regional disparity exists in GHG emissions from cement production in China, which was considered in this study. The GHG emissions from cement production come directly from limestone calcination and combustion of fuels and indirectly from consumption of electricity (Liu et al., 2014; Worrell et al., 2001).

Regarding the calcination of limestone, the main component of limestone is $CaCO_3$. The chemical reaction of $CaCO_3$ decomposition is $CaCO_3 \xrightarrow{Heat} CaO + CO_2\uparrow$. The characteristics of limestone are diversified in different provinces, which causes region-specific GHG emissions factors. The ratio of clinker to cement is also a critical factor determining the environmental impacts. Based on practical situations in China and numerous literature, the clinker/cement (C/C) ratio used in this study is 83% (Hendriks et al., 2003).

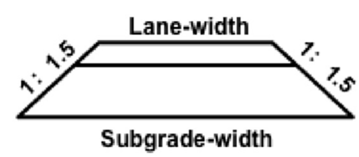


Fig. 5. The cross section of the road (Zhang and Liu, 2015).

Fuel is burnt in the kiln. The types of fuels, such as coal, oil, nature gas, and alternative fuels in different provinces influence the GHG emissions factors from fuel combustion (Details are showed in Supplementary Table 3).

The intensity of GHG emissions from electricity consumption is regionally different depending on power grids, which is determined in this study by referring to official reports (Zhao et al., 2016). The average use of electricity in cement production is 90 kWh/t based on China's actual cement production techniques.

The spatial disparities of GHG emissions factors of cement production are shown in Supplementary Fig. 3 (Zhao et al., 2016). Although province-level GHG emissions factors are difference by area, the effect of the different on calculation process is relatively small. So, in this paper, a production-weighted average GHG emissions factor is employed, which is 755.8 kg CO_2e/t.

2.4.3. GHG emissions factors of the road construction materials

The components of asphalt-paved roads are hot mixture asphalt pavement, cement-stabilized gravel base and graded gravel subgrade. Cement-paved roads include cement concrete pavement, cement-stabilized gravel base and graded gravel subgrade. As mentioned above, the environmental impacts of graded gravel production and construction are quite small, which are ignored in

Table 2
Structure of China's class roads (Ministry of Transport, 2013).

		Expressway			Class I	Class II	Class III	Class IV
Total Lanes		4	6	8	4	2	2	2
Lane width (m)		3.75	3.75	3.75	3.75	3.75	3.50	3.00
Path width (m)		15.00	22.50	30.00	15.00	7.50	7.00	6.00
Asphalt Pavement	Pavement (m)	0.18			0.15	0.09	0.06	0.04
Thickness	Base (m)	0.40			0.40	0.20	0.20	0.20
	Subgrade (m)	0.20			0.20	0.20	0.20	0.15
Cement Pavement	Pavement (m)	0.26			0.24	0.22	0.20	0.16
Thickness	Base (m)	0.30			0.30	0.20	0.20	0.15
	Subgrade (m)	0.20			0.20	0.20	0.20	0.15

this study. Based on the geometry of the road structure and material density, Table 3 shows the composition of the concrete. The usages of the materials are collected based on the Chinese standards: *Budgetary norm of highway project*.

Hot mixture asphalt pavement: an upper pavement layer consists of roughly 4.8% asphalt, 87.6% aggregate (sand and gravel), and 7.6% mineral powder relying on Table 3. The density of asphalt mixture is 2.40 t/m^3. The GHG emissions from hot mixture asphalt construction include asphalt, aggregate and mineral powder acquisition, and mixture heating and mixing. The GHG emissions factor of asphalt and aggregate mixing and heating phase is 29.11 kg CO_2e/t in China (Zhang and Liu, 2015). The GHG emissions factor of hot mixture asphalt pavement construction is 151.1 kg CO_2e/m^3 in total.

Cement concrete pavement: an upper pavement layer consists of roughly 17.4% cement and 82.6% aggregate (mainly sand and gravel) relying on Table 3. The density of cement concrete is 2.30 t/m^3. The main GHG emissions factor of cement concrete construction is from raw material production phase. According to that, the GHG emissions factor of cement concrete pavement construction is 308.3 kg CO_2e/m^3.

Cement-stabilized gravel base: a middle layer consists of roughly 5.5% cement and 94.5% aggregate relying on Table 3. The density of cement-stabilized gravel is 2.20 t/m^3. The GHG emissions factor of cement-stabilized gravel is 97.2 kg CO_2e/m^3.

It should be seriously noted that the emission factors used in this study are the up-to-date emissions factors, which do not reflect the historical techniques. Thus, multiplying the historical road length with current emissions factors does not deliver the actual historical GHG emissions, but delivers the GHG emissions under the assumption that all roads are constructed using the current techniques. For this reason, all GHG emissions referred in this study are actually not the real GHG emissions, but the ‘equivalent’ GHG emissions. Based on the information we already have, the calculation based on 2013 is still convincing. For conciseness, the ‘equivalent’ is only mentioned here. The results must be comprehended with this basic idea in mind.

3. Results and discussion

Fig. 6 presents the GHG emissions intensity of asphalt-paved roads and cement-paved roads. It can be found that GHG emissions intensities of cement-paved roads were generally much higher than asphalt-paved roads. For example, for common four-lane expressways, the GHG emissions intensity of asphalt-paved roads was 1043 t CO_2e/km, while cement-paved roads was 1707 t CO_2e/km. The GHG emissions of cement-paved roads were 64% higher than asphalt-paved roads. When comparing GHG emissions intensities of different classes of roads, the GHG emissions intensity of high quality roads was significantly higher than roads of lower qualities. It shows that the structure and type of the road, and the material input affect the GHG emissions significantly.

Fig. 7 depicts the GHG emissions from road construction in China both on the national and provincial levels. The cumulative GHG emissions of China's road construction was 1104 Mt CO_2e until 2013. Accordingly, the life cycle GHG emissions for all new road construction in China were approximately 44 Mt in 2013. The potential GHG emissions in road infrastructure is enormous with the development of the society in the future. The length of the road affect the GHG emissions in general. Although the GHG emissions intensities of Class III and Class IV roads were quite low, their cumulative GHG emissions accounted for 74% of all emissions due to their dominating position in road length. The percentages of GHG emissions from low quality roads in central and western provinces were a bit larger than coastal provinces.

The regional disparity of GHG emissions from road construction can also be easily observed through Fig. 8. The size of the pie represents the relative GHG emissions from road construction in each province. The per square kilometer GHG emissions from road construction ranged from 10.6 t CO_2e in Tibet to 823.0 t CO_2e in Shanghai. The color grade shows the intensity of the GHG emissions in different provinces. The top five provinces were Shanghai, Tianjin, Jiangsu, Shandong and Beijing. The results suggest that the coastal provinces had higher per square kilometer GHG emissions compared with the central and western provinces. A broader regional classification of provinces reflects that, on average, coastal provinces grew faster than central and provinces (Démurger, 2001). It is clear that the GHG emissions from road construction are closely related to economic growth and population density (Supplementary Figs. 1 and 2). As the road developed very rapidly during the last 30 years, the unequal development of the road illustrates the different reform and open policy between the coastal and noncoastal provinces. Besides, the coastal provinces, endowed with favorable geographical and natural conditions, have historically developed faster than central and western provinces.

Fig. 8 shows the breakdowns of weight and GHG emissions by

Table 3
The component of concrete (unit: t/m^3) (*Budgetary* norm *of highway project*).

Asphalt mixture			Cement concrete		Cement-stabilized gravel	
Asphalt	Aggregate	Mineral powder	Cement	Aggregate	Cement	Aggregate
0.114	2.103	0.183	0.400	1.900	0.120	2.080

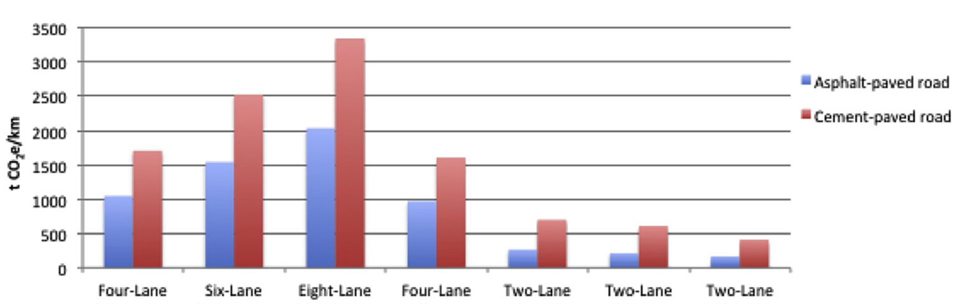


Fig. 6. GHG emissions intensities of different classes of roads.

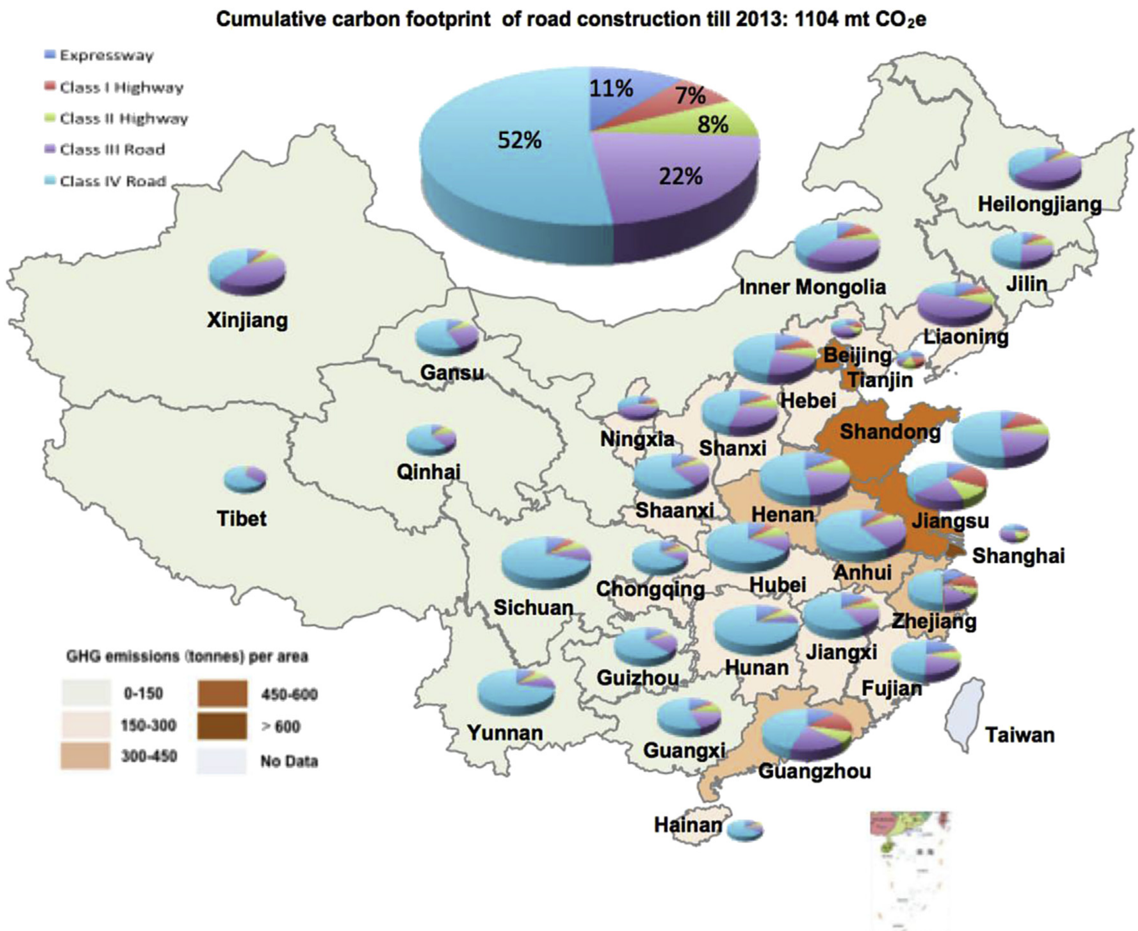


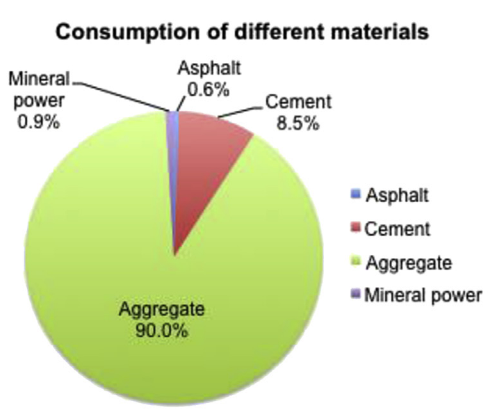
Fig. 7. The GHG emissions from road construction on the national and provincial levels.

different materials. Despite the fact that cement accounted for only 8.5% of total material weight, cement production was responsible for 90.8% of GHG emissions in the raw material production phase. The GHG emissions was mainly caused by the production technology of cement, power generation technology and supply chain of cement. In contrast, although aggregate accounted for 90.0% of total weight, its production was only responsible for 4.0% of total GHG emissions. Based on the processes of cement production, improving the quality of limestone, using alternative low-carbon fuel, eliminating outdated production process and promoting dry rotary kiln cement production technology should be implemented to reduce the GHG emissions (Chen et al., 2015).

In this study, we do not take the part of maintenance and rehabilitation into consideration. Road maintenance and rehabilitation is better than new road construction in environmental impact. Besides, the GHG emissions from bridge and tunnel will be considered as well.

4. Policy implications

As the world's largest GHG emitter, China plays an important role in global climate change mitigation. As demonstrated by this



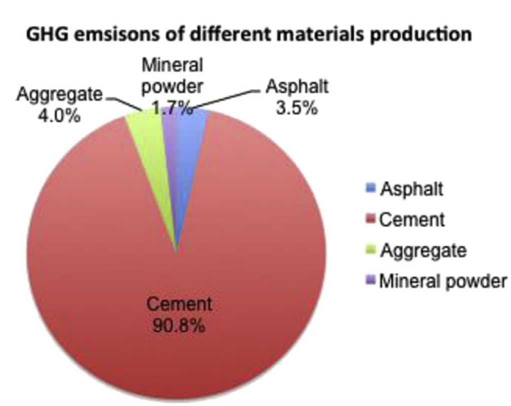


Fig. 8. Breakdowns of weight and GHG emissions by different materials.

study, road construction is a very important GHG emissions contributor. More attentions should be paid on road construction to balance the social benefits and the environmental impacts. The government and industries should implement comprehensive measures to abate GHG emissions from road construction both in the short-term and long-term.

First, it is clear that the construction of asphalt-paved roads emits less GHG emissions than cement-paved roads. Asphalt pavement appears to be a better choice in terms of the GHG emissions from road construction. The raw materials production, the mixing and heating phase are the major sources of GHG emissions. For hot mixture asphalt, the improvement of the mixing and heating plant efficiency and the use of warm/cold asphalt mixture could be helpful to reduce the GHG emissions (Rubio et al., 2013). Numerous studies are focused on developing innovative technologies for road construction. The use of reclaimed asphalt pavement and recycling methods can reduce the GHG emissions from the production of virgin materials (Anthonissen et al., 2015), which should be taken into consideration in future road maintenance.

Second, according to the inventory analysis, the focus of carbon reduction should be strongly put on cement production. Calcination in kilns is responsible for nearly 60% of all emissions from cement production. The reduction of clinker to cement ratio can be realized by using blended cement with supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GBFS) (Taylor et al., 2011). Another effective strategy is to improve the efficiency of machines (Hendriks et al., 2003), and replace high-carbon fuels by low-carbon fuels. Recycling in cement production process is also very important to reduce the environmental impacts.

Third, significant regional disparity of GHG emissions from road construction exists. The unbalanced regional road network and economic development in China lead to discrepancy of GHG emissions in different regions. For the coastal provinces, the demand for new roads is relatively weaker. The main efforts are currently put on the maintenance, rehabilitation and improvement of the roads. The government should implement more sustainable methods for road rebuilding. Recent years, China's government raised the initiative of jointly building the Silk Road Economic Belt and the 21st-Century Maritime Silk Road (hereinafter referred to as the Belt and Road). Facilities connectivity is a priority area for implementing the Initiative. Countries along the Belt and Road should improve the connectivity of their infrastructure construction, especially the transport infrastructure construction, and advance the road network connectivity. For central and western provinces, the potential for new road construction is huge. The government should make efforts to reduce GHG emissions from road construction, such as using asphalt pavement and improving the efficiency of raw materials production, and promote green and low-carbon infrastructure construction.

5. Conclusions

With the boom of road construction in China over recent years, the associated GHG emissions have soared as the same time. The key contribution of this study is to establish a process-based LCA framework to quantify the GHG emissions from road construction in China. The emissions factors of two main paved roads, asphalt-paved roads and cement-paved roads, are respectively estimated in this study. The results indicate that cumulative GHG emissions of China's road construction were around 1104 Mt CO_2e until 2013. With the rapid development of China and the implement of the belt and road policy, the GHG emissions associated with road construction should be paid high attention. The results indicate that the length and type of the road, the material input, and the technology are the major reason of the high GHG emissions. Cement production is responsible for 87% of total emissions, highlighting the importance of taking measures to reduce the GHG emissions from raw materials manufacturing phase. The asphalt-paved road emits 39%–63% less GHG emissions than cement-paved road. It is good to use warm/cold asphalt mixture, recycling or reuse materials and efficient equipment for green and sustainable environment. On the provincial level, the coastal provinces have higher per square kilometer GHG emissions than central and western provinces. In general, the findings of this study assist the policy makers to develop region-specific strategies to reduce GHG emissions from road construction.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.08.243.

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