Evaluating the Environmental Impacts of Pavement Maintenance Strategies Based on Life Cycle Assessment

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Abstract. The concept of sustainable development calls for a change of the way about how projects should be appropriate managed. Generally speaking, maintenance management, as an integral part of the whole life cycle asset management, are well developed based on cost effectiveness and performance improvement. Due to the rising recognition of environmental and social concerns, there is a need to include sustainability into the maintenance management of road projects. This paper will innovatively evaluate the environmental impact of road pavement maintenance strategies in Australia through life cycle assessment. Eight pavement maintenance strategies, from asphalt replacement to slurry seal, are investigated. The results show that 2.15 to 9.92 kg CO_2 e/m^2 can be generated by maintenance strategies at the project level. Maintenance stage has relatively low impact on carbon emissions when compared to the construction stage. However, at the network level, the annual monetary value of the carbon emissions from maintenance strategies is estimated to be A$3.27 million, which is significant when compared to the maintenance budget. The results offer useful insights for road authorities to report their performance on sustainability and make relevant maintenance decisions.

1. Introduction

Global climate change has been recognized one of the biggest threats to human development. In order to address the challenge, environmental consideration, especially greenhouse gas emissions, should be integrated into the decision making process of business, individuals and policy makers [1]. Many major initiatives have been developed in the building industry to address the concerns of global climate change, e.g. the green building initiatives [2] and the carbon labelling schemes for construction materials [3].

Road maintenance is a very large sector in Australia. The maintenance expenditure on all roads in Australia in 2013 was A$7.8 billion [4]. The expenditure on road maintenance is expected to increase [4]. However, the expenditure is not adequate to meet the needs of road maintenance, because maintenance and rehabilitation activities can be very resource-intensive [4]. It is forecasted that with the annual reduction of 15% of maintenance funds, a shortfall of A$17 billion can be expected for road maintenance in Australia between 2010 and 2014 [4]. As such, how to effectively conduct

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maintenance, such as selecting maintenance strategies and allocating maintenance funds, is imperative for Australian road authorities.

Road maintenance has been a well-studied research area, especially in using deterioration modelling techniques to predict the pavement performance [5]. Traditional maintenance management decisions are based on the deterioration models, as well as the life cycle cost of various maintenance strategies. For example, four major maintenance strategies, including rehabilitation, overlay, Microsurfacing and slurry seal are investigated in [5]. A network-level budget allocation program was also developed to optimize two indicators, including pavement performance improvement and budget utilization [6]. It should be noted that as sustainability becomes a rising concern, it is important to understand other aspects of road maintenance, such as the environmental impact of road maintenance activities and effectively integrate these aspects into the maintenance management framework.

It is widely acknowledged that maintenance activities should be conducted before road assets deteriorate to achieve long-term performance. Many studies have therefore been conducted on evaluating the deterioration of road pavement. Generally, the deterioration models have been well developed. For example, Markov model has been widely used for deterioration forecasting and performance under the curve can be used as an indicator of the improvement potential of pavement strategies [7].

Over the past few years, a few other important indicators to evaluate the effectiveness of maintenance strategies have also been developed. The environmental impacts of various maintenance activities can be quite different because the inputs of these activities, such as resources and the use of equipment, vary significantly. Life cycle assessment, which is a method to evaluate the environmental outputs of products or processes based on the inputs, can be adopted [8]. A few commonly adopted system boundaries, i.e. the life cycle stages that are included in the assessment, are cradle-to-grave, cradle-to-gate and gate-to-gate. Cradle-to-grave refers to the full life cycle stages, starting from raw materials extraction to final disposal. Cradle-to-gate refers to the life cycle stages, starting from raw materials extraction to the point when the product leaves the production factory. In addition, gate-to-gate refers to the life cycle stages within an organization, such as manufacturing company or supplier. The assessment procedure has four stages, including scope definition, life cycle inventory analysis to list all inputs (i.e. resources) and outputs (i.e. environmental impacts), impact assessment to convert inputs to outputs, and interpretation [9].

Eight pavement maintenance strategies are investigated in this paper, including:

- ASDG - Dense graded asphalt overlay/replacement. This strategy is related to the use of asphalt replacement. The activities include asphalt mixing, paving and compacting. The equipment used in this strategy include asphalt mixing plant, asphalt paver and asphalt compactor. The depth of the asphalt replacement in this strategy is 30mm.
- ASIM – Intersection mix asphalt overlay/replacement. Similar with ASDG, this strategy is related to the use of asphalt replacement and the depth of the replacement is 40mm.
- ASOG – Open graded asphalt replacement. Similar with ASDG, this strategy is related to the use of asphalt replacement and the depth of the replacement is 30mm.
- ASRS – Structural asphalt work. A full depth asphalt (150mm) will be replaced every 50 years and 5% of road placed will need patching and repair every 50 years.
- GrOL – Granular overlay. This strategy refers to granular overlay with spray and seal.
- RipSeal – RipSeal includes a 150mm cement stabilization, 50mm gravel placement and a seal of 10mm.
- Slurry – Slurry/micro surfacing. This strategy is cold mix surface treatment, including a 3-20mm layer of in-situ mixture of aggregate, bitumen, adhesion agents, water and cement.

- CS – Surface dressing. This strategy refers to simple repair or patching by spraying bitumen on a road surface followed by the spreading of a layer or layers of aggregates.

This paper therefore aims to: 1) investigate the environmental impact, in terms of carbon emissions value, of maintenance activities adopted in Australia; and 2) integrate the environmental impact of maintenance activities into the decision making process, such as selecting optimal maintenance activities.

2. Research method

The life cycle assessment approach is adopted to evaluate the environmental impacts of the eight maintenance strategies. The system boundary of the assessment is shown in Figure 1.

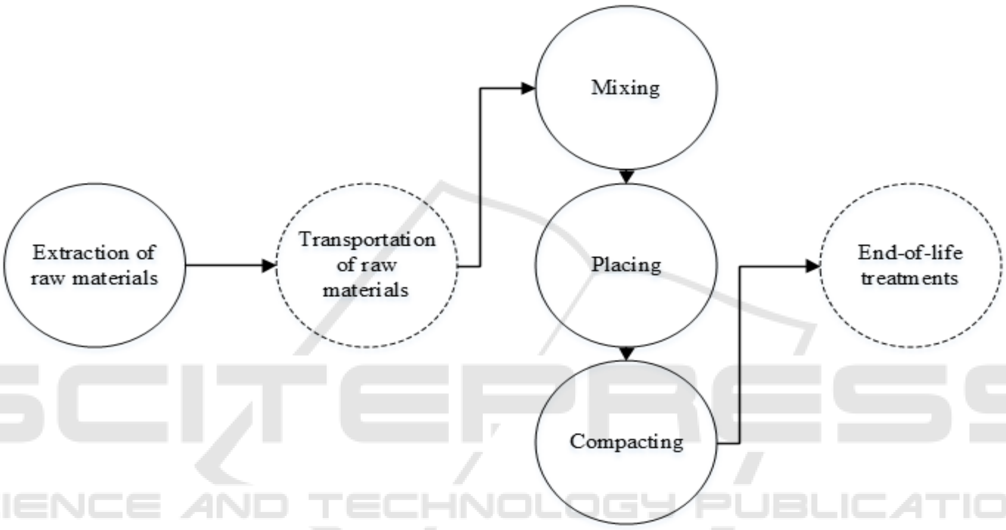

Figure 1. The system boundary of the life cycle assessment study.

As can be seen from Figure 1, this study includes the extraction of raw materials and on-site maintenance activities, but excludes the transportation of raw materials from manufacturing plants to sites, as well as end-of-life treatments. The analysis of the transportation stage requires an estimation of the average transportation distance, on which future studies can help improve the estimation accuracy. The end-of-life treatments involve many uncertainties related to the treatment strategies. These two stages are therefore excluded from this study.

In addition, the functional unit of this study is one square meter of pavement. The Greenhouse Gas Assessment Workbook for Road Projects [10] and the World Bank's study on greenhouse gas emissions mitigation [11] are referred to as the main sources for emission factors. The general equation to estimate the carbon emissions is:

$$C = EF \times Q$$

Where: C refers to the amount of carbon emissions; EF refers to the emission factors of various sources, such as material usage and equipment usage; and Q refers to the quantity of the usage.

2.1. Emission factors

Four commonly adopted construction materials in these maintenance treatment strategies are asphalt, crushed aggregate, gravel and cement. The emission factors of the four types of materials are based on [10] and listed in Table 1.

Table 1. The emission factors of construction materials required in road maintenance.

Materials	Boundary	Unit	Emission factors
Bitumen	Mine to end-of-production	t CO_2-e/t	0.630
Crushed aggregate	Mine to end-of-production	t CO_2-e/t	0.005
Gravel (sand)	Mine to end-of-production	t CO_2-e/t	0.003
Cement	Mine to end-of-production	t CO_2-e/t	0.820

In addition, the emission factors of equipment usage in maintenance activities are calculated, following the recommended factors in [10], [11] and [12]. The emission factors are listed in Table 2.

Table 2. The emission factors of equipment usage in road maintenance.

Materials	Technical specifications	Emission factors or fuel consumption	References
ASDG	Asphalt replacement (30mm)	6.313 L/ m^3	[11]
ASIM	Asphalt replacement (40mm)	6.313 L/ m^3	[11]
ASOG	Asphalt replacement (30mm)	6.313 L/ m^3	[11]
ASRS	Full depth asphalt replacement	4.3 x 10-4 KL/ m^2 (Diesel)	[10]
GrOL	Granular + spray and seal	0.19 L/ m^3	[11]
RipSeal	150mm cement stabilization, 50mm gravel + 10mm seal	0.31 L/ m^3	[11]
Slurry	30mm layer of in-site mixture	2.87kg CO_2-e/ m^2	[12]
CS	Spraying bitumen followed by a layer of aggregates	1.00kg CO_2-e/ m^2	[12]

3. Results

Based on the information provided Main Roads Western Australia, there are 5,007 road sections which have gone through maintenance in 2016. Table 3 presents the treatment areas and number of road sections under each treatment strategy. As can be seen from Table 3, the most commonly adopted treatment strategy is surface dressing with 2,980 road sections. Other commonly used strategies include dense graded asphalt overlay/replacement (ASDG) with 1,077 road sections, ripseal with 261 road sections and intersection mix asphalt overlay/replacement (ASIM) with 254 road sections. Table 4 shows the material consumption rate and cost of the eight maintenance strategies.

Table 3. Background information of the 5,007 road sections under maintenance.

Treatment types	Treatment areas (m^2)	No. of road sections
ASDG	120-107,008	1077
ASIM	78-38,717	254
ASOG	198-98,719	136
ASRS	82-14,672	42
GrOL	84-88,386	169
RipSeal	108-160,066	261
Slurry	270-160,621	88
CS	22-284,520	2980

Table 4. The unit cost and material consumption of maintenance strategies.

Treatment types	Bitumen (L)	Crushed aggregate (m^3)	Gravel (m^3)	Cement (kg)	Unit cost (A$/$m^2$)
ASDG	3.6	0.03	0	0	52.07
ASIM	4.8	0.04	0	0	60.00
ASOG	3.6	0.03	0	0	48.00
ASRS	12	0.1	0	0	138.00
GrOL	1.8	0.0014	0	0	70.00
RipSeal	1.92	0.02	0	0.064	47.00
Slurry	1.8	0.0014	0.05	4.95	12.00
CS	1.8	0.0014	0.15	4.95	5.99

Based on the emission factors presented in Table 1 and Table 2, the carbon emission values of one functional unit (i.e. one square meter of pavement treatment) under the eight treatment strategies are presented in Table 5. As can be seen from Table 5, the carbon emissions value of different treatment strategies vary significantly. Full asphalt replacement (ASRS) has the highest value of carbon emissions (9.92 kg CO_2e/ m^2) due to its high amount of material usage, contributing to 87.5% of the overall carbon emissions generated. On the other hand, other pavement maintenance strategies, such as surface dressing and ASDG, have relatively low carbon emissions value, due to the low amount of material usage. The contribution of material usage to the overall carbon emission values varies from 34.2% (for slurry seal) to 99.3% (GrOL).

Table 5. Emissions of different pavement treatment strategies.

Treatment types	Emissions from extraction (kg CO_2e/m^2)	Equipment usage (l/m3)	Emissions from equipment (kg CO_2e/m^2))	Total emissions (kg CO_2e/m^2)	Environmental cost (A$/$m^2$)	Percentage (%)
ASDG	2.60	6.313	0.55	3.15	0.08	0.16
ASIM	3.47	6.313	0.73	4.20	0.11	0.18
ASOG	2.60	6.313	0.55	3.15	0.08	0.17
ASRS	8.68	Not needed	1.24	9.92	0.26	0.19
GrOL	6.22	0.190	0.08	6.30	0.16	0.23
RipSeal	5.55	0.310	0.04	5.59	0.14	0.31
Slurry	1.49	Not needed	2.87	4.36	0.11	0.94
CS	1.15	Not needed	1.00	2.15	0.06	0.93

4. Discussions

Global climate change has been recognized as an emerging issue that should be integrated in decision making [13]. The issue has already re-shaped the decision making process of many areas. For example, sustainability has been integrated into the decision making system of selecting structural materials [14], including concrete [15] and precast components [16]. As road agencies are now under increasing pressure to report their performance against environmental sustainability criteria, it is important that the environmental emissions of road maintenance activities are accurately and transparently reported [17].

The results of the study indicate that different maintenance strategies have different carbon emission values when being implemented. The results are useful when making relevant maintenance management decisions, especially when considering the impact of potential carbon tax [3]. In 2011, the Australian government introduced the carbon tax as an effective measure to achieve the emission reduction target. Although the carbon tax was abolished in 2014, it provides a useful indicator of the monetary value of carbon emissions in Australia. A carbon tax of A$23 per tonne of carbon dioxide was charged by the Australian Government. An inflation of 2% is assumed to calculate the carbon tax at the time of this study. Based on the carbon tax of A$23 and an inflation of 2%, the carbon tax of Australia in 2017 is calculated to be A$25.90.

The monetary values of emissions from maintenance strategies are shown in Table 5. As can be seen in Table 5, the monetary value of carbon emissions of maintenance strategies are relatively low when compared with the unit cost of the maintenance treatment. The average percentage values vary from 0.16% to 1%. It appears that the environmental cost of the maintenance stage is relatively low when compared to the construction stage. A hybrid input-output analysis was conducted to investigate the energy consumption of road construction [18]. The results show that the embodied energy of concrete road construction is 27.2GJ/m. Based on the emission factors provided by IPCC [19], the estimated carbon emissions from the construction stage of road projects is 251.9 kg CO_2 /m^2 (assuming that the average treatment width is 8m, based on the 5,007 road sections in this study).

5. Conclusions

This study uses the process life cycle approach to investigate the carbon emissions of eight maintenance strategies in Australia. The results indicate that the carbon emission values from maintenance are relatively low when compared to the construction stage. Road maintenance can lead to emissions from 2.15 to 9.92 kg CO_2 e/m^2, which is around 1% of the emissions from construction. As such, it can be usefully concluded that for a single and non-repeating road maintenance project, maintenance strategies have relatively low impact on the carbon emission values of the project at a specific time. However, it should be noted that the life cycle performance of maintenance strategies should be investigated as the strategy can happen multiple times in the road project's life cycle. In addition, the carbon emission values at the network level is not an insignificant number to be overlooked. For the 5,002 road sections, the annual emission value is 126,295 tonne CO_2e, which is equivalent to A$3.27 million. As sustainability has been an emerging issue for all industries, including the building industry [19, 20, 21] and the infrastructure and urban planning [22, 23], it is extremely important that the environmental impact is included in the decision making process.

It should, however, be noted that the emission values calculated in this study are based on a single and non-repeating cycle. In real life cases, a life cycle consideration of maintenance strategies should be conducted. In addition, this study does not evaluate the strategies that can be used to mitigate carbon emissions. Useful methods, such as the lean philosophy [24] and carbon labelled materials [17, 25] can be tested and evaluated.

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