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Article

Estimating Greenhouse Gas Emissions from Road Construction by Considering the Regional Differences in Carbon Emission Factors of Cement: The Case of China

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Abstract: Rapid road construction and expansion in China resulted in massive GHG emissions. The carbon emission factors of raw materials, particularly cement, have a significant influence on the calculation of GHG emissions from road construction. This study estimates GHG emissions from road construction by taking into account regional differences in cement carbon emission factors. The results indicate that (1) total GHG emissions from road construction have a "U" shape from 2009 to 2019, with the highest level being 437 million t CO_2e 2009 and the lowest level being 184 million t CO_2e in 2017; (2) Class-IV roads account for roughly 80% of total GHG emissions from road construction; and (3) GHG emissions from road construction are shifting from east to west regions. This is the first paper to calculate GHG emissions from road construction by taking into account both road type and cement carbon emission factors. The findings of this study could provide references for transportation agencies to better understand the impacts of road construction to climate change and improve policymaking, especially for the development of road construction technologies and raw material production technologies.

Keywords: GHG emission; road construction; carbon emission factor; regional differences; China

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1. Introduction

Greenhouse gas (GHG) emissions have long been a source of concern around the world due to their contribution to climate change, which endangers the natural and human environment and ecosystems [1]. Many countries have devised strategies to reduce GHG emissions. China has announced that it will reach a peak in carbon emissions by 2030 and achieve carbon neutrality by 2060 [2]. Roads, as an important mode of transportation, emit considerable amounts of GHG throughout their entire life cycle [3]. Large amounts of roads have been built in recent years all over the world, particularly in developing countries, and over 25 million kilometers of new roads will be built by 2050 [4]. As the world's largest developing country, China faces a significant challenge of increasing GHG emissions due to its extensive road network [5].

During the life cycle of road projects, the construction phase accounts for the majority of GHG emissions [6]. Road construction has been shown to consume a lot of resources in Europe [7] and contribute significantly to GHG emissions in the United States [8]. Activities such as materials extraction and production, to-site transportation, and construction machinery generate emissions that account for 5% to 25% of the total emissions from road transport during the construction stage [9]. Between 2009 and 2019, the length of China's roads increased from 3.86 million kilometers to 5.01 million kilometers [10]. Given the continued high demand for passenger and good transportation, road construction, reconstruction, and expansion are likely to remain a major issue for some time [11]. In recent years, China has taken many energy saving and emission reduction measures in the road construction stage, such as warm mix asphalt technology, waste recycling technology, photovoltaic pavement technology, etc., but these technologies are not mature enough [12]. As a result, environmental impacts and GHG emissions from road construction will receive increased attention.

Numerous studies on GHG emissions from road construction have been conducted. Stripple [13] estimated GHG emissions from roads for the first time using LCA method and discovered that activities during the construction stage dominate total GHG emissions. Karlsson, Rootzén, and Johnsson [14] assessed the potential for reducing CO_2 emissions of road construction and alternative abatement measures to realize the potential. Loijos, Santero, and Ochsendorf [15] investigated GHG emissions from roads in the United States and discovered that cement production was the major sources of emissions. Many studies in China estimated GHG emissions from road construction in different regions. Li et al. [16] investigated the endogenous carbon dioxide emissions from tunnel construction machinery in China. Wang et al. [17] used a case study in China's southwest region to estimate carbon dioxide emissions from highway construction. Chen et al. [18] applied LCA to calculate the GHG emissions from road construction at the province-level. However, these studies failed to take into account the effects of raw material production in different regions on emissions. The source of raw materials has a significant impact on the calculation result of GHG emissions from road construction because raw material production and transportation vary with the level and location of production.

China, as the world's largest cement producer, contributes roughly 60% of the global total and emits a significant amount of GHG [19]. Furthermore, the cement industry is an important source of CO_2 emissions in China, accounting for 14.3% of total CO_2 emissions in this country [20]. Cement, unlike other materials, is typically produced in local cement factories and transported to sites. According to Zhao et al. [21], differences in the quality of limestone for cement and the type of coal used in the cement production line caused carbon emission coefficient differences between provinces and regions. As a result, the impact of spatial variability on cement production carbon emission factors is significant and cannot be overlooked.

The type of road also has an impact on the outcome of the calculation of GHG emissions from road construction. Different road types, such as highway [22], interstate road [23], interurban road [24], and rural road [25], are used to calculate carbon emissions. The road structure in China divides roads six hierarchies: expressways, Class-I roads, Class-II roads, Class-III roads and Class-IV roads. It was reported that expressways, Class-I roads, and Class-II roads are mostly paved with asphalt. Cement concrete pavements are used on Class-III roads and half of Class-IV roads [18]. Carbon emissions from different types of roads vary greatly due to differences in construction scale, construction environment, and construction technologies.

Existing studies have laid a solid foundation for calculating GHG emissions from road construction. However, the impact of regional differences in raw material production is still unclear. To fill such a gap, with the aim to make this work a support for improving calculation accuracy, this study took regions differences in carbon emission factors of cement when estimating GHG emissions from road construction. Moreover, road type was taken into account when analyzing the sources of GHG emissions from road construction. The following are the main questions that we hope to address through this study. (1) What are the regional differences in carbon emission factors for road construction? (2) How do the GHG emissions from road construction differ between different road types? (3) What are the regional differences in GHG emissions from road construction? Addressing these questions would help to put forward road construction technologies and raw material production technologies from the perspective of GHG emission mitigation. In order to address these issues, the research steps are as follows. First, the system boundary, GHG, and measurement methods were defined. Second, the raw material mass density was calculated by combining the road structure of each road type. Third, carbon emission factors were calculated by taking regional differences in the production of cement into account. Finally, GHG emissions from road construction in China was estimated. In this way, regional differences in GHG emissions from road construction and differences between road types were discussed and policies were suggested in the final section.

2. Methodology

2.1. System Boundary

This study calculates the GHG emissions from road construction. The components and steps included within the system boundary for this study are depicted in Figure 1. The system consumes materials and energy and emits GHG. GHG emissions from road construction are calculated using both asphalt and cement pavements. The calculation of asphalt pavements includes two major processes: raw material production and pavement construction. The construction process includes the phases of mixing, mixture transportation, laying down, compacting, and curing. The calculation for cement pavements includes three major processes: raw materials production, concrete manufacturing, and pavement construction. Due to data limitations, the pavement construction process includes Portland cement concrete (PCC), but excludes earthwork and the construction of road base and subbase [26].

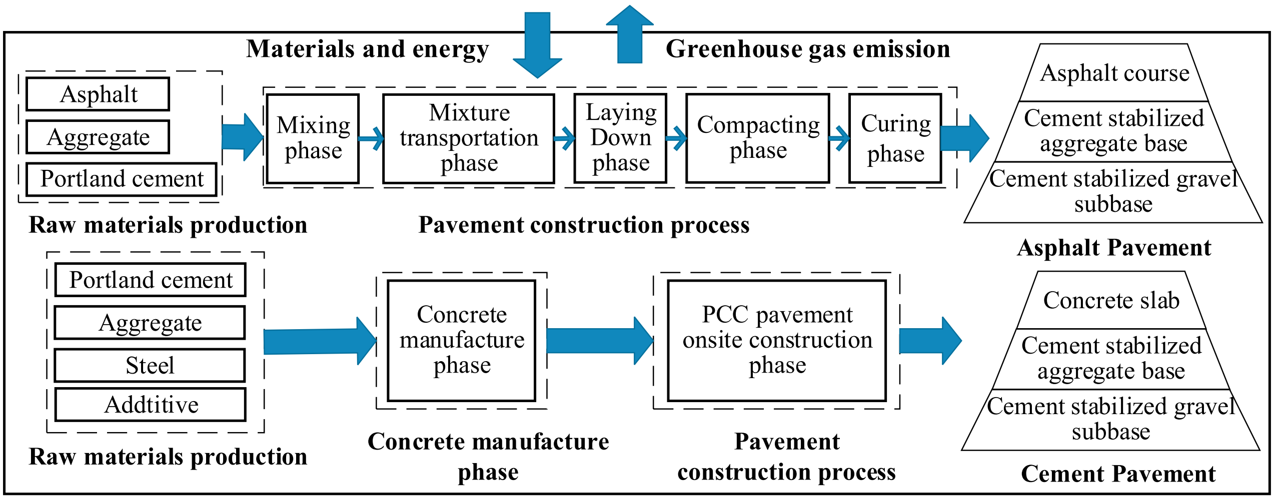

Figure 1. System boundary of this study.

2.2. Data

2.2.1. GHG and Measurement

The GHG in this study includes CO_2, CH_4, and N_2O, which account for 98.9% of carbon emissions from road construction [27]. Global warming potential (GWP) is a widely used characterization method for measuring the impacts of GHG emissions on climate change, and it is used in this work to normalize GHG emissions of these gases by carbon dioxide equivalents (CO_2e).

2.2.2. Mass Density of Raw Materials

As illustrated in Figure 2, a typical road has three layers. The surface of an asphalt pavement is made of hot mixture asphalt course, the base is made of cement stabilized aggregate, and the subbase is made of cement stabilized gravel. A cement pavement has a cement concrete surface, a cement stabilized aggregate base, and a cement stabilized gravel subbase. The slope of the road is 1:1.5 [28].The thickness of each layer are derived from the Ministry of Transport [29], which provides the Chinese road structure standard, as shown in Table 1.

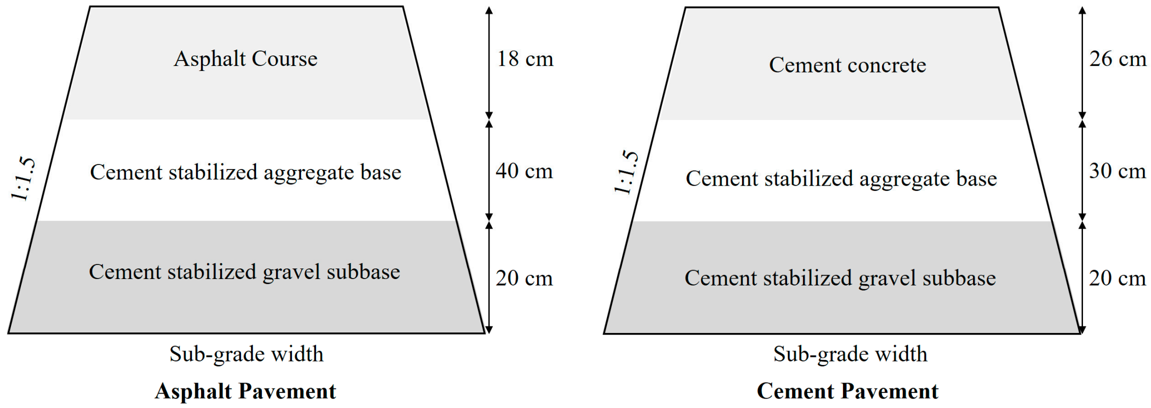

Figure 2. Typical structure of asphalt and cement pavement.

Table 1. Road structure in China.

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

Combining data from previous studies on road size and material components of each layer [18,21,30], mass density of each layer are obtained, as shown in Figure 3.

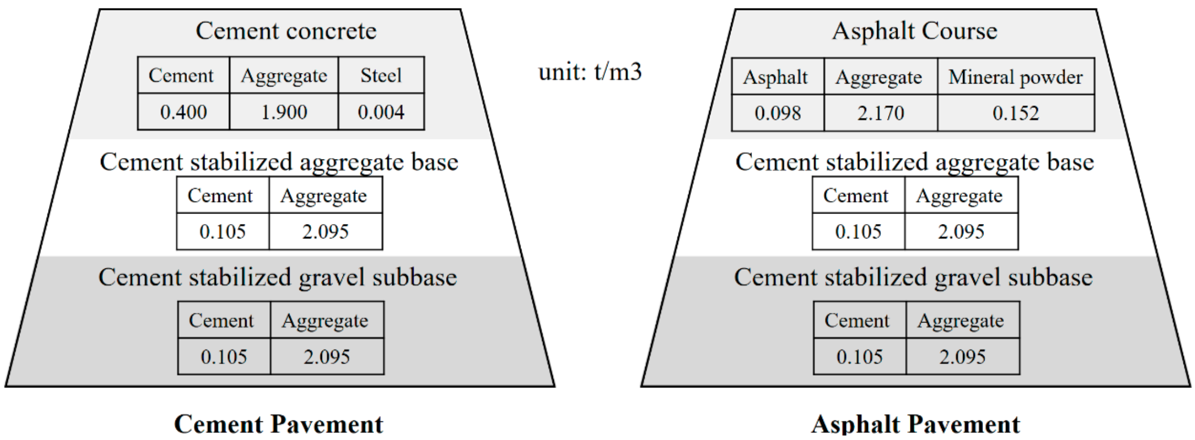

Figure 3. Mass density of raw materials of cement and asphalt pavement.

2.2.3. Carbon Emission Factors

As stated in the system boundary section, the GHG emissions from road construction are primarily caused by two phases: raw materials production and construction process. For both cement pavement and asphalt pavement, cement is an essential material. In this work, we cite carbon emission factors data from Zhao et al. [21], who sampled 198 new dry process cement production lines in China and measured the spatial variability of cement production carbon emission factors, as shown in Figure 3. On this basis, we used data from Shaanxi Province [26] as the baseline and calculated the carbon emission factors of cement production for each province and region according to the differences in Figure 4. The final carbon emission factors for each province and region are presented in Figure 5.

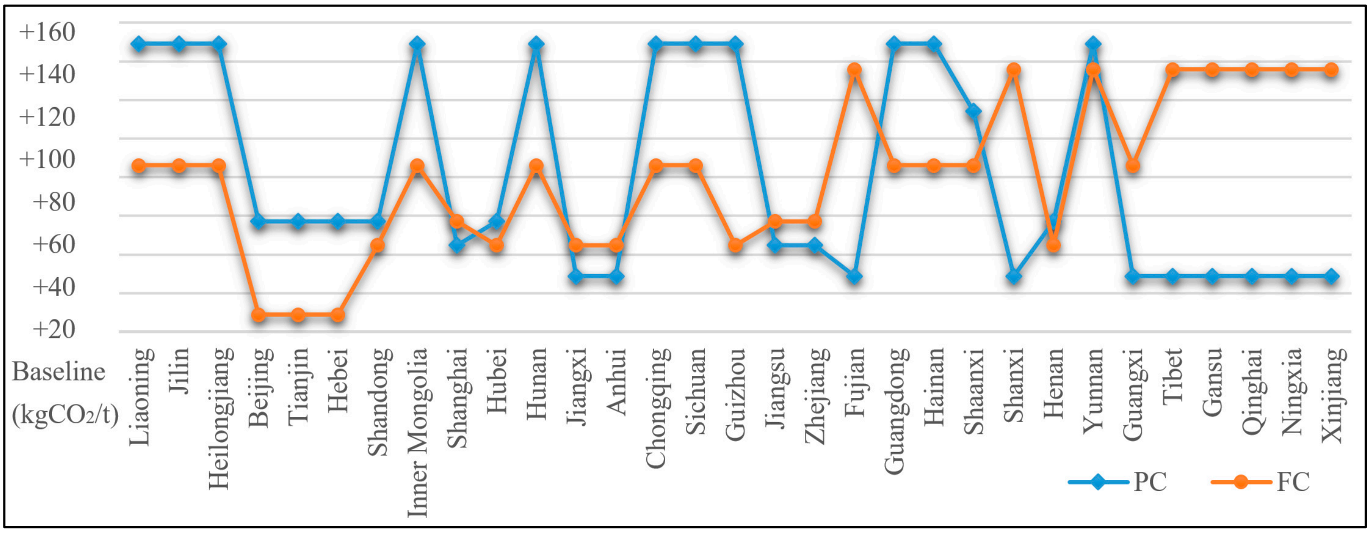

Figure 4. Difference of cement process carbon emission (PC) coefficient and fuel carbon emission coefficient (FC) between 31 provinces.

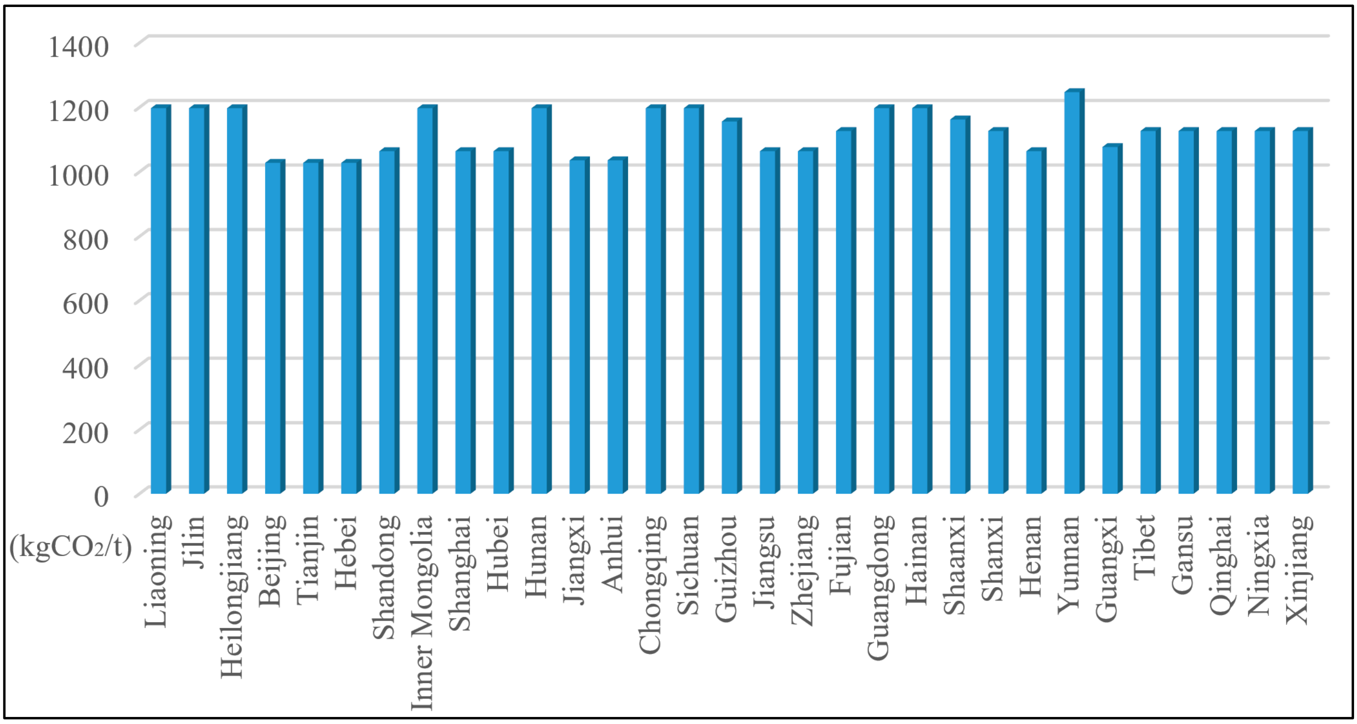

Figure 5. Carbon factors of cement production in 31 provinces.

Carbon emission factors for other raw materials are derived from previous studies [18,30], as shown in Table 2.

The carbon emission factors of each road structure in each province and region during construction phase are obtained by combining the information in Table 1, Figure 1, and Table 2, as shown in Table 3. The figures with dark blue backgrounds represent the lowest and highest levels of carbon emission factors of asphalt pavement. The figures with dark gray backgrounds represent the lowest and highest levels of carbon emission factors of cement pavement.

Table 2. Carbon emission factors of each pavement structure (units: kg/t).

Phase	Structure	Asphalt Pavement		Cement Pavement	
Raw materials production	Course	Asphalt binder Aggregate Mineral powder	439.8 5.84 133.4	Cement Aggregate Steel	- 5.36 15,299.39
	Base	Cement Aggregate	- 5.7	Cement Aggregate	- 5.36
	Subbase	Cement Aggregate	- 5.61	Cement Aggregate	- 5.36
Construction process	Course	Asphalt binder mixing, transportation, paving, and compacting	25.38	Laying down, compacting, curing	320.51 kg/(lane·km)
	Base	Cement mixing, transportation, laying down, compacting, and curing	2.76	Cement mixing, transportation	74.45 (kg/m^3)

Table 3. Carbon emission factors of each road structure during construction phase (Blue background for asphalt pavement and grey background for cement pavement; units: kg/t).

Provinces or Regions	Road Type	Expressway			Class-I (4-Lane)	Class-II (2-Lane)	Class-III (2-Lane)	Class-IV (2-Lane)
		4-Lane	6-Lane	8-Lane				
Beijing, Tianjin, Hebei	Asphalt Pavement	1646	2409	3173	1575	529	463	334
	Cement Pavement	22,516	47,753	82,364	20,845	5516	4489	2724
Jiangxi, Anhui	Asphalt Pavement	1651	2416	3182	1580	531	464	335
	Cement Pavement	22,535	47,781	82,402	20,863	5524	4496	2729
Shandong, Shanghai, Jiangsu, Zhejiang, Henan, Hubei	Asphalt Pavement	1670	2445	3220	1599	536	469	339
	Cement Pavement	22,605	47,884	82,538	20,929	5554	4522	2747
Fujian, Shanxi, Tibet, Gansu, Qinghai, Ningxia, Xinjiang	Asphalt Pavement	1713	2507	3302	1642	546	478	348
	Cement Pavement	22,759	48,112	82,839	21,075	5620	4580	2785
Guizhou	Asphalt Pavement	1733	2536	3340	1661	551	483	352
	Cement Pavement	22,832	48,219	82,981	21,144	5651	4608	2804
Shannxi	Asphalt Pavement	1737	2543	3349	1666	552	484	352
	Cement Pavement	22,848	48,242	83,011	21,159	5658	4614	2807
Liaoning, Jilin, Heilongjiang, Guangdong, Hainan, Chongqing, Sichuan, Inner Mongolia	Asphalt Pavement	1760	2577	3394	1689	558	490	357
	Cement Pavement	22,934	48,369	83,179	21,241	5695	4646	2829
Yunnan	Asphalt Pavement	1794	2627	3459	1723	567	497	364
	Cement Pavement	23,056	48,550	83,418	21,357	5747	4692	2860

Table 3. *Cont.*

Provinces or Regions	Road Type	Expressway			Class-I (4-Lane)	Class-II (2-Lane)	Class-III (2-Lane)	Class-IV (2-Lane)
		4-Lane	6-Lane	8-Lane				
Guangxi	Asphalt Pavement	1679	2458	3237	1608	538	471	341
	Cement Pavement	22,637	47,931	82,600	20,959	5568	4534	2755

2.3. Model

The GHG emissions from road construction are influenced by two factors: carbon emission factor and the length of the road. The GHG emissions from road construction for each type of road are calculated by multiplying the carbon emission factor of each road type by its length.

Equation (1) shows that the total GHG emissions from road construction of a region are obtained by summing GHG emissions of all types of road in this region up.

$$GE_j = \sum_i EF_{i,j} L_{i,j}. \quad (1)$$

where GE_j is the total GHG emissions from road construction of region j (tCO_2e), $EF_{i,j}$ is the carbon emission factor of type i road in region j (tCO_2e/km), and $L_{i,j}$ is the length of type i road in region j (km).

Equation (2) shows that the total GHG emissions from one type of road construction are obtained by summing GHG emissions of this type of road in all regions up.

$$GE_i = \sum_j EF_{i,j} L_{i,j}. \quad (2)$$

where GE_i is the total GHG emissions from road construction of type i road (tCO_2e), $EF_{i,j}$ is the carbon emission factor of type i road in region j (tCO_2e/km), and $L_{i,j}$ is the length of type i road in region j (km).

3. Results and Discussion

3.1. GHG Emissions from the Construction Phase of Different Types of Roads

Figure 6 depicts the GHG emissions from the construction phase of various types of roads and Table 4 gives detailed figures in Figure 6. Total GHG emissions shows a "U" shape from 2009 to 2019. The figure ranges from 180 to 440 million t CO_2e. Compared with other years, GHG emissions from road construction were the highest in 2009, at 437 million t CO_2e, and the lowest in 2017, at 184 million t CO_2e. It shows a remarkable decline from 2009 to 2011, a relatively stable period from 2011 to 2017, and a steady increase from 2017 to 2019. Compared with developed countries, the total amount is much higher [31]. As the largest emerging economy, China has invested heavily in transportation infrastructure, including roads. Huang et al. [31] pointed out that the construction of infrastructure and buildings in emerging economies cause about 60% of the total GHG emissions in the construction sector. GHG emissions from road construction in China are significant.

It is indicated that the GHG emissions from Class-IV road construction are estimated to be the largest source of total GHG emissions. According to the results, GHG emissions from Class-IV road construction account for roughly 80% of the total. However, the construction length of Class-IV roads only account for roughly 60% of the total [32]. GHG emissions from Class-IV road construction exceeded the total GHG emissions of other road types. Despite the rapid development of high-speed roads in China, Class-IV roads form a road network in nearly every corner of the country and play an important role in national unity, local management, resource development, and poverty alleviation. In recent years, the scale of Class-IV road has rapidly expanded to keep up with the rate of economic development [33,34], especially for the development of rural areas. However, the population in poor and rural areas remains large, and Class-IV roads will continue to be an important public facility for getting people out of the mountainous areas and to the nearest town for a long time in the future. It is clear that the key to reducing GHG emissions from road construction in China is to reduce GHG emissions from Class-IV road construction.

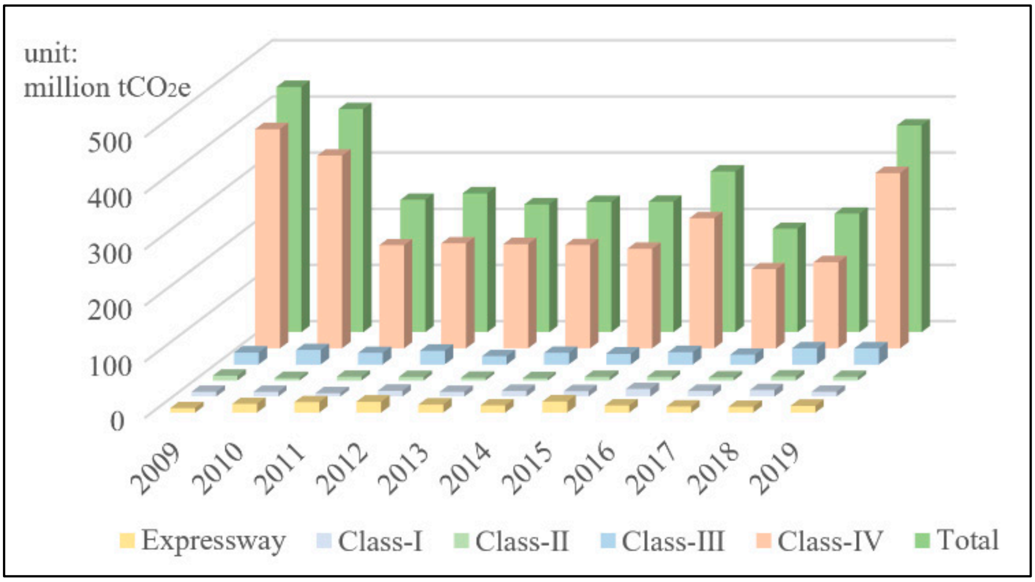

Figure 6. GHG emissions from the construction of road each type during 2009–2019.

Table 4. Detailed figures of GHG emissions from the construction of each road type during 2009–2019 (unit: million t CO_2e).

	Expressway	Class-I	Class-II	Class-III	Class-IV	Total
2009	7.81	8.29	11.27	40.09	371.79	439.25
2010	14.90	8.19	6.05	48.37	326.77	404.28
2011	17.92	6.05	9.13	38.55	174.97	246.62
2012	18.60	9.66	8.47	46.25	178.05	261.03
2013	13.65	8.19	6.53	27.91	176.66	232.94
2014	12.34	9.58	5.81	38.83	175.35	241.90
2015	19.09	9.23	8.82	35.85	168.78	241.78
2016	12.27	12.99	8.85	41.30	220.59	296.00
2017	10.50	9.50	7.13	32.65	134.08	193.87
2018	10.12	11.24	9.64	54.33	145.84	231.17
2019	11.51	8.54	8.69	53.96	297.28	379.97

3.2. Regional Differences in GHG Emissions from Road Construction

Figure 7 depicts the regional differences in GHG emissions from road construction in China. Western regions had higher GHG emissions from road construction than eastern regions between 2009 and 2019. This result contradicts Chen et al. [18]'s findings, which showed that eastern coastal regions had higher per square kilometer GHG emissions than western regions. The reason for this is that Chen et al. [18] used cumulative GHG emissions from road construction up to 2013. According to Chen et al. [18], the potential for new road construction in western regions is enormous, and the majority of road construction occurred in western regions during 2009–2019.

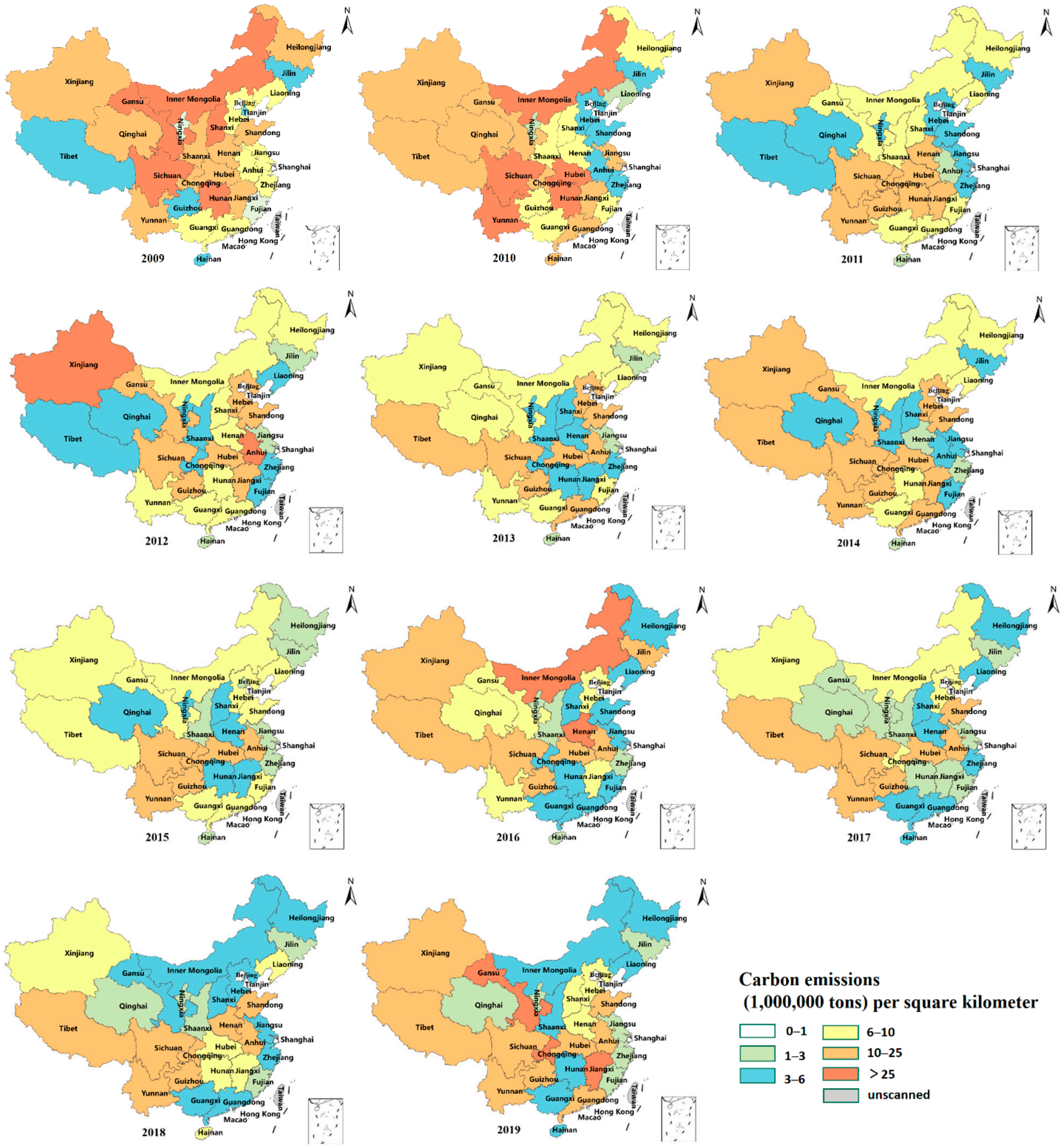

Figure 7. Regional differences in GHG emissions from road construction during 2009–2019.

It is also indicated in Figure 7 that GHG emissions from road construction are shifting from east to west regions. When the years 2009 and 2019 are compared, almost all of the eastern regions on the map have changed from yellow to green in 2019, while many provinces in the western region have turned orange, indicating a significant decrease of GHG emissions in eastern regions and increase in western regions. Transportation infrastructure is widely regarded as a valuable tool for a region's economic development [35]. Since the reform and opening up policy was implemented in 1978, the eastern regions have experienced rapid economic growth, and there is a polarization between eastern coastal and inland regions [36]. Later policy centered on western region development resulted in a large amount of transportation infrastructure construction in western regions. As a result, the center of GHG emissions from roads shifted from the east to the west.

However, some provinces, such as Sichuan, Hubei, Yunnan, Guizhou, and Anhui, maintained high levels of GHG emissions from road construction (with an average amount of about 10–25 million t CO_2e per square kilometer). GHG emissions from road construction in these five provinces accounted for 48% of national emissions in 2017. These provinces had poor transportation conditions in the past due to their topography, which all have large areas of mountainous regions. Road construction in a mountainous area is usually thought to emit more GHG emissions than in other regions. However, due to the limitation of data, the influence of topographic condition on GHG emissions from road construction was ignored. According to Liu et al. [37], building a road in the mountainous requires deep-cutting and high-filling subgrades, as well as additional slope protection work. Liu et al. [37] also stated that road construction projects in mountainous areas are time-consuming and material-intensive. Furthermore, topography influences the construction schedule, equipment, and material selection of a road construction project, all of which are closely related to the projects' GHG emissions [6,23]. As a result, GHG emissions from road construction in these mountainous areas was underestimated. In addition, as a result of the large amount of road construction in these areas, it is expected that GHG emissions from road construction will remain high.

4. Policy Implications

From a policy standpoint, China has implemented numerous policies to reduce GHG emissions from road traffic. However, given the vast amount of road construction in China, GHG emissions from the construction phase should not be overlooked. We make three policy recommendations based on the findings of this study.

The first is to develop localized policies to reduce GHG emissions from road construction. According to our findings, there are significant regional differences in GHG emissions from road construction. As a result, the national government should establish reasonable GHG emission reduction goals based on the reality of road construction in different regions. Meanwhile, provinces with higher levels of GHG emissions, such as Sichuan and Yunnan, may place a greater emphasis on GHG emissions from road construction than those with lower levels.

The second measure is to promote GHG-emission-reducing road construction technologies for Class-IV roads. According to the findings of this study, the construction of Class-IV roads emits the most GHG. Furthermore, as Liu et al. [37] pointed out, road construction in mountainous areas emits more GHG than other areas. More specific policies should be developed in this regard in order to improve technologies, such as developing technical solutions that require less cutting and filling, increasing the energy efficiency of construction equipment, and encouraging the economical use of materials under the premise of ensuring the construction plan.

The third measure is to establish policies regarding advanced layout of road construction support facilities and make improvements regarding raw material production. Our study demonstrates that there are regional differences in the carbon emission factors of road construction raw materials, resulting in regional differences in GHG emissions from road construction. As a result, on the one hand, the allocation of raw material production plants would better meet the proximity principle. Regions with higher carbon emission factors for raw materials, on the other hand, should consider increasing the level of emission reduction for raw material production. Mitigation measurements include material use and mass handling requirements optimization, increased recycling of steel, asphalt, and aggregates, and increased use of alternative binders in concrete [14].

5. Conclusions

China is now emitting a large amount of GHG emissions due to rapid road construction and expansion, and some researchers have paid attention to this issue. These studies, however, did not take into account the impacts of raw material production in different regions on emissions. The level and location of production influence raw material production and transportation. Differences in carbon emission coefficients between provinces and regions were caused by differences in the quality of limestone for cement and the type of coal used in the cement production line. This study estimates GHG emissions from road construction by taking into account regional differences in cement carbon emission factors. The study's main contribution is to provide a more considerate method to calculate GHG emissions from road construction in China.

Our analysis reveals that total GHG emissions from road construction decreased dramatically from 2009 to 2011, remained relatively stable from 2011 to 2017, and increased steadily from 2017 to 2019. It peaked at 437 million t CO_2e in 2009 and peaked at 184 million t CO_2e in 2017. Class-IV roads are the largest source of total GHG emissions from road construction, accounting for roughly 80% of the total. Because the majority of road construction occurred in western regions from 2009 to 2019, the western regions had higher GHG emissions from road construction than the eastern regions. Furthermore, GHG emissions from road construction are shifting from east to west regions as a result of policy preferences focusing on the development of western regions. Because construction technologies are more difficult in mountainous areas, road construction emits more GHG than in other areas. Three policy recommendations were raised based on the research findings, including developing localized GHG emission reduction policies for road construction, promoting the construction technologies of Class-IV roads, and advancing the layout of road construction support facilities. In this study, we estimated the GHG emissions from road construction. Although this makes an improvement compared with existing studies that ignored regional differences in carbon emission factors of cement, the calculation result is still not accurate enough. On one hand, future research should broaden the system boundary to include earthwork and the construction of road base and subbase during the pavement construction stage. On the other hand, more accurate estimations should take into account roads' topographic conditions.

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