Mitigating life cycle GHG emissions of roads to be built through 2030: case study of a Chinese province

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Abstract

The expansion of road networks in emerging economies such as China causes significant greenhouse gas (GHG) emissions. This development is conflicting with China's commitment to achieve carbon neutrality. Thus, there is a need to better understand life cycle emissions of road infrastructure and opportunities to mitigate these emissions. Existing impact studies of roads in developing countries do not address recycled materials, improved pavement maintenance, or pavement-vehicle interaction and electric vehicle (EV) adoption. Combining firsthand information from Chinese road construction engineers with publicly available data, this paper estimates a comprehensive account of GHG emissions of the road pavement network to be constructed in the next ten years in the Shandong province in Northern China. Further, we estimate the potential of GHG emission reductions achievable under three scenario sets: maintenance optimization, alternative pavement material replacement, and EV adoption. Results show that the life cycle GHG emissions of highways and Class 1-4 roads to be constructed in the next 10 years amount to 147 Mt CO_2-eq. Considering the use phase in our model reveals that it is the dominant stage in terms of emissions, largely due to pavement-vehicle interaction. Vehicle electrification can only moderately mitigate these emissions. Other stages, such as materials production and road maintenance and rehabilitation, contribute substantially to GHG emissions as well, highlighting the importance of optimizing the management of these stages. Surprisingly, longer, not shorter maintenance intervals, yield significant emission reductions. Another counter-intuitive finding is that thicker and more material-intensive pavement surfaces cause lower emissions overall. Taken together, optimal maintenance and rehabilitation schedules, alternative material use, and vehicle electrification provide GHG reduction potentials of 11%, 4%-16% and 2%-6%, respectively.

1. Introduction

Roads are one of the dominant forms of transportation infrastructure globally, along with rail lines, shipping ports, and airports. Roads can accelerate economic development and improve quality of life by providing connections between regions, and thus enabling the circulation of products, technologies, and knowledge (Banister, 2012; Yu and Lu, 2012; Yu et al., 2012). However, road construction leads to greenhouse gas (GHG) emissions both because pavement construction causes high emissions and because the increased availability of roads leads to induced traffic which is predominantly carried out with polluting fossil-fuel powered vehicles (Yu and Lu, 2012). Road infrastructure is still unevenly distributed at a global level with limited road access in low-income countries (Meijer et al., 2018; Weiss et al., 2018). An estimated 800,000 km of roads will be needed to provide the vast majority of the global population with quasi-universal road access (Wenz et al., 2020). In order to achieve this, an estimated 2 Gt of CO_2 would be emitted, representing around 0.25% of the carbon budget still available for compliance with the 2°C target (Wenz et al., 2020).

China's scale of infrastructure construction is unprecedented among all developing countries. The expected pavement construction, upgrade and expansion in the coming decades will make it more difficult for China to meet its goal of carbon neutrality. According to forecasts by the China Highway Construction Industry Association and the Ministry of Transport, the expected total investment for road construction in 2021-2030 is around $2.94 trillion. This encompasses 3,365,000 km of pavement of all pavement levels (Yicai, 2018). Further, maintenance and rehabilitation (M&R) of the existing short-lived network of pavements adds to the impact of new construction (Wang, 2013). To achieve the recently proposed target of carbon neutrality (Wang and Zhang, 2020), an environmentally preferable system of road construction and management is needed.

China is currently piloting and promoting alternative materials and engineering methods in order to improve the quality and energy efficiency of pavement construction. In addition to commonly promoted materials such as recycled asphalt and pavement, China is also experimenting with the use of recycled materials for in-situ hot or cold recycling, in-plant cold recycling, and full-depth cold recycling (Ministry of Transport, 2019). However, these materials and technologies are not currently implemented at a large scale in the country, and their life cycle environmental impact and the corresponding potential for GHG mitigation remain unclear. Moreover, current road construction and M&R decisions rarely consider the full life cycle impact of roads reasonably and comprehensively.

Established pavement LCA models for high-income countries are inadequate for China or other developing countries. Pavement characteristics depend on countries' individual design and construction standards and practices, which change with economic development (Liu et al., 2020). For example, China's pavement has been found to have a notably shorter design life compared to developed countries, which is caused by a combination of engineering and social factors such as overloaded traffic (Gao and Cao, 2001; Huang, 2000), insufficient structures such as thin pavement layers (Liu et al., 2020), and poor construction quality.

This paper thus estimates the GHG emissions of the pavements to be built in the next ten years 2021-2030 in a selected province of China: Shandong province. Firsthand data from Chinese road engineers and publicly available data were combined for the research.

1.1 Pavement life cycle assessment

Life cycle environmental assessment of pavement quantifying the impacts of (1) material production, (2) transportation, (3) construction, (4) use, (5) M&R, and (6) end-of-life, is well established in the literature (Jiang and Wu, 2019). The product system 'pavement' is defined in such a way that the use-phase addresses additional energy use and emissions of vehicles caused by sub-optimal road conditions, e.g. roughness and deflection on the road surface. There are only a limited number of LCA studies addressing pavement in China and these studies are limited in scope. For example, Chen et al. (2017) find that emissions of new road construction vary widely between 10.6 and 823 t CO_2-eq/km^2 among China's provinces but limit their analysis to the construction phase only. Guo et al. (2014) also include the maintenance stage using a simplified approach. They conclude that the production and M&R stages emit 1.85 kt CO_2-eq/km and 1.76 kt CO_2-eq/km, respectively. Guo et al. (2017) find that the production stage contributes most to the life cycle environmental impacts but do not consider M&R and use stages appropriately. In addition, none of the mentioned studies use primary data from Chinese road construction engineers.

The use phase can significantly change the life cycle emissions of pavements, especially due to pavement-vehicle interaction (PVI). PVI focuses on the excess energy consumption of vehicles caused by road roughness, texture, and deflection, and can account for a significant percentage of the total vehicle energy consumption (Beuving, 2004). Two of the major models of PVI are roughness-induced PVI and deflection-induced PVI (Louhghalam et al., 2017; Louhghalam et al., 2014; Louhghalam et al., 2015; Pouget et al., 2012). Deflection-induced PVI is primarily influenced by pavement structure with stiffer pavements having less deflection, while roughness-induced PVI can significantly increase with time due to damages to the road surface. In existing studies, the PVI emissions often accounted for more than 50% of the total life cycle GHG emissions of pavements (Araújo et al., 2014; Noshadravan et al., 2013; Xu et al., 2019; Yu and Lu, 2012; Zhang et al., 2010). However, the majority of previous studies on PVI did not consider the mitigation potential from vehicle electrification.

1.2 GHG emission reduction strategies

Previous research has investigated improvement strategies across all life cycle stages. Here we adopt three of these. M&R equipment and schedules depend on pavement structure (Yu and Lu, 2012; Yu et al., 2013), traffic volume (Wang et al., 2012), and soil conditions (Thenoux et al., 2007) among others and significantly impact the magnitude and variability of pavement life cycle emissions. Optimization of M&R can therefore contribute to significant life cycle emission reductions (alongside cost reductions) (Chan et al., 2008; Labi and Sinha Kumares, 2005; Mandapaka et al., 2012; Praticò et al., 2011; Zhang et al., 2010).

The use of novel materials for road engineering shows potential for reduction of environmental impacts (and cost), with RAP, fly ash and polymer identified as the most popular new materials (Balaguera et al., 2018). Some of the novel materials, such as RAP and recycled concrete aggregates (RCA), have a significantly lower environmental impact compared to hot mix asphalt (HMA) (Chiu et al., 2008; Kucukvar and Tatari, 2012; Vidal et al., 2013) in addition to a cost advantage (Ponte, 2016). Other materials, such as glass (Chiu et al., 2008; Huang et al., 2009), ash from the incineration of municipal solid waste (Olsson et al., 2006), and industrial waste (Schwab et al., 2014) do not show a significant advantage over traditional HMA pavement due to leachate and a reduced life cycle performance of the resulting roads. The potentially reduced performance of pavements, which can lead to more use-phase vehicle emissions, have been studied for multiple materials (Araújo et al., 2014) and production methods such as warm mix asphalt (WMA) (Anthonissen et al., 2015). However, the available studies on new paving materials focus on roads in North America and Europe. The environmental, social, and economic implications discussed in these studies are therefore not applicable to China or other developing countries (Balaguera et al., 2018).

In summary, existing studies have demonstrated that pavement GHG emissions can be quantified for specific contexts. However, the complete life cycle pavement GHG emissions including the stages of use or M&R have not been quantified for China. In addition, the life cycle mitigation potential of alternative materials, optimized M&R schedule, and EV adoption have not been captured in this context. Finally, we are not aware of existing studies using primary data from Chinese road construction engineers.

1.3 Study objective

Hence, the objectives of the current study are to develop a representative LCA model for pavements in one of China’s Northern provinces utilizing firsthand data, and to explore the GHG emission reduction possibilities for these pavements. The sets of scenarios explored are 1) M&R schedule, 2) alternative low carbon materials, 3） and EV adoption. The knowledge gained can be used to provide environmental information and insights for policy makers and practitioners in decisions regarding pavement structure and M&R.

2. Methodology

2.1. Goal and scope

The goal of the study is to assess the life cycle global warming potential of five classes of asphalt pavement in the Shandong Province as shown in Table 1. The Shandong Province is selected to represent the typical pavement situation in Northern China. The functional unit is one lane-km (1 km) over the entire pavement lifetime. The scope of this study includes the stages of material production, transportation, construction, use, and M&R. The projected length of the newly constructed road network pavement is reported in Table S1, while the system boundary of this analysis is shown in Figure 1.

Table 1 The five technical classes of asphalt pavement analyzed in this study

	Highway	Class I	Class II	Class III	Class IV
Speed (km/h)	80-120	60-100	60-80	30-40	20-30
Average daily traffic (PCU, passenger car unit)	>15,000	>15,000	5,000-15,000	2,000-6,000	<2,000
Number of lanes	≥4	≥4	2	2	2
Life span assumed (years)	20	20	15	15	15
Percentage of heavy trucks	14%	14%	7%	7%	7%

Source: National standards JTG F10-2006 and JTG B01-2014

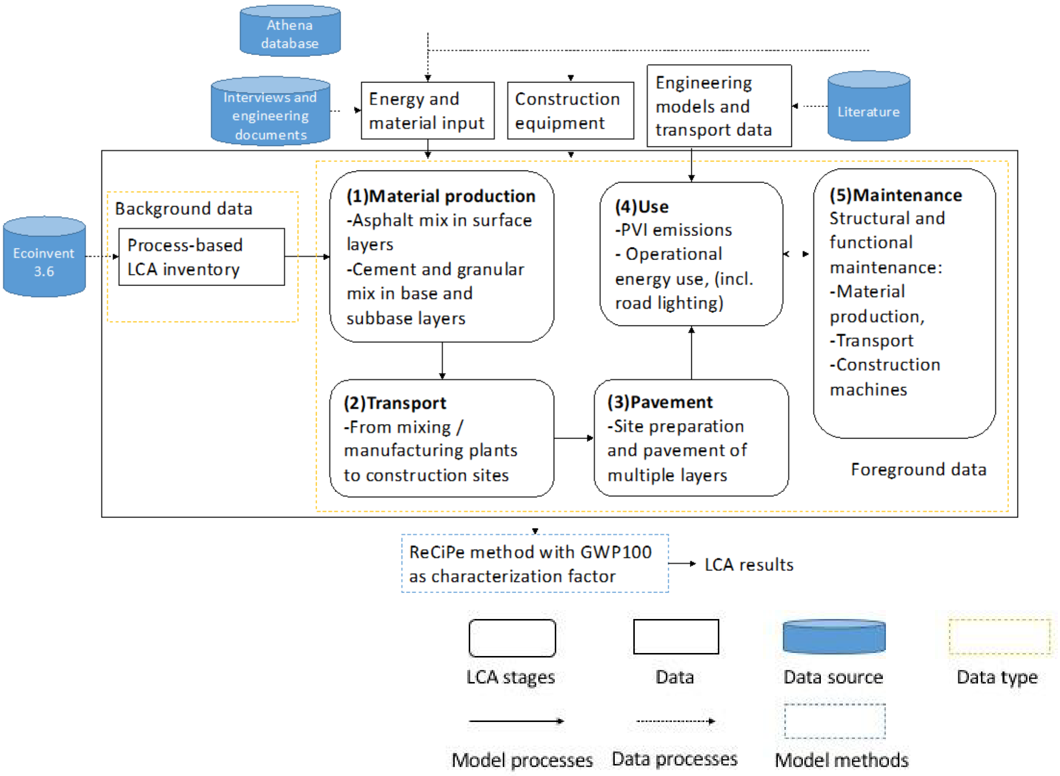


Figure 1. Data input and system boundary of pavement LCA.

Data for pavement structure and materials is collected from national standards (Li and Li, 2006; Ministry of Transport, 2004, 2006a, b, 2008, 2014, 2015; Yao, 2006), engineering papers, and interviews with Chinese engineers. LCA calculations are conducted with OpenLCA utilizing background data from the ecoinvent database 3.6. We assume that all production and use stages are typical for the context of the Shandong Province. For details on additional methods and data please see section 1 and 5 in the SI. Emission factors of materials and data quality are listed in Table S15 and S16.

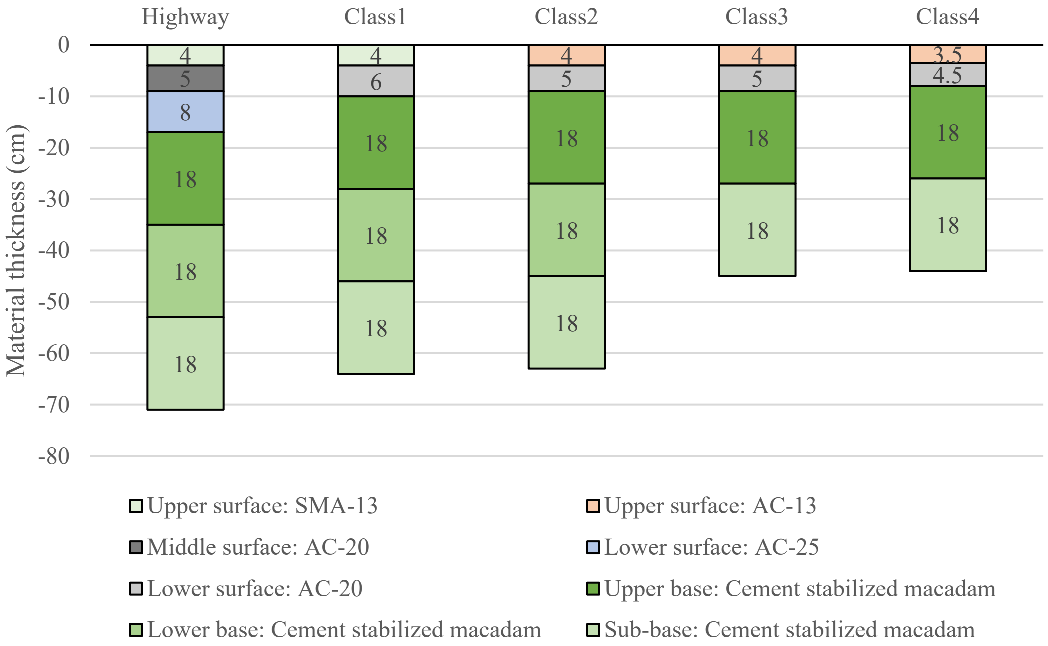


Figure *2: Material thickness of 5 classes of asphalt pavement, where 0 represents the surface. SMA: stone-matrix asphalt. AC: asphalt concrete. Number (e.g. 13 in SMA-13) refers to nominal maximum aggregate size (mm). See Table S2.*

2.2 Scenarios sets and Sensitivity

This study explores the uncertainty of both pavement-related GHG emissions as well as the potential for their mitigation. Three sets of scenarios are summarized in Table 3. They consider the key factors defined for this study including: M&R schedule, alternative materials, and vehicle electrification. The study also varies parameters of binder and moisture content, energy consumption in manufacturing and construction, transport distance, and traffic growth rate covering the range of reported values in various reports and peer-reviewed papers (Tables S7, S8).

Scenario 1: Maintenance and Rehabilitation schedule

M&R schedules can have a significant impact on the full life cycle GHG emissions of pavement by consuming materials and energy while influencing pavement performance in the use phase. Studies have been conducted on optimizing the total cost of M&R considering the user cost and agency cost throughout the life cycle (Chan et al., 2008; Guo et al., 2019; Guo et al., 2020; Mandapaka et al., 2012; Pratico et al., 2011) while the discussion on carbon optimization is relatively limited (Pellicer et al., 2016; Renard et al., 2021; Torres-Machi et al., 2014). The central question to be answered in this optimization problem is which M&R option to choose at each stage to achieve a minimization of GHG emissions over the entire life cycle. The level of roughness and deflection were restricted in the optimization model in a way that met the requirements of pavement service performance and standards (Ministry of Tranpsort, P., 2018). The detailed description of the optimization model is summarized in the SI (Table S9 and Eq S5-S19).

Scenario 2: Alternative low carbon material

Materials can directly and indirectly contribute to a significant percentage of life cycle GHG emissions of pavement. Among many recycled materials discussed, RAP and

RCA show considerable advantages in availability and relatively satisfactory road performance. However, it is still challenging to use 100% of these recycled materials as they might not provide the same function as traditional materials. Therefore, the percentage of recycled materials should be decided on in tandem with the production method and the use of additives (e.g. sasobit), considering the required pavement quality and energy input. The change in road features can have important impacts on use-phase emissions. See Table S8 in the SI for detailed assumptions and discussions on material content, energy consumption, density, and stiffness changes.

Scenario 3: Adoption of EVs

The promotion of EVs can potentially reduce GHG emissions of the use phase. This section discusses the use-phase GHG emissions under different scenarios with EV adoption rate, EV on-board energy consumption, and carbon intensity of electric charging. For simplicity and considering the low average age (3.3 years) of passenger cars in China (Launch Tech and DataEye, 2015), we use projected EV sales percentages in 2030 as a replacement percentage. Detailed assumptions on EV adoption rates, future EV energy use improvements, and carbon intensity of electricity can be found in Table S11, Table S12, and Table S13. The most optimistic scenario, for example, assumes very high adoption rates and energy use improvements of EVs, and an electricity mix consistent with the international 2℃ target. While the High EV scenario considers a substantial uptake of EVs, no change in the pavement design code is reported by the respective authorities as a result of fleet electrification (Ministry of Transport). While the increasing trend in the use of EVs can substantially reduce the use-phase impact of the pavement life cycle, their effect on pavement design and future code adoption remains an open question.

Table 2 Summary of the factors and scenarios for emission reduction

Scenario Set	Scenarios
M&R schedule	- Fixed schedule - Maintenance optimization
Alternative materials *Key parameters varied:* - Material composition - Energy consumption - Stiffness - Density - Cement content - Moisture content	For surface asphalt (A) layer: - A1: Typical materials and method (HMA) - A2: 20% RAP, with 30% of asphalt binder in RAP function as binder - A3: 40% RAP + 3% Sasobit, with 50% of asphalt binder in RAP function as binder - A4: WMA (3% Sasobit)
	For base granular (G) layers: - G1: Traditional materials and method with 4.8% cement - G2: 40% RAP with 4.5% cement - G3: 42% RCA with 4.3% cement - G4: 40% RAP + 60% milled granular layer with 4.5% cement - G5: Traditional materials for production + Cold-in-place recycle for structural M&R with 4.5 cement - G6: 40% RAP + 60% milled granular layer for production + Cold-in-place recycle for structural M&R with 4.5 cement
EV adoption *Key parameters varied:* - Fuel economy - Electricity GHG emission factor - EV adoption rate	EV adoption rate: - None - Low (L): 8.5-37% passenger, 0.5% truck - Medium (M): 11.7-44.5% passenger, 1.3% truck - High (H): 14.8-52% passenger, 2.0% long-haul truck
	On-board energy consumption: - Current - 2030 prediction
	Carbon intensity of the electricity mix: - 2018 electricity - 2030 BAU - 2030 New policy - 2030 450 ppm policy (2℃ target)

3. Results

3.1 LCA results at provincial level

Figure 3 shows the life cycle GHG results of the newly constructed road network in the province of Shandong through 2030. The life cycle GHG emissions of highway and Class 1-4 roads to be constructed in the next 10 years are about 24, 48, 11, 58, and 7 Mt CO_2-eq, respectively, with a total of 147 Mt CO_2-eq under the business as usual (BAU) scenario. Estimated impacts under various alternative scenarios are shown in Figure 3. Material replacement has a major influence on the results, with a potential reduction of up to 16% reduction or 24 Mt CO_2-eq. Similarly, M&R optimization and EV adoption could reduce life cycle GHG emissions by about 17 Mt (11%) and by up to 9 Mt (6%), respectively.

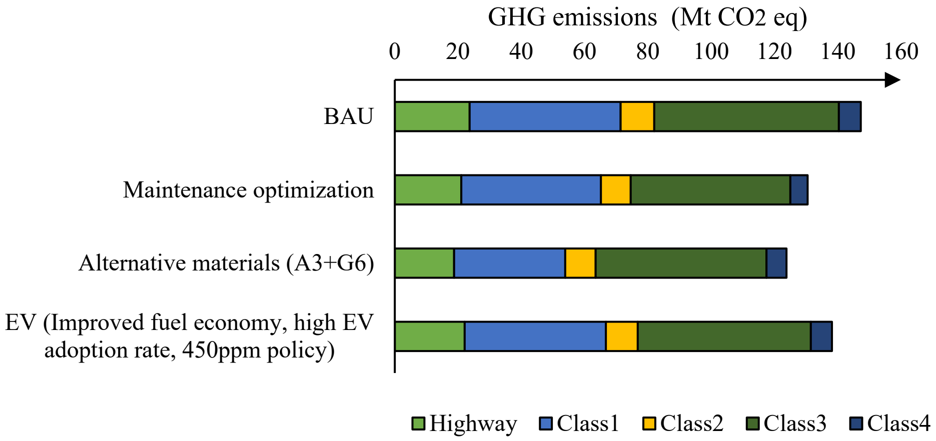
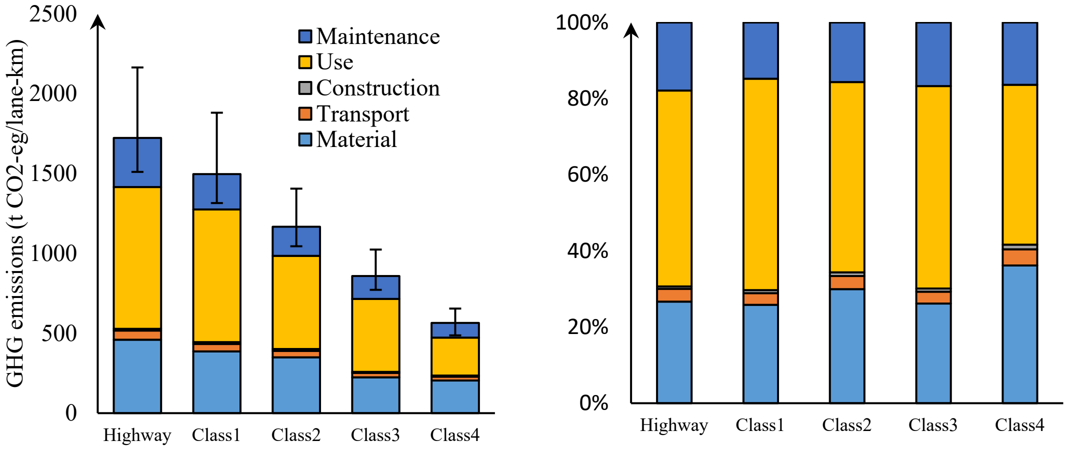


Figure 3. Life cycle GHG emissions of newly built roads in the Shandong Province through 2030 and across selected scenarios. The expansion of the road network is by 2287, 5317, 4560, 22998, and 6145 km for highways and class 1-4 roads, respectively (Table S1).

3.2 Life cycle GHG emissions of pavement per functional unit

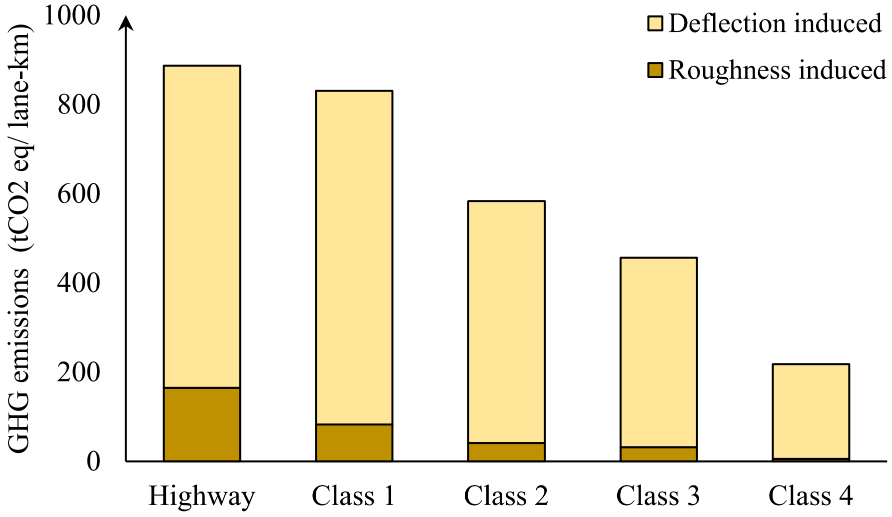
Pavement design and assumed traffic volume have a large influence on life cycle GHG emissions. The life cycle GHG emissions (see Table S5) for Highway, Class 1, Class 2, Class 3, Class 4 are on average 1,720, 1,500, 1,170, 860 and 570 tons CO_2-eq/lane-km as shown in Figure 4. Pavements experiencing higher traffic volumes require more material and energy inputs during the manufacturing, construction, and transport stages. The results for each class of pavement generally vary from around -15% to +25%, depending on parameter selection, as shown by the error bars in Figure 4(a).

A large share of impacts are due to the PVI effect in the use phase. As shown in Figure 4(b), the use phase emissions of all roads (except for Class 4) account for about 50-55% of per-unit GHG emissions, while production emissions represent around 25-30% of life cycle impacts per lane-km. The M&R phase, which includes the production and transport of materials, and fuel consumption for on-site construction, contributes about 15-18% to specific GHG emissions. For the lower-traffic Class 4 roads, M&R has a significantly higher impact share. Transport of materials and operation of on-site machinery jointly accounts for less than 5% of emissions. Deflection-induced PVI, which primarily impacts truck, dominates use-phase emissions (over 80%, Figure 4(c)).



(a) Life-cycle emissions with error bars illustrating the sensitivity of results.

(b) Relative contribution of each life cycle stage.



(c) GHG emissions of the use stage.

Figure 4 GHG emissions by pavement class and life cycle stage.

3.3 Scenarios Analysis

3.3.1 Life cycle GHG emissions under M&R schedule

Optimization of the M&R schedule can achieve reductions in GHG emissions, as shown in Figure 5. Surprisingly, the optimization procedure identified longer maintenance intervals than current practice to reap maximum emissions reductions. Taking highways as an example, an optimal maintenance schedule would foresee a functional maintenance in year 15, whereas current practice is to perform a functional maintenance in year 7 and a structural maintenance in year 14, reducing M&R-related emissions by 87%, while roughness-induced emissions increase by 46%. Overall, a combined reduction in emissions of approximately 40% is achieved for highways and Class 1 pavements. Reductions for Class 2-4 pavements are even higher, at 63%, 70%, and 93%. Corresponding absolute emission reductions are 191 t, 113 t, 135 t, 116 t and 118 t CO2-eq per lane-km. In relative terms, the reduction in emissions for class 2-4 is around 10%.

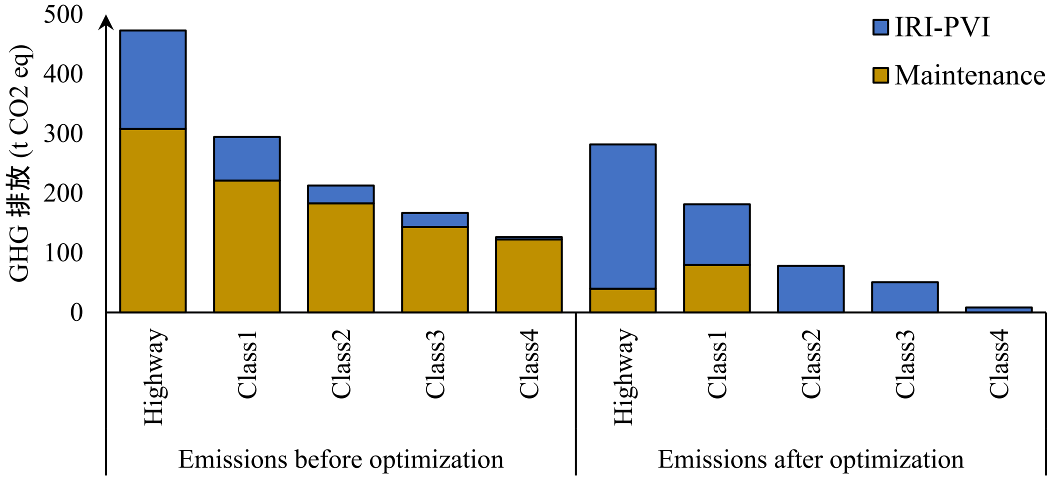
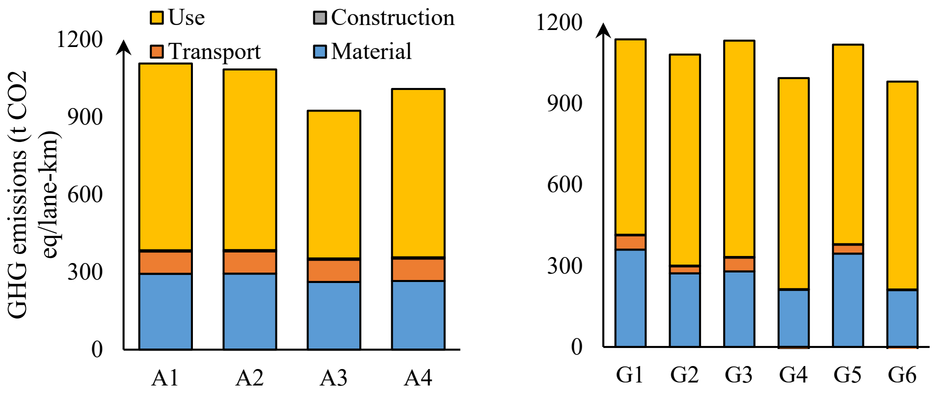


Figure 5. Maintenance and roughness-induced PVI emissions under non-optimized and optimized conditions.

3.3.2 Life cycle GHG emissions under scenarios of alternative low carbon materials

Low-carbon surface and base materials can realize a combined reduction of specific life cycle emissions of up to 16% for highway pavements. The life cycle impacts of replacing surface materials and base materials for highways are shown separately in Figure 6, where the categories "material" and "transport" indicate the total production and transport of materials for both the construction and maintenance stages. For highways, scenarios A2, A3 and A4 can reduce emissions by 2.1%, 16.5%, and 8.9%. Material input, energy demand and stiffness changes are the underlying factors of overall GHG emissions. For example, A3 shows an 11% emissions reduction in the material production stage, whereas A2 achieves only a 0.3% reduction. This is due to the fact that A2 requires lower material inputs but increased energy demand for heating RAP. By contrast, the significantly reduced energy consumption of WMA combined with reduced heating energy requirements for fewer raw materials is responsible for the fact that the largest mitigation potential is achieved in scenario A3. Stiffness change, as shown in table S10, leads to use-phase GHG reductions of 3%, 21% and 10% in the scenarios A2, A3 and A4 respectively. In addition, emissions due to hauling RAP from the demolition site to the plant are offset by its avoided transport emissions from the demolition site to the landfill.



(a) *Surface layer emissions.* *(b) Base layer emissions.*

Figure 6. Highway pavement emissions by life-cycle stage with alternative low carbon materials. A1: Traditional materials and method (HMA); A2: 20% RAP, with 30% of asphalt binder in RAP function as binder; A3: 40% RAP + 3% Sasobit, with 50% of asphalt binder in RAP function as binder; A4: WMA (3%Sasobit). G1: Traditional materials and method with 4.8% cement; G2: 40% RAP with 4.5% cement; G3: 42% RCA with 4.3% cement; G4: 40% RAP + 60% milled granular layer with 4.5% cement; G5: Traditional materials for production + Cold-in-place recycle for structural M&R with 4.5% cement; G6: 40% RAP + 60% milled granular layer for production + Cold-in-place recycle for structural M&R with 4.5% cement.

For highways, the total life cycle GHG reduction under the scenarios G2, G3, G4, G5 and G6 in all stages are 4.9%, 0.4%, 13.4%, 1.7%, and 15.2%. The decline in GHG emissions in base layers mainly stems from the reduction in cement content. Cement production accounts for 71% of the GHG emissions in the original base material production stage. With RAP and RCA, the cement content is reduced from 4.8% to 4.5% and 4.3%, respectively, resulting in a notable decline in GHG emissions. In addition, production of crushed aggregates and gravel represents 14% and 7% of specific GHG emissions, providing carbon mitigation potential for the replacement with RAP or RCA. On the contrary, reduced base layer stiffness increases GHG emissions during the use phase. The other road classes exhibit the same pattern as discussed for highways, see Figure S1 and Figure S2. For Class 1-4 pavements, the G6 scenario achieves the largest reductions in all stages combined, on the order of 19%, 23%, 15%, and 25%, respectively.

3.3.3 Life cycle GHG emission under scenarios of EV adoption

EV adoption only has a modest effect on emission reductions. Figure 7 illustrates the use phase GHG emissions of each highway class with varying assumptions on EV adoption rate, on-board energy use, and carbon intensity of electricity, as specified in Table S11, S12 and S13. Assuming the current electricity mix and average EV energy consumption, use-phase GHG emissions could be reduced by 31, 41 and 50 t CO2-eq/lane-km under scenarios of low, medium and high EV adoption compared to the 100% ICEV scenario, which is labeled as ‘No EV’. The ideal scenario combination of high EV adoption rate, low carbon electricity and reduced energy consumption would yield a 13% use phase emissions reduction. Note that even in the high EV adoption scenario, only 2% of long-haul trucks are assumed to be EV, which partly explains the modest results. While EV replacement would contribute 6%, energy efficiency and electricity de-carbonization would contribute 3% and 4%. For road classes 1-4, use-phase emission reductions are on the order of 11% under the ideal scenario (Figure S3).

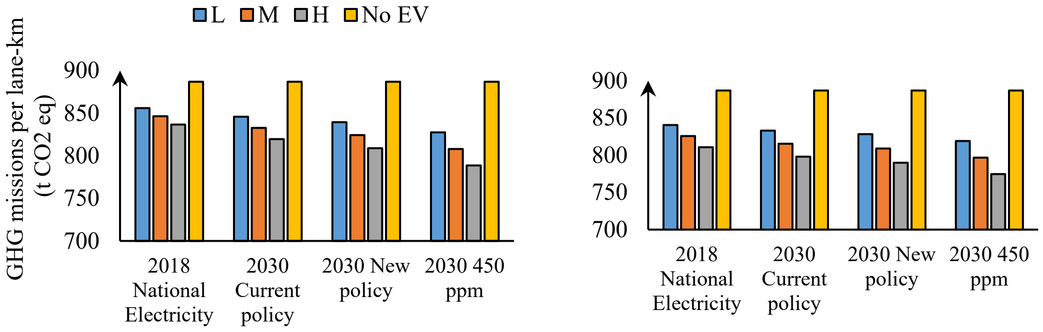


Figure 7. Use-phase emissions under various scenarios of vehicle electrification and electricity-decarbonization, assuming (left) current EV on-board energy use and (right) improved EV energy efficiency . L: low adoption rate of EVs; M: medium adoption rate of EVs; H: high adoption of EVs; No EV: No adoption of EVs.

4. Discussion

This work identified a potential for considerable GHG reductions in the life cycle of pavements in China. The total emissions from new pavement to be constructed in the Shandong province is roughly equivalent to the combustion emissions of 6.5 million of China's most popular vehicle, the VW Jetta, traveling for 15,000 km each year for 10 years (assuming an emissions factor of 151g CO_2/km (DOE, 2020)). Considering that Shandong is already one of the leading provinces in terms of transport infrastructure maturity, there is an urgent need to mitigate these emissions. We find that not only the construction of new pavements is carbon-intensive but also the rehabilitation of the existing pavement stock. In our calculations and projections, the use-phase and M&R stages, which have been commonly neglected in previous research, have the largest contribution to life-cycle emissions per lane-km (more than 60%). Managing these phases in an optimal way can therefore provide a considerable carbon reduction opportunity for the transport sector. The use of alternative materials has a large potential for emission reductions as well, albeit to a lesser degree.

Our results indicate that pavement construction in China is more carbon-intensive per lane-km compared to developed countries. For example, despite the fact that our assumptions on lifespan are much shorter than those of Xu et al., 2019, who study life cycle emissions of pavement construction in the US, we find comparable life cycle emission results for pavements with similar assumptions (i.e. Road 4 in Xu's study vs our Class 1, Road 5 vs. our Class 4), as shown in Figure S5 and Table S14.

The thinner surface layer used for Shandong's pavements and the resulting high deflection-induced PVI indicate an important opportunity for low-carbon pavement design. Assuming a 30% increase in surface layer height, which would be in accordance with the design code and practice of developed countries, would lead to a 23% reduction of deflection-induced PVI emissions. After taking into account the increased material and construction emissions, the net reduction in life cycle pavement emissions are still in the range of around 5 -8%. The findings of this paper support recommendations for further improvements in road quality in China from the perspective of life cycle carbon management (cf. Liu et al., 2020; Wang, 2013).

The substantial carbon reduction potential of the M&R optimization scenario supports the need for further quality assessment of pavements and M&R planning. However, there are still factors that deserve further consideration. One possible criticism of our work is the simplified assumption of constant layer height, which allows for unchanged deflection-induced PVI in our model. In reality, popular M&R methods like overlays can influence deflection-induced PVI with altered layer height. Another potential drawback is the insufficient consideration of the cost of road users, i.e. drivers. Given that user cost is an important factor affecting the economics of road M&R schedule (Chan et al., 2008; Mandapaka et al., 2012; Praticò et al., 2011), the current model may overestimate the potential cost effectiveness. In addition, M&R decisions in China require comprehensive consideration of several indicators(Ministry of Transport, 2018) in addition to life cycle carbon emissions (Figure S6). Finally, although we carefully selected data appropriate for the context of the Shandong province, whenever possible, further context-specific data may be needed in the future, such as emission factors for asphalt materials, sales scenarios for electric vehicles, as well as pavement deterioration curves.

Specific emissions of each stage calculated in this study are generally consistent with existing research, except for a remarkably large gap between deflection-induced PVI and roughness-induced PVI (Akbarian, 2012; Akbarian, 2015; Louhghalam et al., 2017; Xu et al., 2019). The disproportionately high emissions from deflection-induced PVI can be explained by two main factors: (1) the notably thin pavement surface, and (2) the high truck traffic in China. The slow growth of IRI as calculated by the selected IRI model further contributed to the disproportionally high use-phase emissions. However, the academic discussion of IRI prediction models for roads in China is scarce (Wu and Zhou, 2009; Wang and Han, 2007; Zhao et al., 2018).

In practice, pavement design and M&R frequency largely depend on various factors, including local geography, traffic volume, and available construction funds. In this work, simplified assumptions for these factors were necessary due to limited data. Changes in pavement stiffness due to the use of alternative materials should ideally be based on real-world experimental data, which was not available for this work. However, for this study input data was selected with great care based on a synthesis of a large number of mutually independent studies, interviews with engineers, and official government documents. Future research should include albedo effects, which can further influence use phase emissions.

5. Conclusion

The goal of this study was to provide a systematic environmental management perspective on road construction in a Chinese province that can be replicated and widely applied. Pavements cause significant GHG emissions throughout their life cycle. While previous work omitted the use phase, this work demonstrates that it contributes the most to total emissions, followed by material production, and M&R. Optimized pavement structure designs and M&R schedules can substantially reduce life cycle GHG emissions by up to 16% and 11% respectively. Vehicle electrification has a negligible impact on the reduction of use-phase emissions (up to 6%). Carbon management should be incorporated into decision-making for new road planning and M&R.

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