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Measuring Carbon Emissions of Pavement Construction in China

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Abstract: While various methodologies for quantifying carbon emissions of pavement construction are developed worldwide, adopting and promoting the existing tools to China's market is found fairly challenging due to institutional constraints. Therefore, the objectives of this study are to propose a methodology for measuring carbon emissions of pavement construction compatible with the fixed pricing systems prevalent in China; and develop an automatic tool for carbon estimations. The total carbon emissions are measured by aggregating emissions of energy consumption and materials used along with four stages, namely material manufacture, transportation, construction, and disposal. A set of composite carbon emission factors for energy and materials was calculated based on existing emission factors with the consideration of the boundaries concerned. The quantity of energy and materials used in pavement construction are obtained through bills of quantity and the fixed price system. The database of the emission factors for energy and materials was embedded into a C# based tool, and validated in a real case.

Keywords: carbon emission calculation; pavement construction; China

1. Background

It is predicted that, by 2020, carbon emission of infrastructure projects in China will reach 0.197 billion tons [1]. Pavement construction is one of the significant contributors. According to the China Statistical Yearbook (2012), the numbers of municipal projects including pavement projects under construction and planned were 47097 and 30079, respectively in 2011 [2]; and these numbers are still increasing along with the rapid urbanization. To reduce carbon emissions, quantifying them is of significant importance. While various methodologies are available for quantifying carbon emission of pavement construction worldwide, adopting and promoting the existing tools to China's market is found to be fairly challenging due to the institutional constraints. Research widely recognized that carbon emission calculation varies across different countries due to difference associated with parameters, data source, construction methods and regional conditions [3,4]. This renders the comparison between different countries complex and difficult [4]. Another hindrance to carbon emission estimation for pavement construction is the scarcity of reliable data [5]. It is worth noting that, recently, Wang et al.'s (2015) and Ma et al.'s (2016) studies presented a list of carbon emission factors for pavement construction in China [6,7]. However, uptake of these factors would face challenges as practitioners have to collect a separate panel of data for the calculation methodology.

The objectives of this study are to develop a carbon emission calculation methodology with a customized database; and develop an automatic tool for carbon emission estimation. The customized database is compatible with the fixed pricing systems (Dinge) prevalent in China. Therefore, practitioners could calculate carbon emissions based on the bill of quantities which could be directly extracted from the project cost estimation software.

The structure of this paper is organized as follows. In Section 2, a literature review of tools for measuring carbon emissions of pavement construction is carried out, and their applicability to the China's context is discussed. Section 3 reports the proposed methodology and Section 4 focuses on developing specific parameters for the methodology application. Section 5 introduces a C# based tool which embeds the proposed methodology and derived parameters. The methodology and the automatic tool are, in the end, validated in a real case in Section 6. The last section provides the conclusions and recommendations.

2. Literature Review

LCA tools for measuring carbon emissions are formalized by the International Organization for Standardization (ISO) 14040 series, particularly the ISO 14040:2006−Principles and Framework [8] and ISO 14044:2006—Requirements and Guidelines [9]. These two together describe the basic concepts and methodologies for LCA studies. For measuring carbon emissions of pavement projects, various practical tools have been developed. For instance, in 1997–1999, Euro bitume conducted an LCI study on paving grade bitumen. A new version in 2011 included polymer-modified binder and bitumen emulsion [10]. The bitumen LCI as a cradle to gate study covers: extraction of crude oil; transport to Europe including pipeline and ship transport; manufacturing of bitumen; and hot storage of the product. It also takes into account the construction of production facilities [10].

In 2011, UK Transport Research Laboratory, in collaboration with the Highways Agency, Mineral Products Association and Refined Bitumen Association, built an asphalt Pavement Embodied Carbon Tool (asPECT) [11]. This UK-based tool is able to produce PAS (Publicly Available Specification) 2050-compliant cradle-to-grave carbon footprint reports for asphalt [12]. The boundary covers: the cradle to gate CO_{2e} (CO_2 equivalent) of each constituent material and ancillary material; the transport CO_{2e} from factory gate to plant; CO_{2e} arising from all forms of energy involved in producing the asphalt at the mixing plant, other than that involved in heating and drying, but including energy for offices on site; and CO_{2e} arising from the process of heating [11].

Huang et al. (2009) developed a spreadsheet-based LCA tool for construction and maintenance of asphalt pavements. The model consists of five worksheets. These are process parameters (e.g., energy in transportation), pavement parameters (e.g., pavement dimensions), unit inventory (i.e., energy production), project inventory (e.g., production process), and characterization results (e.g., global warming) [3].

International Road Federation designed a greenhouse gas calculator—Calculator for Harmonized Assessment and Normalization of Greenhouse-gas Emissions for Roads (CHANGER)—for road infrastructure projects. It is compatible with the International Panel on Climate Change (IPCC) guidelines and could be used to monitor and assess greenhouse gas emissions (GHG) generated during the different stages of the road construction process [13,14].

In 2007, Portland Cement Association published Environmental Life Cycle Inventory of Portland Cement Concrete, originally published in 2000 and updated in 2002 [15]. This report presents the results of the LCI of three concrete products, namely ready mixed concrete, concrete masonry, and precast concrete. The system boundary includes cement and slag cement manufacture, aggregate production, transportation of fuel, cement, supplementary cementitious materials, and aggregates to the concrete plant, and concrete plant operations [15].

Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) was developed by the Federal Highway Administration. INVEST considers the lifecycle of projects and has three modules to evaluate the lifecycle of transportation services, including system planning, project development, and operations and maintenance. Each of these modules is based on a separate collection of criteria and can be evaluated separately [16].

Roadprint is an Excel-based tool, which can facilitate knowledge that will: implement pavement LCA in a standardized and reproducible manner; conduct probabilistic analysis; and generate well-analyzed presentations of results to interpret LCA outputs [17].

The BE2ST-in-Highways system incorporates standardized measurement methods of LCA and life-cycle cost analysis (LCCA) [18]. The system is equipped with a tool to weight sustainability indexes using the analytical hierarchy process and is embedded in an Excel spreadsheet. The evaluation steps include creating alternative pavement designs, predicting the service life of each design, identifying rehabilitation strategies, and conducting LCA and LCCA. Four criteria were considered in LCA: energy consumption, GHG emissions, water consumption, and generation of hazardous wastes. These four are defined by the U.S. Resource Conservation and Recovery Act.

Although various tools have been developed worldwide, it is widely recognized that a LCA model from one country cannot be simply applied to another due to difference between construction materials, construction techniques, and the validity and applicability of the data [3]. Yu and Lu (2012) argued that it seems impossible to perform straightforward comparison of the results due to the differences in approach, functional units, analysis periods, system boundaries, regional differences, and difference in input data [4]. Especially, the scarcity of reliable data would undermine the quality of carbon emission calculation [5]. Thus, for measuring carbon emissions of pavement construction in China, the methodology should be localized, with supporting database customized to the local context.

Ma et al. (2016) established an inventory analysis method to evaluate the greenhouse gas emissions from Portland cement concrete pavement construction in the west of China. The boundary of the concrete pavement construction process consists of raw material production, concrete manufacture, and pavement onsite construction. However, they failed to provide a transparent method to calculate the quantity of energy and material consumption. This might impede the uptake of this tool in practice [7].

In addition, Wang et al. (2015) estimated carbon emissions for three types of projects, namely subgrade, pavement, and bridges and tunnels [6]. The boundary comprises raw material production, material transportation, and onsite construction. They derived the material and energy consumption and machine working hours from the budget sheet. However, they did not provide evidence on scope match between emission factors and bill of quantities. For example, material wastes are often incurred on site, but might not be directly calculated in the carbon emission.

A lack of sufficient professionals in quantifying carbon emissions is another significant hindrance to the tool adoption. There is a huge deficiency of trained professionals in evaluating carbon emissions if the government is going to initiate carbon emission calculation or audit in road projects either in a voluntary or mandatory manner. The challenges to train a large group of professionals in a short term will be enormous. Thus, it will be more feasible to develop a methodology which is featured by labor-saving.

This study aimed to propose a methodology for measuring the carbon emissions of pavement construction compatible with the fixed pricing systems prevalent in China and develop a tool with built-in database of carbon emission factors to assist in the carbon estimations. This tool has the advantages of embedding a China contextualized database and being labor-saving.

3. Quantifying Carbon Emissions of Road Construction Projects

The boundary of carbon emission comprises four stages: material manufacture, transportation, construction, and disposal (see Equation (1))

$$CE(S) = CE(S_1) + CE(S_2) + CE(S_3) + CE(S_4) \quad (1)$$

where $CE(S_1)$: Carbon emissions at the material manufacture stage; $CE(S_2)$: Carbon emissions at the material transportation stage; $CE(S_3)$: Carbon emissions at the construction stage; $CE(S_4)$: Carbon emissions at the disposal stage.

Equation (1) could be further converted in to the Equation (2) in accordance with the methodology shown in Figure 1. In the end, the total carbon emissions are aggregated under the energy consumption and materials used. For calculating Equation (2), quantity of energy consumption and material usage could be directly accessible by combing the bills of quantity and the fixed pricing system. The fixed price system in China is developed and maintained by the Ministry of Housing and Urban-Rural Development, China. The cost administration agency in each city and province could calibrate this system to its local context. This fixed price system has an authorized database for quantifying the material usage and energy consumptions. The database is updated on a regular basis. Therefore, the accuracy of calculating carbon emission could be guaranteed when it is designed to be compatible with the database.

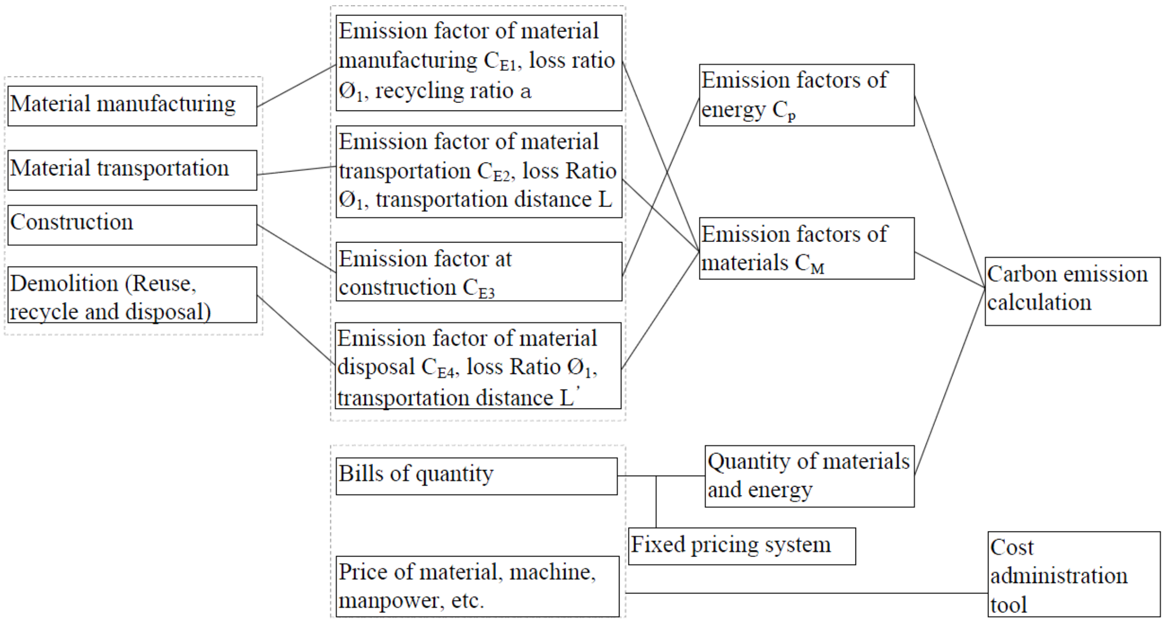

Figure 1. Framework for measuring carbon emission.

$$
\begin{aligned}
CE(S) &= CE(S_1) + CE(S_2) + CE(S_3) + CE(S_4) \\
&= \sum_i (1+\varphi_{1i}) \times Q_{Mi} \times C_{E1_i} + \sum_i (1+\varphi_{1i}) \times Q_{Mi} \times C_{E2_i} \\
&+ \sum_j Q_{Pj} \times C_{E3_j} + \sum_i Q_{Mi} \times \varphi_{1i} \times C_{E4_i} \\
&= \sum_i \left\{ Q_{Mi} \times (1+\varphi_{1i}) \times \left[C_{E1_i} + C_{E2_i} + C_{E4_i} \times \frac{\varphi_{1i}}{(1+\varphi_{1i})} \right] \right\} + \sum_j Q_{Pj} \times C_{E3_j} \\
&= \sum_i Q'_{Mi} \times \widetilde{C}_{Mi} + \sum_j Q_{Ej} \times C_{Pj}
\end{aligned}
\quad (2)
$$

where $\widetilde{C}_M$: emission factors of materials; Q'_{Mi}: quantities of materials (including wastes).

As can be seen from Equation (2) and Figure 1, two major steps of this methodology are to identify quantities of energy consumptions and material usage, and estimate a set of composite emission factors (i.e., $\widetilde{C}_{Mi}$, C_P) (see Figure 1). The first step could be easily completed by using the bill of quantity and the existing cost management system. The estimation of a set of composite emission factors is elaborated below.

The composite emission factors of materials ($\widetilde{C}_{Mi}$) are transformed from emission factors of material manufacturing C_{E1}, material transportation C_{E2}, material disposal C_{E4}. The emission factor of energy (C_P) is estimated from construction stage emission factors (C_{E3}).

3.1. Material Manufacture Stage

At the material manufacture stage, the boundary of carbon emissions is defined from raw material to the final product, including energy use, transportation, and manufacturing process. Equation (3) is used to quantify carbon emission at the manufacture stage. Wastes during the construction are also taken into account.

$$CE(S_1) = \sum_i (1 + \varphi_{1i}) \times Q_{Mi} \times C_{E1_i} \tag{3}$$

where Q_M: net quantity of material use; C_{E1}: emission factors of the material at the manufacture stage; φ_1: percentage of wastes; i: type of materials.

In Equation (3), the emission factors for the materials at the manufacture stage C_{E1} are calculated using Equations (4) and (5).

$$C_{E1} = (C_{m1} + C_{m2} + C_{m3}) \times (1 - \alpha) + s \times \alpha \tag{4}$$

where C_{m1}: emission factors for the raw material manufacture; C_{m2}: emission factors for the raw material transportation; C_{m3}: emissions factors for energy use at the manufacture stage; α: percentage of material recycled; and s: emission factors for using the re-cycled material.

$$C_{m3} = \sum_j M_{P_j} \times C_{P_j} \tag{5}$$

where

$$C_{P_j} = C_{P_{j,k}} \times GWP_k$$

where M_P: energy consumption at the material manufacturing; C_P: emission factors of stationary energy; $C_{P_{j,k}}$: emission factors of type k GHG for type j energy; GWP_k: GWP; j: type of energy; k: type of GHG (i.e., CO_2, CH_4, N_2O).

3.2. Material Transportation

At the material transportation stage, energy consumption for transporting materials from the manufacture site to the construction site is the principal source of CO_{2e} emission. Carbon emission at the material transportation stage could be estimated by using Equation (6). The emission factors are calculated by using Equation (7). In Equation (7), $P \times C'_P$ denotes the intensity of carbon emissions, with the unit of carbon emission per unit of material per unit distance.

$$CE(S_2) = \sum_i (1 + \varphi_{1i}) \times Q_{Mi} \times C_{E2_i} \tag{6}$$

where Q_M: Net material use; C_{E2}: Emission factors of the materials at the transportation stage.

$$C_{E2} = \sum_j L \times P_j \times C'_{P_j} \tag{7}$$

where

$$C'_{P_j} = \sum_k C'_{P_{j,k}} \times GWP_k$$

where L: Distance from manufacture site to the construction site; P: Energy consumptions per distance per unit of material; C'_P: Emission factors for the mobile source; $C'_{P_{j,k}}$: Emission factors of k type GHG for j type energy.

3.3. Construction Stage

At the construction stage, CO_{2e} is mainly emitted from the energy consumption (i.e., electricity, diesel, petroleum gas) in the machinery operation. Thus, the carbon emission could be quantified using Equations (8) and (9).

$$CE(S_3) = \sum_j Q_{Pj} \times C_{E3_j} \quad (8)$$

where Q_P: Energy consumptions; C_{E3}: Emission factors during the construction stage; j: types of energy.

$$C_{M3} = \sum_j C_{P_{j,k}} \times GWP_k \quad (9)$$

where $C_{P_{j,k}}$: Emission factors of type k GHG for type j energy.

3.4. Construction Waste Disposal Stage

During the waste disposing stage, energy is consumed for transporting waste to landfill site. It is assumed that the vehicles are fully loaded and only one-way energy use is considered. It is also assumed that two recyclable materials are steel and aluminum given a high recycling ratio of these two materials. The equations are presented in Equations (10) and (11).

$$CE(S_4) = \sum_i Q_{si} \times C_{E4i} = \sum_i Q_{Mi} \times \varphi_{1i} \times C_{E4i} \quad (10)$$

where Q_s: quantity of waste; C_{E4}: emission factors of waste disposal.

$$C_{E4} = \sum_j L' \times P_j \times C'_{P_j} \quad (11)$$

where L': the distance from the construction site to the landfill site; C'_P: emission factors for mobile sources.

4. Parameters in the Methodology

Using the methodology and equations presented in Section 3, this section aims to calculate three types of parameters, namely basic parameters (e.g., disposal transportation distance, recycling ratio), emission factors for energy and materials. When identifying these three types of parameters, the data source is preferred in the order of publications from public agencies, technical papers published by institutions, and academic findings in China.

4.1. Basic Parameters

Three types of basic parameters are presented in Table 1. Given a high recycling ratio of steel and aluminum, only these two materials are assumed to be recycled. Material losses during the stack at the site, re-processing, and construction are also taken into account. Besides, it is assumed that the transportation distance for the waste disposal (L') is 50 km [19].

Table 1. Basic parameters and their descriptions.

Basic Parameters	Descriptions	Source
Recycling ratio	Section steel: 0.9 Steel bar: 0.5 Aluminum: 0.95	[20]
Percentage of material waste (%)	Steel: 6 Cement: 2 Concrete: 1.5 Sand: 3 Gravel: 3	[21]
Transportation distance(km)	Cement: 100 Steel: 125 Sand and gravel: 200 Timber: 80 Brick: 50	[19]

4.2. Emission Factors for Energy

This study adopts CO_2e to represent three types of GHG (i.e., CO_2, CH_4 and N_2O). The Global Warming Potentials (GWP) are adopted from [22]. Only electricity and fuel consumption are taken in to account. Emission factor for electricity (0.816 kg/Kwh) is adopted from [23], which is locally available for the Jiangsu Province where the selected case is located.

Both stationary and mobile fuels are consumed in the road construction. Given a lack of authorized database of emission factors for fuel consumptions in China, the database provided by the IPCC (2006) was adopted [24]. This dataset was also previously used by the Chinese Government [25]. Under the IPCC,

$$\text{Carbon emissisons from energy combusitions} = \text{Combustion acitivity (TJ)} \times \text{emission factors} \left(\frac{\text{kg}}{\text{TJ}}\right)$$

As the unit of TJ is not commonly used in China, a further transformation was carried out as follows.

$$\begin{aligned}\text{Carbon emissions} &= \text{Combustion activitie (unit)} \times \text{emisson factor} \left(\frac{\text{kg}}{\text{TJ}}\right) \times \text{fuel value} \left(\frac{\text{kg}}{\text{GJ}}\right) \\ &= \text{Combustion activities (unit)} \times \text{emission factors}_{transformed} \left(\frac{\text{kg}}{\text{unit}}\right)\end{aligned}$$

where emission factors (kg/TJ) were accessed from [24].

Using these equations, the emission factors for stationary and mobile fuels are obtained (see Tables 2 and 3).

Table 2. Emission factors for stationary fuels (C_P).

Types of Fuels	Unit	CO_2 Emission Factors	CH_4 Emission Factors	N_2O Emission Factors
		kg/unit	kg/unit	kg/unit
Raw coal	kg	1.825	6.27×10^{-6}	1.05×10^{-5}
Other coals	kg	0.730	2.51×10^{-5}	4.18×10^{-6}
Coke oven gas	m^3	0.624	5.02×10^{-5}	5.02×10^{-7}
Other oven gas	m^3	0.195	1.57×10^{-5}	1.57×10^{-7}
Crude oil	kg	2.973	4.18×10^{-5}	8.36×10^{-6}
Petrol	kg	2.907	4.31×10^{-5}	8.61×10^{-6}
Diesel	kg	3.097	4.27×10^{-5}	8.53×10^{-6}
Fuel oil	kg	3.157	4.18×10^{-5}	8.36×10^{-6}
Liquefied petroleum gases	m^3	2.114	1.17×10^{-5}	1.17×10^{-6}
Other petroleum product	kg	3.019	4.18×10^{-5}	8.36×10^{-6}

Table 3. Emission factors for mobile fuels (C'_P).

Types of Fuels	Unit	Emission Factors (kg/TJ)			Carbon Emission Factors C'_P (kg/unit)
		CO_2	CH_4	N_2O	
Petrol	kg	67,500	9.6	0.96	2.930
Diesel	kg	72,600	1.6	1.3	3.115

4.3. Emission Factors for Materials

Emission factors for materials are aggregated from three sub-emission factors (i.e., C_{E1} at the manufacturing stage, C_{E2} at the transportation stage and C_{E4} at the waste disposal stage). The database of composite emission factors for materials is shown in Table 4. The results were achieved through two-stage calculation.

Table 4. Database of emission factors for materials.

Material	Unit	Emission Factors (kg/unit)			
		C_{E1}	C_{E2}	C_{E4}	C_M
Large reinforced steel *	t	1172.361	22.118	22.118	1216.597
Medium-small reinforced steel *	t	937.778	22.118	22.118	982.014
Wire rod *	t	1753.446	22.118	22.118	1797.682
Hot-rolled strip steels *	t	1840.822	22.118	22.118	1885.058
Cold-rolled strip steels *	t	2336.323	22.118	22.118	2380.559
Cement 52.5	t	1246.282	17.695	8.847	1272.823
Cement 42.5	t	1094.972	17.695	8.847	1121.513
Cement 32.5	t	792.829	17.695	8.847	819.371
Lime	t	1180.000	17.695	8.847	1206.542
Reinforced concrete C20	m^3	230.000	8.847	8.847	247.695
Reinforced concrete C25	m^3	250.000	8.847	8.847	267.695
Reinforced concrete C30	m^3	270.000	8.847	8.847	287.695
Reinforced concrete C35	m^3	290.000	8.847	8.847	307.695
Reinforced concrete C40	m^3	310.000	8.847	8.847	327.695
Reinforced concrete C50	m^3	350.000	8.847	8.847	367.695
Asphalt concrete	t	29.000	8.847	8.847	46.695
Plastic pipe	m	6.308	0.035	0.018	6.361
PVC pipe	m	9.400	0.035	0.018	9.453
Glass	t	1657.480	17.695	8.847	1684.022
Ceramics	t	1400.000	18.579	8.847	1427.427
Aluminum *	t	1020.000	17.695	17.695	1055.389
Brick	1000	320.000	14.156	14.156	348.311
Timber	t	200.000	14.156	8.847	223.003
Copper	t	3800.000	17.695	8.847	3826.542
Coating	t	2058.600	14.156	8.847	2081.603
Petroleum bitumen	t	285.000	17.695	8.847	311.542
Emulsified bitumen	t	211.000	17.695	8.847	237.542
Gravel and sand	t	4.667	23.593	5.898	34.158
Acetylene	t	3385.000	0.000	0.000	3385.000

Note: *: recycling ratio is taken into account; Emission factors at the manufacturing stage (C_{E1}) are adopted from [26].

(1) Manufacture stage (C_{E1})

Emission factors for 29 materials are identified (see Table 4). To illustrate the methodology, the case of calculating C_{E1} for reinforced steels is elaborated below (see Table 5). C_{E1} for reinforced steels is calculated by aggregating emissions from manufacturing process and transportation and energy consumption by using Equations (4) and (5). Three types of GHG are taken into account, namely

CO_2, CH_4, and N_2O. Gong (2004) provided the data inputs about emission factors for manufacturing processes [26]. Aggregating these three emission factors yields a C_{E1} for reinforced steels.

Table 5. Examples for calculating the emission factors for material manufacture.

Type of Steel	Process	Emission Factors (kg/t)			C_{E1} (kg/t)
		CO_2	CH_4	N_2O	
Reinforced steel	Energy use	1880.556	0.014	0.007	1882.929
	Manufacturing process	611.700	225.000	2.030	6841.640
	Raw material transportation	109.970	0.002	0.002	110.617
	Total	**2602.226**	**225.017**	**2.039**	**8835.186**

(2) Transportation (C_{E2}) and waste disposal (C_{E4})

It is assumed that, at the material transportation and final disposal stage, trucks are the principal transportation vehicle which consumes diesel. The emission intensity for transportation is shown in Table 6 and emission factors for steel transportation and disposal are presented in Table 7. Equations (6) and (7) are used to calculate these emission factors. Wang (2009) found that energy consumption at the disposal stage accounts for 20%–50% of the new material manufacturing [27]. Therefore, a mean value of 35% was adopted in this study.

Table 6. Emission intensity for transportation.

Methods for Delivery	Energy Consumptions kJ/(t·km)	Emission Factor for Mobile Fuels (kg/TJ)			Emission Intensity kg/(t·km)
		CO_2	CH_4	N_2O	
Petrol	3662	67,500	9.6	0.96	0.249
Diesel	2423	72,600	1.6	1.3	0.177

Table 7. Emission factors for material transportation and material disposal transportation.

Categories	L (km)	L' (km)	Emission Factors for Material Transportation (kg/t)				Emission Factors for Material Waste Disposal (kg/t)			
			CO_2	CH_4	N_2O	C_{E2}	CO_2	CH_4	N_2O	C_{E4}
Steel	125	125	21.989	4.85×10^{-4}	3.94×10^{-4}	22.118	21.989	4.85×10^{-4}	3.94×10^{-4}	22.118

Note: (1) It is assumed that only diesel is consumed during material transportation and waste disposal transportation; (2) The transportation distance data is adopted from [19].

5. A C# Based Tool for Carbon Emission Calculation

This methodology was programmed into a tool with the help of C# and Visual Studio 2010. This tool has multiple features. First, it is compatible with the outputs of all cost management software currently available in China. Thus, adoption of this tool would contribute to boost productivity of quantifying carbon emission. Second, the tool is user-friendly as it is designed with a similar interface to Microsoft Office. Third, the quantification process is transparent and verifiable, with the aid of a reliable database. In addition, the emission factors and associated basic parameters could be further fine-tuned to any specific project if following the methodology proposed in this study.

Besides the basic function of carbon emission estimation, this tool also produces project background reports, has the function of managing the database of emission factors, and generates a carbon emission report. The carbon emission report comprises the total carbon emission and breakdown of the carbon emission of each type of material and energy. All the functions are shown in Table 8.

Table 8. Functions of the carbon emission calculation tool.

Category	Functions
Basic information	Project characteristics Profile of the assessor
Quantification of carbon emissions	Data inputs Automatic estimation
Report generation	Carbon emission report
Data base management	Data set edit Built-in dataset updates

Operating the tool includes four steps: coding the material types; specifying the unit of each type of materials; inputting the database of the composite emission factors; and inputting quantity of materials and energy consumption. As the tool is compatible with spreadsheet format data, users can use the spreadsheet to prepare the material codes, unit of the material, and emission factor database.

6. Case Study

In order to verify the effectiveness of the tool, a road project located in Suzhou city, Jiangsu province, China was examined. Another purpose of the case study is to reach an initial recognition of the intensity of carbon emissions in China's pavement construction. The structure of the road is shown in Figure 2. The project comprised road and affiliated drainage works and pedestrian roads. It was about 0.56 km long and 26 m wide, with four 3.75 m lanes, plus a 3.5 m bicycle lane and 2 m sidewalk on both sides.

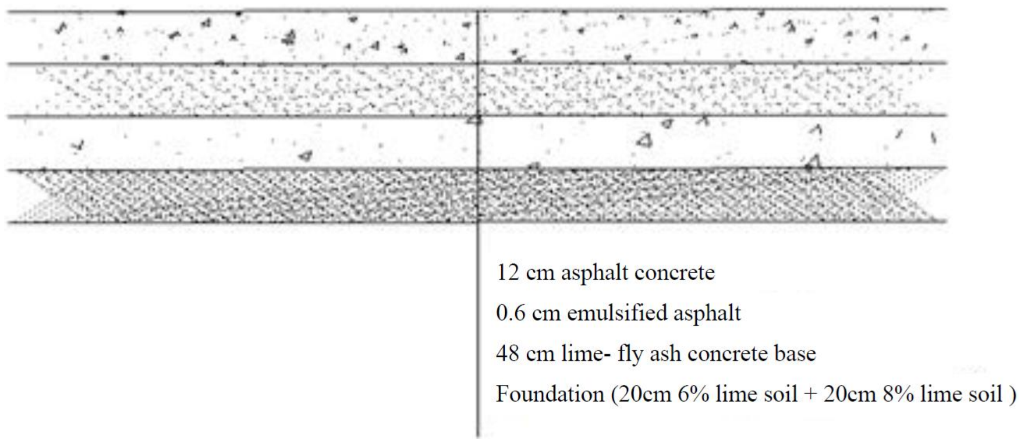

Figure 2. Structure of the pavement.

The boundary of carbon emission comprises material manufacture and transportation, construction, and construction waste disposal. The physical boundary contains construction of the road, affiliated drainage, and sidewalks. The functional unit is one-km four-lane road.

As shown in Figure 1, quantifying carbon emissions requires inputs of quantities of materials and energy consumptions and the composite emission factors. The quantities of materials were directly accessed from commercial software used for cost administration. In this case, it is "weilai qingdan". The mechanism for calculating the quantity of energy consumptions and material usage is based on the fixed pricing system, which is built in "weilai qingdan". The final results could be saved in a spreadsheet as an input for the carbon emission calculation.

The procedure of operating the tool consisted of creating a new project, inputting the list of quantity of materials and energy consumptions; selecting the emission factor for each type of materials;

and clicking the calculation button. In the end, a report of carbon emission was obtained. For this case, the total carbon emission is 3744.457 t (see Figure 3). Thus, the carbon emission per functional unit is 1672 t/lane km. The breakdown of carbon emissions shows that the use of lime accounts for 70% of the carbon emissions.

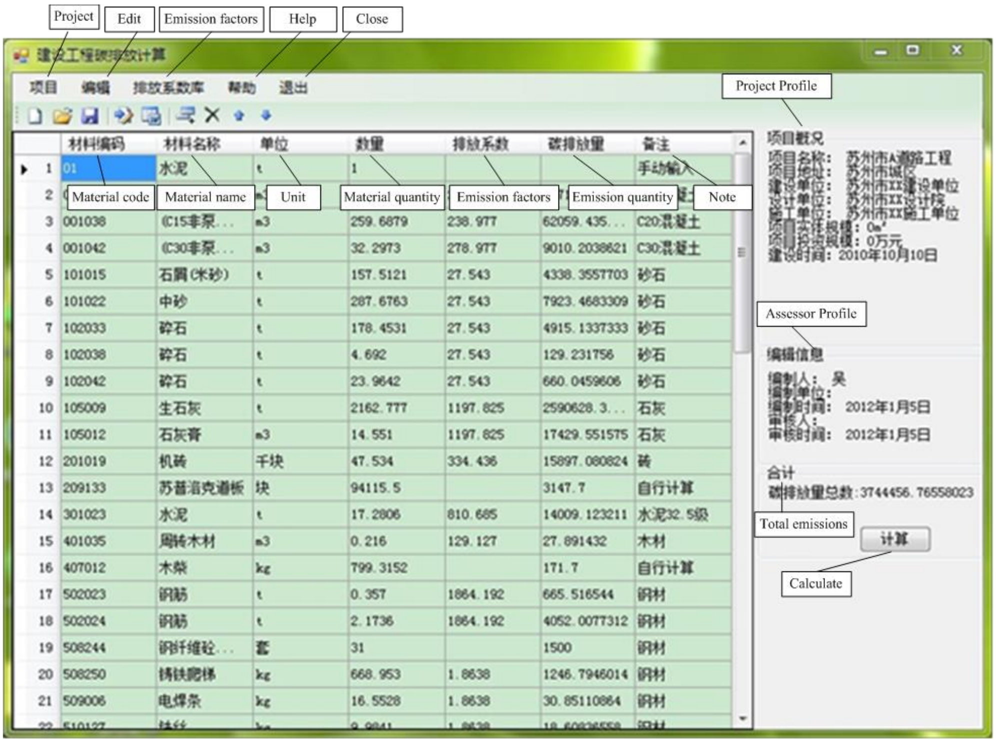

Figure 3. Carbon emission results.

7. Conclusions and Recommendations

While a number of methodologies for quantifying carbon emissions of road projects are developed in China and worldwide, adopting and promoting these tools to the China market is found fairly challenging due to the institutional constraints. To fill in this knowledge gap, a carbon emission calculation methodology compatible with the current fixed pricing systems used in China was proposed in this study. This methodology was programmed into a C# and Visual 2010-based tool and further validated in a real case.

This study contributes to the extant literature by presenting a carbon emission calculation tool customized to the China's context. This tool developed was proven to be user-friendly through the case study. The methodology underpinning the practical tool could generate a reliable database, thereby ensuring accurate carbon emission quantification. The proposed methodology and tool also have advantages of facilitating the uptake as the quantity of the material and energy consumption could be directly obtained from the existing cost management software. This tool provides practitioners with an accurate and user-friendly platform to estimate carbon emissions of pavement construction. Besides, this study established a database of composite emissions factors for energy and materials for the Jiangsu Province context.

Generalizing such methodology to other countries or regions should be read with caution as the advantage of such a tool is its compatibility with the fixed pricing system in China and the emission factors are suitable for the Jiangsu Province context. However, this limitation is not unique to this study given that the boundary and methodology used in carbon calculation tools are expected to be compliant with the existing regulations and policy. The regulations and policy would vary considerably across geographic regions.

Another limitation is that this study did not consider the carbon emission from operation and maintenance stages. Thus, for future studies, adopting an LCA approach is suggested (see life cycle approach in [28–30]). In addition, the environmental impact of pavement construction, other than the carbon emissions, could be incorporated in the LCA (see [28,30]). The emission factors for 29 types of materials and energy were identified in this study. Although most of them are the major materials in construction, they only constitute a small proportion of construction materials. Nonetheless, the methodology used in this study is applicable for calculating emission factors for other types of materials. Thus, future studies that enlarge this database are recommended.

The third limitation is concerned with the effects of concrete on carbon emission. This study mainly focused on the concrete which contributes to carbon emission. However, increasing studies found that high performance concrete would expand their lifespan and generate less carbon emissions (e.g., [31,32]). Thus, future studies that examine different types of concrete should take the variation of carbon emission factors into account.

This study assumed that all data source and input parameters are fixed across different project types. However, this assumption might not hold true as data sources and input parameters are subject to various uncertainties (see [28]). Thus, future studies that examine the uncertainty effect of the key data sources and input parameters would be suggested.

The last limitation is the simplification of concrete structure demolition. This study only takes the transportation of waste during the disposal stage into account. Existing studies found that extra carbon emission could also be generated during the disposal stage (see [33]). Future studies that present a holistic approach to investigate the carbon emissions during the disposal stage would be recommended.

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