Green Decision Making Framework for Pavement Surface Rehabilitations

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Abstract

Global climate change is influencing decision-making around the world. In Saskatchewan, for instance, Bill 126 has introduced policies governing the control and pricing of Greenhouse Gas (GHG) emissions. This will alter the cost-of-business for large-scale emitters – including, possibly, Saskatchewan Ministry of Highways and Infrastructure (SMHI) – and may, therefore, influence decisions reached. In this study, GHG output and cost estimates are incorporated within a risk-based Life Cycle Costing (LCC) framework to compare two alternative pavement rehabilitation strategies: (i) Hot Mix Asphalt Concrete (HMAC), and (ii) Hot In-place Recycling (HIR). The results suggest that while life cycle costs are expected to be lower for the HIR alternative, the ranking of the two alternatives is not particularly sensitive to differences in – and the uncertainty surrounding – GHG output and cost.

Introduction

In 2009, the Government of Saskatchewan introduced Bill 126 – The Management and Reduction of Greenhouse Gases Act. Through some combination of emissions targets and pricing mechanisms (e.g., carbon emissions pricing and/or cap-and-trade scheme), the Act will influence the costs of business incurred by so-called large-scale emitters – a category of emitters that may include Saskatchewan Ministry of Highways and Infrastructure (SMHI) and/or its larger contractors. In relative terms, such changes are expected to bias decisions in favour of more emissions-friendly roadway design and rehabilitation alternatives.

To test the possible influence of the Act on decision-making within SMHI, a study was contracted to compare the greenhouse gas (GHG) emissions and costs associated with two pavement rehabilitation alternatives for a four-lane divided highway: (i) Hot Mix Asphalt Concrete (HMAC), and (ii) Hot In-place Recycling (HIR). The HMAC alternative involves removing the existing Asphalt Concrete (AC) surface and replacing it with: (i) rubberized AC mat in the driving lane (mixing crumb rubber with the paving material), (ii) conventional AC in the passing lane, and (iii) reclaimed AC for the shoulders and shims. The HIR alternative employed the latest incarnation of HIR technology designed, developed and manufactured in Cut Knife, Saskatchewan. The HIR train is designed to heat, strip, mix (with an admix) and re-lay a fresh AC mat for the driving lanes and shoulders. Each rehabilitation alternative was used in differing pavement resurfacing projects over the course of the study (see pictures 1 and 2). And in each case, field measurement of materials and fuels consumed was recorded to support the subsequent GHG and cost comparison of the alternatives.

The two rehabilitation alternatives were compared, sequentially, using four criteria: (i) GHG emissions (in kg CO_2 equivalent emissions per tonne of AC), (ii) Social Cost of Carbon (SCC, in $ per tonne AC), (iii) total surface rehabilitation project costs (in $ per tonne AC), and (iii) Life Cycle Costs (LCC, in $ per tonne AC). Moreover, since a wide range of supporting data was highly variable (e.g., unit emissions and cost-of-carbon data), the modeling exercise applied sensitivity and risk analyses to explore the influence of uncertainty on the rankings derived. The means and results of the comparison are summarized in the discussion to follow. For a detailed discussion, see the project report [1].

It should be noted that the rehabilitation project undertaken with the latest incarnation of HIR technology was delayed a number of times due to production and performance issues (not unusual where new technology is concerned). These delays affected the collection of field data. Fortunately, a detailed technical review of the HIR process permitted the derivation of materials consumption estimates based on the requirements of the intended surface rehabilitation project [2].

Model

The model employed to compare the HMAC and HIR rehabilitation alternatives is summarized in Figure 1. At the top of the diagram is Life Cycle Cost (LCC) – consisting of total surface rehabilitation project costs and accumulated and residual life cycle costs. Accumulated and residual life cycle costs consist of all costs incurred prior to and following the considered rehabilitation options. For the analysis, it was assumed that the pavement rehabilitation occurred in Year 20 of a 30-year service life. Since Year 20 is essentially the base year of the analysis, all estimated past (accumulated) costs were compounded to Year 20 while all future (anticipated residual) costs were discounted to Year 20. The basic process applied is illustrated in Figure 2 (using the example of a 70mm HMAC overlay at Year 20). Assuming a real annual discount rate of 4.0% (i = 4.0%), the accumulated and residual life cycle costs for each alternative amounted to approximately $298 per tonne AC laid.

Returning to Figure 1, it can be seen that the total surface rehabilitation costs consist of: (i) the Quantities and Cost Estimating (QCE) project costs, (ii) SMHI gravel (material) costs, and (iii) the Social Cost of Carbon. The QCE project costs reflect the internal costing process employed by SMHI to estimate the costs of considered projects. Since the study preceded the cost verification process, pre-tender cost estimates were employed for both the HMAC and HIR alternatives. Gravel material cost estimates were included in total surface rehabilitation costs since the QCE process does not include the implied material cost of gravel obtained from SMHI-operated pits. The Social Cost of Carbon (SCC) is included to effectively internalize the differing cost of GHG emissions associated with each pavement alternative.

Estimates for SMHI gravel material costs were derived by multiplying gravel material consumption (in tonnes, obtained through field measurement) by an implied price mirroring gravel costs from private pits (ranging from $3 to $10 per tonne). Estimates of the SCC were derived by multiplying the unit cost of carbon output (ranging from $0 to $61 per tonne of CO_2 equivalent emissions) by CO_2 equivalent output (CO_2e, in tonnes per tonne AC). In turn, CO_2 equivalent output estimates were derived as a function of: (i) materials use (fuel, gravel, bitumen, etc.), (ii) the Global Warming Potentials (GWP) of differing GHG gases, and (iii) the unit GHG emissions associated with differing paving components. Note that paving components for the HMAC rehabilitation alternative includes rubberized AC, conventional AC and reclaimed AC. Paving components of the HIR alternative includes the HIR train and the admix.

To estimate the GHG emissions associated with each paving component of each rehabilitation alternative, it was necessary to first detail the corresponding process flow diagrams (since the process flow determines the cradle-to-grave consumption of varying GHG-producing hydrocarbons such as diesel fuel, bitumen and waste oil). Consider, for example, the process flow diagram for the conventional AC component of the HMAC alternative (Figure 3). Upstream inputs to the HMAC mobile asphalt plant include the extraction, processing and transport of: (i) Lime, (ii) Bitumen, (iii) Diesel fuel, (iv) Waste oil, (v) Aggregate, and (vi) Mobilization of the plant. Downstream outputs include the transport of the HMAC to the project site and the actual paving process. (Note as well the inclusion of the reclaim AC stockpile in Figure 3.)

The completed process diagrams were subsequently mated to data obtained from various literature sources as well as on-site field measurements from the actual paving projects to estimate the corresponding GHG emissions for each component of each surface rehabilitation alternative. Although the resulting computational process is rather involved, the basic steps of the modeling procedure are fairly straight-forward. The first step in the procedure was to measure the on-site consumption of inputs required to produce each tonne of AC (e.g., tonnes of aggregate required for the HMAC and HIR projects). The process applied to produce and transport each required material input then dictated the type and quantity of hydrocarbon-based fuels consumed (e.g., litres of diesel fuel burned to support the extraction, crushing, transport and use of aggregate within the paving projects). The type and quantity of fuels consumed were then multiplied by estimated unit GHG emissions (e.g., kg of CO_2, CH_4 and N_2O per litre of diesel fuel burned) to derive the total mass of GHG emissions associated with that material input. The Global Warming Potential (GWP) of each greenhouse gas was then multiplied by the estimated emissions to derive a CO_2 equivalent (CO_2e) measure of GHG emissions (e.g., from a global warming perspective, each tonne of CH_4 emitted is equivalent to approximately 25 tonnes of CO_2 emissions). Finally, the GHG emissions estimate for each paving component were then appropriately weighted and averaged to derive a comparable GHG output measure for each rehabilitation alternative (in kg CO_2e per tonne of AC laid).

Since a wide variety of data obtained for this project is subject to uncertainty, the model developed and applied in this project allows the use of Low, Nominal and High estimates for many model variables (e.g., unit gravel costs, unit cost of carbon estimates, unit emissions estimates, etc.). Using Swanson's 30/40/30 Rule [3], discrete probabilities of 30%, 40% and 30% were applied to each of Low, Nominal and High estimates obtained. This permitted the application of sensitivity and risk analyses in the GHG and cost comparisons of the HMAC and HIR alternatives (as illustrated in the Results section of this paper).

The model itself was implemented using Microsoft Excel and Decision Programming Language (DPL) software. The Excel component of the model embedded most of the data and model calculations. The linked DPL component controlled the execution of the Excel component to facilitate sensitivity and risk analyses. Ultimately, this allowed the derivation and comparison of risk profiles and expected value results for each rehabilitation alternative – our basis for ranking the competing rehabilitation alternatives in the context of uncertainty.

Data

A wide variety of data was collected to satisfy the requirements of the model. These include: (i) Material inputs data gathered from field observations (HMAC project) and extrapolation from technical reviews and project requirements (HIR project), (ii) Unit GHG emissions data translating material inputs, ultimately, to CO_2, CH_4 and N_20 emissions estimates, (iii) Unit GWP factors translating emissions estimates to CO_2 equivalent (CO_2e) emissions measure, (iv) Unit cost of carbon data translating CO_2e estimates to comparable, dollar-valued SCC estimates, (v) Pre-tender project cost data obtained from the SMHI QCE process, (vi) Gravel material price estimates based on comparable prices at private pits, and (vi) Residual and accumulated LCC data for structural pavements obtained from SMHI. Since a vast quantity of data was gathered for the purposes of this project, we review only sample instances in the discussion to follow. For a complete review, see the project report [1].

Table 1 provides a sample of the field data collected during the HMAC surface rehabilitation project near Piapot, Saskatchewan. In this case, the data pertains to the delivery and consumption of diesel fuel within the mobile asphalt plant (asphalt plant inputs also include waste oil, bitumen, lime and aggregate – as well as crumb rubber and reclaimed AC where required). As can be seen, the volume of diesel fuel consumed by generators and loaders is combined with the volume of diesel fuel consumed by trucks used to deliver the fuel to the mobile plant in order to estimate total diesel fuel consumption for the purpose of producing asphalt. Moreover, the recorded consumption is divided, approximately, across the differing pavement components produced (i.e., rubberized AC, conventional AC, and reclaimed AC) and subsequently totalled (or averaged) across the project as-a-whole. Combining such field data with unit GHG emissions data and GWP factors allows the derivation of the CO_2e output estimates sought. Repeating this field data collection and computational exercise for all fuel types and processes illustrated in the process flow diagrams allowed the derivation of CO_2e output estimates for the entire project.

Notice that the data in Table 1 includes no Low or High estimates. In general, the field data collected accurately reflects the consumption of hydrocarbon-based fuels during the course of the project. And, in the case of the HIR project, the estimates derived were well-supported by detailed technical review of the HIR process and actual requirements of the intended surface rehabilitation project. Therefore, little uncertainty surrounds the estimates obtained.

While the field data collected is known with some certainty, the same cannot be said for the unit GHG emissions data obtained from various literature sources [4, 5, 6, 7, 8]. Based on our survey, for example, we found that the cradle-to-gate CO_2e output associated with diesel fuel production varied from 0.32 kg CO_2e / litre to 0.56 kg CO_2e / litre (see Table 2 for relevant sample data). Moreover, the production of various greenhouse gases through combustion the delivered diesel fuel varies according to equipment type (e.g., truck versus loader versus generator) and across literature source. In any event, the uncertainty in unit GHG estimates translates – when combined with GWP factors – to uncertainty across the CO_2e output estimates. For example, as shown in Table 2, CO_2e estimates for diesel fuel combustion by semi-trailer tractors vary from approximately 2.59 kg CO_2e / litre to 2.93 kg CO_2e / litre. Notice that the Nominal values reported in Table 2 correspond to the most common estimates found while the Low and High values correspond to outlier values.

In general, although some uncertainty surrounds GWP estimates, most studies reviewed for the purposes of this project tend to agree on the likely warming potentials of CH_4 and N_20 relative to CO_2 [4, 5, 6, 7, 8]. The GWP for CH_4 is approximately 21 to 25 times that of CO_2 (in other words, the warming potential associated with a single tonne of CH_4 emissions equates to approximately 25 tonnes of CO_2 emissions). And the GWP for N_2O is approximately 298 to 310 times that of CO_2.

A particularly interesting result of the literature review surrounds economic estimates of the unit cost of carbon. An exhaustive summary of peer-reviewed literature by Tol [9] suggests that the unit cost of carbon – from society's standpoint – varies approximately between $0 and $61 per tonne of CO_2e output (with a modal value of approximately $14 per tonne of CO_2e output and a mean value of approximately $20 per tonne CO_2e output). (In fact, the variability in estimates reported by Tol is even wider. Study participants approximated the values lying within a 95% confidence interval for the purposes of this project.) The economic rationale and techniques employed to derive these estimates are somewhat involved. Interested readers may refer to work by Pearce [10] for an excellent review. Through discrete approximation of the statistical results derived by Tol, the unit cost of carbon estimates (in $ per tonne CO_2e emitted) and corresponding probabilities employed in this study to derive Social Cost of Carbon (SCC) estimates were: (i) $0 (7%), (ii) $7 (23%), (iii) $14 (40%), (iv) $38 (23%), and (v) $61 (7%).

As noted previously, the Quantities and Cost Estimating (QCE) process employed by SMHI does not include a material cost for gravel when aggregate is taken from SMHI pits. Nonetheless, such costs must be included since gravel is clearly not a "free" resource. In this project, unit gravel (material) cost estimates employed were based on the participants' knowledge of aggregate pricing at private pits. Since private sector prices are highly variable, values of $3, $5 and $10 dollars per tonne were used, respectively and the Low, Nominal and High estimates in the costing analysis undertaken.

All other project-related costs (i.e., cost estimates not involving GHG emissions or aggregate materials) were derived from pre-tender bid estimates summarized within the SMHI QCE process. The estimated project-related costs for the HMAC surface rehabilitation alternative reached approximately $117 per tonne AC. In contrast, the estimated project-related costs for the HIR surface rehabilitation alternative reached approximately $96 per tonne AC. Although there is undoubtedly uncertainty surrounding these costs (particularly in the case of the newer HIR technology), no attempt was made to capture this uncertainty since the principal focus of the investigation involves the relative influence of GHG-related costs on agency decisions.

As discussed above, the accumulated and residual LCC estimate applicable to both rehabilitation alternatives is $298 per tonne AC. As illustrated in Figure 2, the rehabilitation alternatives are assumed to take place in Year 20 of a 30-year service life for an AC pavement. For this reason, a real annual discount rate of 4.0% was applied to compound costs incurred in the past and discount costs likely to occur in future. As in the case of other project cost estimates, no attempt was made to capture the potential uncertainty in these estimates since the principal focus of the investigation involves the influence GHG-related costs on Ministry decisions.

Results

As noted previously, the two rehabilitation alternatives were compared, sequentially, using four criteria: (i) GHG emissions (in kg CO_2 equivalent emissions per tonne of AC), (ii) Social Cost of Carbon (SCC, in $ per tonne AC), (iii) total surface rehabilitation project costs (in $ per tonne AC), and (iii) Life Cycle Costs (LCC, in $ per tonne AC). The corresponding results – expressed in terms of expected values and corresponding risk profiles – are reviewed below.

Table 3 presents the expected value (i.e., statistical mean) results in terms of GHG emissions for the HMAC and HIR rehabilitation alternatives and associated paving components. As expected, the HIR rehabilitation alternative generates lower GHG emissions than the comparable HMAC alternative. However, the difference is only on the order of about 25% (i.e., 53.6 kg CO_2e per tonne AC versus 66.3 kg CO_2e per tonne AC). While the HIR train itself is quite economical from a GHG perspective, the admix employed generates little net gain compared against the rubberized or conventional AC of the HMAC process. (Note that SMHI is anticipating a shakedown of HIR equipment on Highway 14 during the spring of 2013. An attempt will be made to use the equipment with no admix. This may result in adjustments to the top lift HMAC thickness to offset the loss of admix. If this approach proves satisfactory, then, on balance, we would expect that the GHG emissions of the HIR process would fall further.)

As illustrated by the risk profiles (cumulative probability distributions) of Figure 4, the variability surrounding the GWP factors and – in particular – the unit GHG emissions data can substantively influence the range of likely CO_2e output for each surface rehabilitation alternative (but especially in the case of the HMAC alternative). However, we can see that the variability is insufficient to sway the ranking of the two alternatives (i.e., from a GHG standpoint, the HIR alternative stochastically dominates the HMAC alternative).

Table 4 adds expected value Social Cost of Carbon (SCC) estimates to the carbon output estimates of Table 3. Naturally, since the carbon output expected of the HIR alternative is lower than the carbon output expected of the HMAC alternative, the SCC of the HIR alternative is, on average, lower than the SCC of the HMAC alternative (i.e., an average of $1.07 per tonne AC versus an average of $1.33 per tonne AC). Notably, however, the scale of advantage for the HIR alternative in this regard is critically influenced by the cost of carbon assumed (in $ per tonne CO_2e emitted). This observation is illustrated by the risk profiles of Figure 5. At a unit carbon cost of $0 per tonne CO_2e emitted, the SCC for both rehabilitation alternatives is, logically, $0 per tonne AC. As the cost of carbon estimates climb upwards, however, the "gap" separating the two risk profiles widens. At an assumed carbon cost of $61 per tonne CO_2e emitted, for example, the SCC gap widens to approximately $1.00 per tonne AC (the difference between approximately $4.50 per tonne AC for the HMAC alternative and approximately $3.50 per tonne AC for the HIR alternative). Indeed, the uncertainty surrounding the unit cost of carbon clearly dwarfs the influence of uncertainty surrounding unit GHG emission and GWP factor estimates. *It is the contentious cost of carbon output rather than the variability in unit GHG emissions that more strongly influences the relative advantage of HIR over HMAC in this regard.*

Table 5 adds the project cost and Life Cycle Cost (LCC) results of the analysis to Table 4. As can be seen, the project costs alone clearly dwarf any differences in the Social Cost of Carbon (SCC) between the two rehabilitation alternatives. Even at a High cost of $61 per tonne CO_2e emitted, the relative advantage of HIR over HMAC is very small. Other project costs (including an implied price for gravel sourced from SMHI pits) simply overwhelm any differences in the SCC estimates for the two alternatives. And, based on pre-tender estimates, the project costs of the HIR alternative are substantively lower than the pre-tender estimates for the HMAC alternative. Similar observations apply to the LCC results (where only project averages apply). Any difference in SCC between the two rehabilitation alternatives is virtually lost in the context of total life cycle costs for the pavement structure undergoing surface rehabilitation. While this observation is not intended to discourage good stewardship in the context of environmental concerns, it merely points out that the relative advantage of HIR in this regards is somewhat minute in the context of all costs incurred to construct and maintain pavement structures over their service lives.

With this in-mind, we see that project cost estimates are clearly more critical to the decision-making process than any differences in GHG emissions and associated carbon costs. So, logically, one would expect that any uncertainties in project cost estimates – particularly for a relatively new and only recently tested HIR technology – would be expected to dominate uncertainties surrounding, for example, unit GHG emissions and cost of carbon estimates.

Hence, future investigations may well benefit from an analysis of uncertainty across the project cost estimates associated with novel technologies.

Concluding Remarks

The purpose of this study was to compare differing pavement surface rehabilitation alternatives in the context of cost as well as GHG emissions (a study motivated, in part, by the introduction of GHG legislation in Saskatchewan that may lead to explicit pricing of GHG emissions). Two alternatives were compared (both employed in actual surface rehabilitation projects in Saskatchewan): (i) a HMAC alternative consisting of a rubberized AC driving lane, conventional AC passing lane and reclaimed AC for the shoulders and shims, and (ii) a Hot In-place Recycling (HIR) alternative based on the latest incarnation of HIR technology. Ostensibly, the HIR train and relatively limited material requirements was expected to generate both lower cost and GHG emissions than the HMAC alternative. The questions are: (i) How much of a difference? and (ii) How likely is this to influence decision-making within SMHI?

As the results clearly indicate, the HIR alternative appears, on average, to reduce cradle-to-grave GHG emissions by about 25%. In economic terms, however, that advantage translates to a mere $0.26 savings per tonne of AC produced and laid (the average SCC estimate for the HIR alternative is approximately $1.07 per tonne AC whereas the average SCC estimate for the HMAC alternative is approximately $1.33 per tonne AC). Such savings are dwarfed by the total costs of the two projects – estimated at $98 per tonne AC for the HIR alternative and $123 per tonne AC for the HMAC alternative. These results suggest two things: (i) while the pricing of GHG emissions may influence the costs incurred by SMHI or major contractors (as a large-scale emitters), its relatively minute impact on costs is unlikely to sway decisions one way or another, and (ii) in relative terms, any uncertainties in the QCE costing process are likely to overwhelm any uncertainties in GHG estimates and related carbon costs (particularly where novel technologies are introduced and applied). This suggests a role for such techniques as sensitivity and risk analysis within cost estimating procedures.

References

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Picture 1. HIR surface rehabilitation project in Saskatchewan, Summer 2011 (HIR pug-mill and paver in centre; HIR heater-scarifier unit on far right).

Picture 2. Mobile asphalt plant used in HMAC surface rehabilitation project in Saskatchewan, Summer 2010.

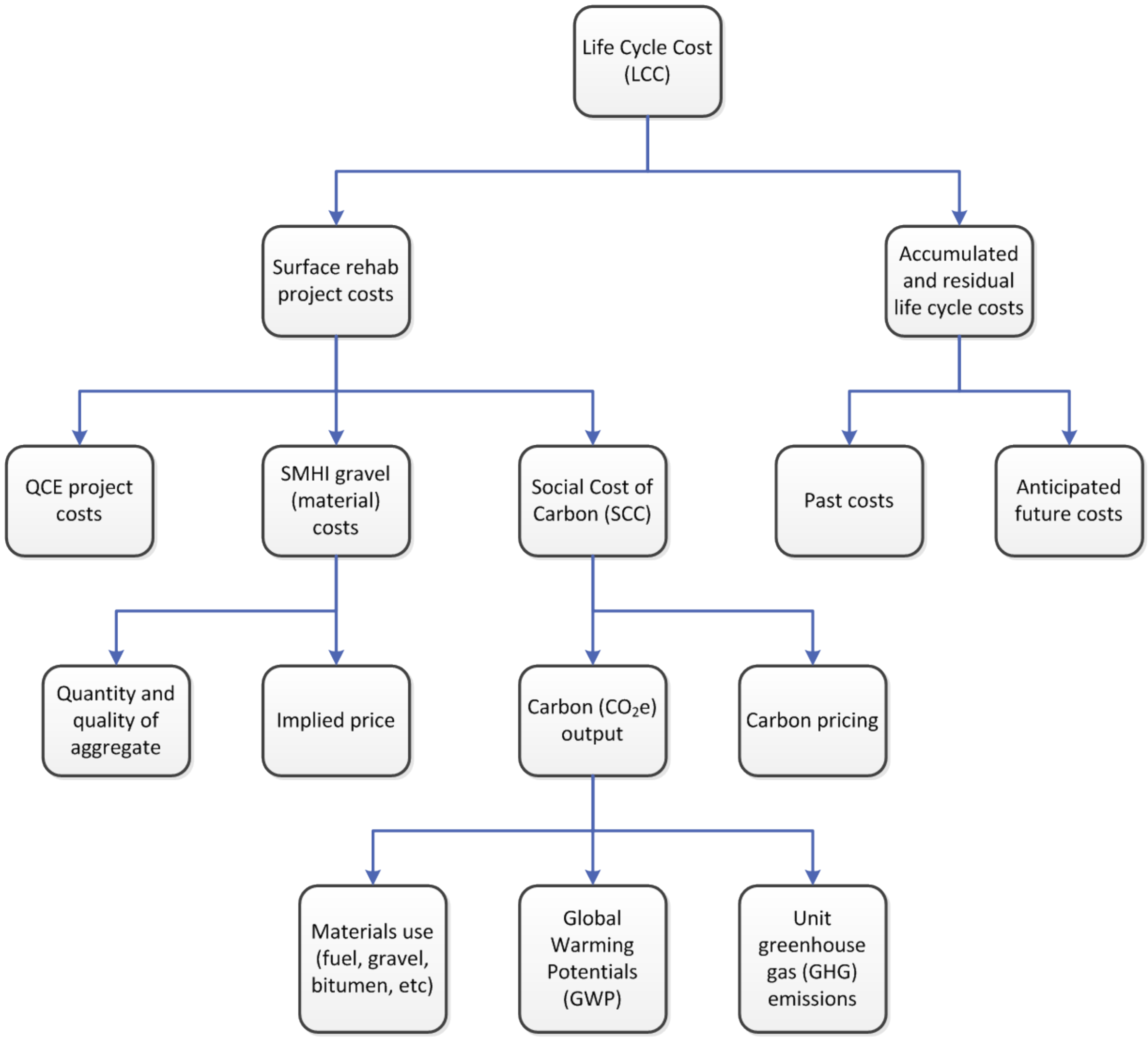

Figure 1. Model design.

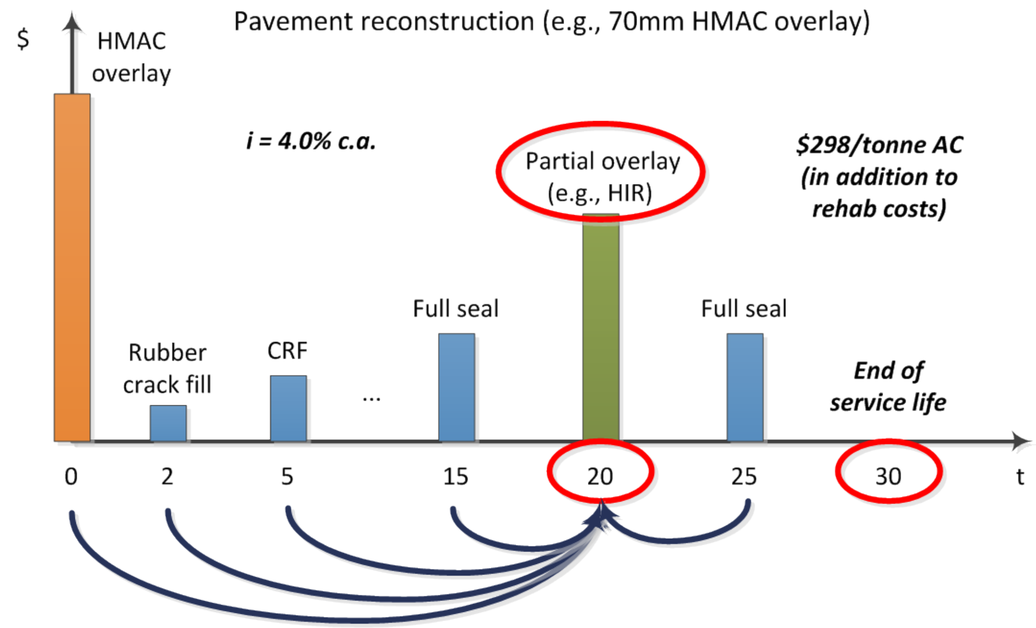

Figure 2. Method of estimating Life Cycle Costs for base Year 20.

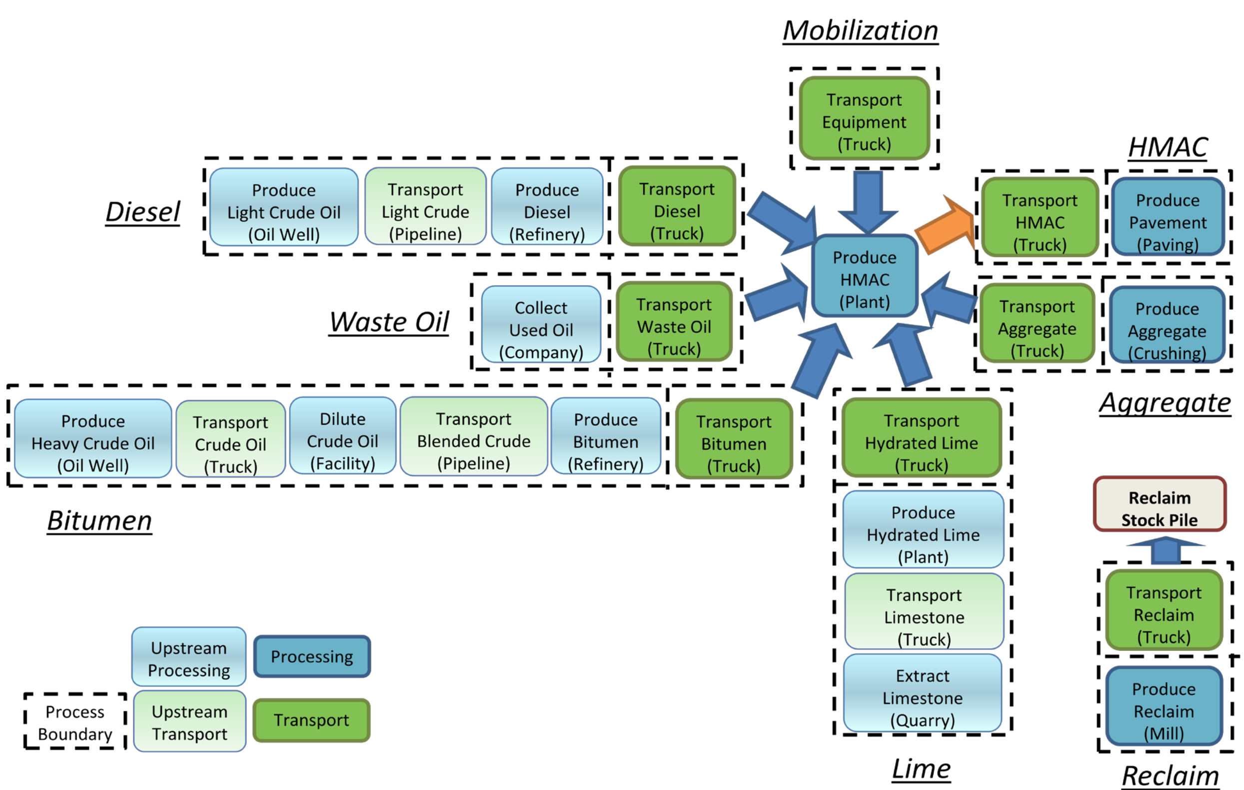

Figure 3. Process flow diagram for conventional AC component of HMAC rehabilitation alternative.

Table 1. Sample field data collected during HMAC pavement surface rehabilitation project.

Description	Units	Rubberized AC	Conventional AC	Reclaim AC	Project Average
Inputs					
Asphalt Plant					
Diesel (Asphalt Plant Generators) - Process 2					
Large Generator - Total Diesel Used	Litres	13,600	7,600	3,100	24,300
Small Generator -Total Diesel Used	Litres	4,950	0	0	4,950
Loader - Total Diesel Used	Litres	3,600	3,400	2,200	9,200
Delivery Distance of Diesel (One Way)	Km	50.0	50.0	50.0	50.0
Fuel Used (One Way)	Litres	15.0	15.0	15.0	15.0
# of Deliveries	Deliveries	5.0	4.0	2.0	11.0
Truck Capacity	Litres	17,000	17,000	17,000	17,000

Table 2. Sample unit GHG emissions data.

Diesel - Process 2	Units	Low	Nominal	High
Cradle to Gate Diesel	**kg CO_2e/litre**	**0.32**	**0.39**	**0.56**
Density of Diesel	tonnes/litre	0.00085	0.00085	0.00085
GHG Transportation (Diesel - Semi's)				
CO_2	kg CO_2/litre	2.561000	2.701000	2.905000
CH_4	kg CH_4/litre	0.000140	0.000140	0.000140
N_2O	kg N_2O/litre	0.000082	0.000082	0.000082
CO_2e	**kg CO_2e/litre**	**2.588936**	**2.728936**	**2.932936**

Table 3. Expected value carbon output results.

Rehab project & components	CO_2e (kg/ tonne AC)
HMAC	
- Rubber AC	74.3
- Conventional AC	73.0
- Reclaim AC	42.4
- Project average	**66.3**
HIR	
- HIR train	43.1
- Admix	63.5
- Project average	**53.6**

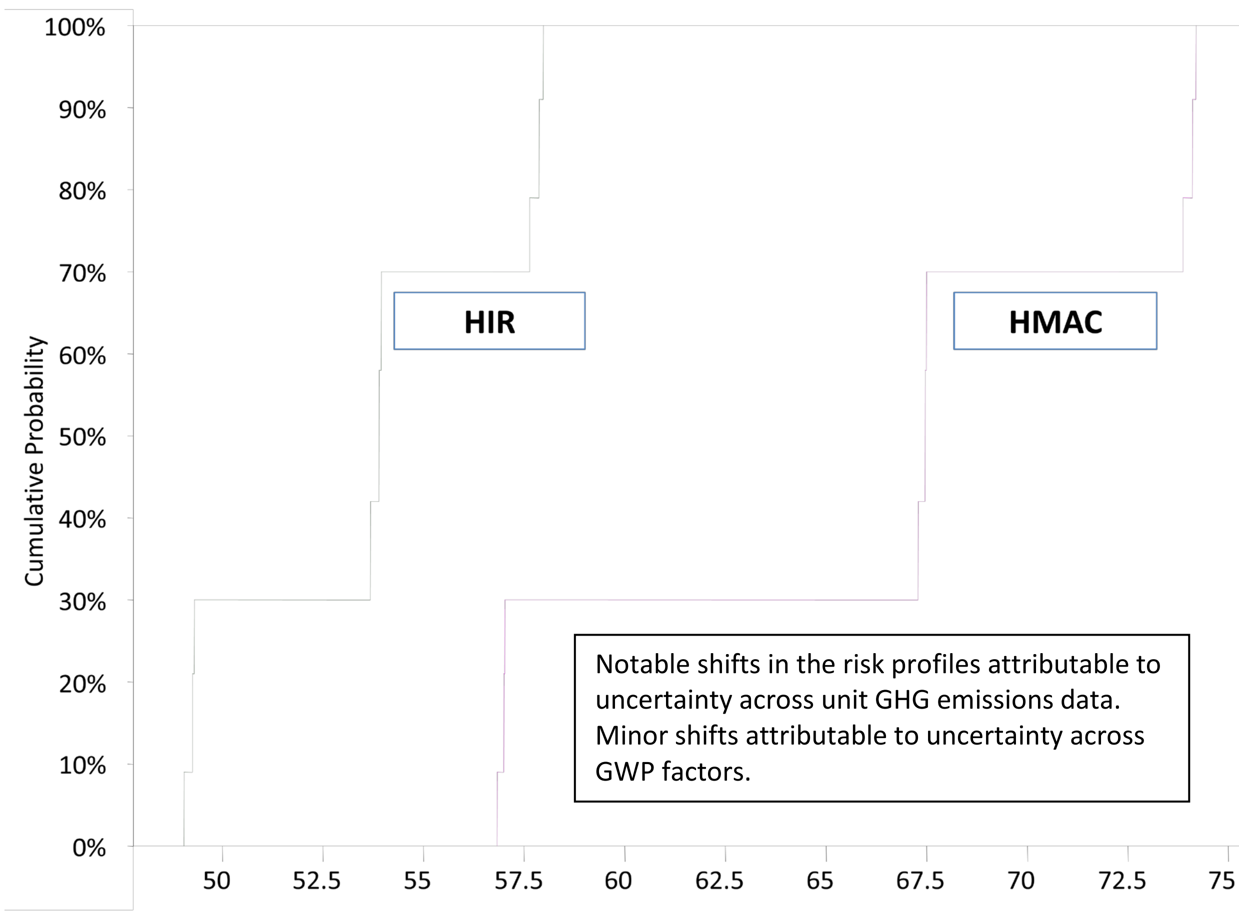

Figure 4. Risk profiles of carbon output results (in kg CO_2e / tonne AC).

Table 4. Expected value carbon output and SCC results.

Rehab project & components	CO_2e (kg/ tonne AC)	SCC ($/ tonne AC
HMAC		
- Rubber AC	74.3	1.48
- Conventional AC	73.0	1.46
- Reclaim AC	42.4	0.85
- Project average	**66.3**	**1.33**
HIR		
- HIR train	43.1	0.86
- Admix	63.5	1.27
- Project average	**53.6**	**1.07**

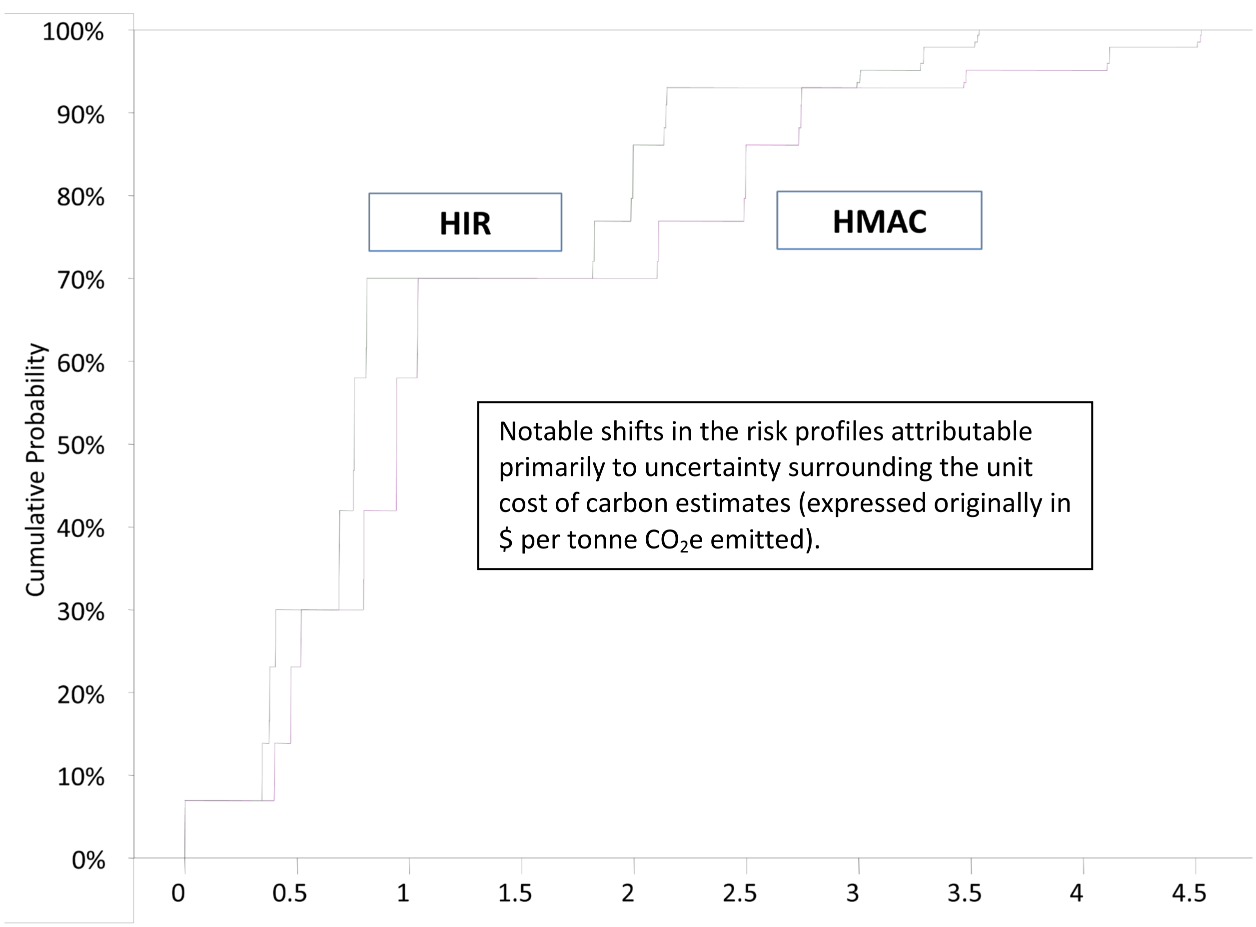

Figure 5. Risk profiles of Social Cost of Carbon (SCC) results (in $/tonne AC).

Table 5. Expected value results and rankings.

Rehab project & components	CO_2e (kg/ tonne AC)	SCC ($/ tonne AC	Project ($/ tonne AC	LCC ($/ tonne AC
HMAC				
- Rubber AC	74.3	1.48	158	n/a
- Conventional AC	73.0	1.46	106	n/a
- Reclaim AC	42.4	0.85	94	n/a
- Project average	**66.3**	**1.33**	**123**	**421**
HIR				
- HIR train	43.1	0.86	96	n/a
- Admix	63.5	1.27	107	n/a
- Project average	**53.6**	**1.07**	**98**	**396**