QUANTIFYING ENERGY CONSUMPTION AND CARBON DIOXIDE EQUIVALENT GENERATION IN TYPICAL ROADWAY CONSTRUCTION PROJECTS

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ABSTRACT

All roadway agencies monitor and maintain their infrastructure as it deteriorates over time. Agencies allocate the money that they have for maintenance, rehabilitation and reconstruction operations across their entire network. Regular and timely maintenance and rehabilitation treatments can postpone the need for reconstruction on a roadway.

The need for infrastructure sustainability has been brought to the forefront of society and has become an important part of any public agency's decision making processes. To achieve sustainable roadways social, economic and environmental benefits must be achieved while maintaining technically sound solutions. By considering the amount of energy that is consumed and the amount of greenhouse gas (GHG) emissions generated through various roadway treatments, sustainability can be brought into the decision making process.

The objective of this research was to develop a probabilistic model that quantifies the amount of energy that is consumed and carbon dioxide equivalents (CO_2e) generated for typical roadway construction, maintenance, rehabilitation and reconstruction projects in Saskatchewan and Alberta.

The model constructed within this work was divided into three sub-models: 1) material production, 2) equipment usage and 3) material transport. For every variable that was required to be entered into each sub-model, a low, average or most likely and high value was determined. By using a range of input values the uncertainty of the values entered was incorporated and sensitive parameters were identified.

A base case study of a one lane-kilometer (lane-km), 3,700 m^2, section of rural roadway was analyzed. For the initial construction of a lane-km of traditional flexible pavement roadway it was determined that 1,870 GJ (giga joules) of energy is required. Based on an annual average amount of energy used per home in Saskatchewan, 126 GJ/year, 1,870 GJ would power

approximately 15 homes for one year. Similarly it was determined that 152.4 tonnes (t) CO_2e are emitted for the construction of a lane-km of traditional flexible pavement roadway. Based on an average CO_2e generation value of 5.1 t per passenger vehicle per year the GHG emissions generated from the construction of a lane-km of roadway is equivalent to the GHG emissions released by approximately 30 passenger vehicles over one year. It was also determined that the volume of CO_2e generated for initial construction compared to the volume of material in the roadway was a ratio of 30 to 1.

The base case study also reviewed various maintenance, rehabilitation and reconstruction treatments for the amount of energy consumed and GHG emissions generated for one lane-km. From the modeled values it was found that the order of energy consumed and CO_2e generated from least to greatest for maintenance treatments is: fog seal, slurry seal, micro surfacing, single, double and triple chip seal and ultra thin overlay. For rehabilitation and reconstruction treatments the order of energy consumed and CO_2e generation from least to greatest is: cold in-place recycling, mill and fill, full depth reclamation, remove and replace with recycled materials and remove and replace with virgin materials.

Through a sensitivity analysis of the input parameters, it was observed that for maintenance treatments the sensitive parameters were the equipment efficiency (EFE) value, the placement rate of the treatment, the aggregate application rate and the amount of asphalt binder included in the treatment. For rehabilitation and reconstruction treatments, the two most sensitive parameters were the asphalt concrete plant energy and the application rate of the Portland cement.

Further investigation into how each sub-model contributed to the overall amount of energy consumed and CO_2e generated found the production of materials contributed the greatest to the overall values. When examining the production of each layer in a traditional flexible pavement roadway structure, the asphalt layers contributed the greatest to the energy consumed at 72.1 percent of all materials produced. The asphalt layers also contributed the greatest to the GHG emissions generated from the production of materials at 42.7 percent. Further breaking down the production of the asphalt layers, the energy requirements at the hot mix asphalt concrete plant account for 75.9 percent of the energy consumed and 52.0 percent of the CO_2e generated for the production of the materials of the asphalt layers.

The cost of each treatment was reviewed based on the cost of diesel at $1.21/litre and the amount of energy consumed. The costs of energy for the maintenance treatments ranged from $174/lane-km for fog seal to $5,488/lane-km of the ultra thin overlay. The cold in-place recycling and mill and fill rehabilitation treatments had energy costs of $13,545 and $21,440/lane-km respectively. The costs of the energy consumed for the reconstruction treatments ranged from $21,710/lane-km for full depth reclamation and $71,164/lane-km for remove and replace with virgin materials. Based on a review of the City of Saskatoon’s 2012 proposed treatment plan for its roadway network the cost of energy was estimated at $1,232,000 for work on 93 lane-km of roadway.

The costs of GHG emissions were also determined based on the amount of CO_2e generated and the value of one tonne of carbon on the voluntary carbon credit market at $6/tonne. The costs of carbon for the maintenance treatments ranged from $3/lane-km for fog seal to $64/lane-km for the ultra thin overlay. For the rehabilitation treatments the cost of carbon for the cold in-place recycling was $224/lane-km and $266/lane-km for the mill and fill treatment. The reconstruction treatments ranged from $524/lane-km for full depth reclamation and $1,062 for remove and replace with virgin materials.

Finally four field case studies were reviewed to determine the amount of energy consumed and GHG emissions generated through construction. The first was the reconstruction of Range Road 232, a rural roadway with virgin materials. The second was the reconstruction of Kenderdine Road with recycled materials. The energy consumed and GHG emissions generated for these construction projects are 1,917 and 1,146 GJ/lane-km, and 150.3 and 92.6 t CO_2e/lane-km, respectively. The third case study further reviewed the use of warm mix asphalt concrete (WMAC) and the use of recycled asphalt pavement (RAP) in the Kenderdine Road pavement structure. This research determined that with the incorporation of WMAC and 10 percent RAP in the asphalt layers and with the use of recycled materials in the base layers the amount of energy consumed would be reduced by 31.8 percent and the GHG emissions reduced by 34.8 percent compared to a traditional virgin pavement structure. The final case study reviewed the City of Saskatoon's 2012 proposed roadway restoration and reconstruction plan. From the model it was found that 38,281 GJ of energy was consumed and 2,617 t CO_2e was generated.

This work shows that the probabilistic model developed in this research may be applied to a variety of roadway treatments from maintenance to reconstruction in urban and rural applications. With the use of the model, roadway project managers can make informed decisions for roadway treatments based on energy consumption and GHG emission generation values. By incorporating the amount of energy that is consumed and GHG emissions generated into the decision making process of roadway infrastructure management, more sustainable infrastructure management can be achieved.

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LIST OF ABBREVIATIONS

ACB: asphalt concrete base
AC: asphalt cement
ACon: asphalt concrete
ACO: asphalt concrete overlay
Avg: average
CAC: Cement Association of Canada
CCS: cement stabilized subgrade
CFCs: chlorofluorocarbons
CH_4: methane
CHANGER: Calculator for Harmonized Assessment and Normalisation of Greenhouse Gas Emissions for Roads
CIPR: cold in-place recycling
CO: carbon monoxide
CO_2: carbon dioxide
CO_2e: carbon dioxide equivalent
DPL: Decision Programming Language
EFE: equipment efficiency
Eurobitume: European Bitumen Association
FC: fuel consumption
FDR: Full Depth Reclamation
FHWA: Federal Highway Administration
FW: fuel weight
g: grams
GBC: granular base coarse
GJ: Gigajoule
GHG: Greenhouse Gas
GHGs: Greenhouse Gases
GreenLITES: Green Leadership in Transportation and Environmental Sustainability
HCl: hydrochloric acid
HFCs: hydrofluorocarbons
HMAC: hot mix asphalt concrete
HP: horsepower
HPF: horsepower factor
INVEST: Infrastructure Voluntary Evaluation Sustainability Tool
IRF: International Road Federation
kg: kilogram
km: kilometer
l: liter
LEED: Leadership in Energy and Environmental Design
m^2: square meter
m^3: cubic meter
MJ: Mega Joule
ML: most likely
mm: millimeter
Mt: megatonne

MTO: Ontario's Ministry of Transportation
N_2O: nitrous oxide
NO_x: mono-nitrogen oxides NO and NO_2
NYSDOT: New York State Department of Transportation
PaLATE: Pavement Life Cycle Assessment Tool for Environmental and Economic Effects
PCC: Portland Cement Concrete
PFCs: perfluorocarbons
PM_{10}: particular matter 10
PMBs: polymer modified binders
RAP: reclaimed asphalt pavement
RR: Range Road
R&R: remove and replace
SBS: styrene butadiene styrene
SF_6: sulphur hexafluoride
SO_2: sulphur dioxide
TJ: terra joules
t: metric tones
UNFCCC: United Nations Framework Convention on Climate Change
U.S.: United States of America
US EPA: US Environmental Protection Agency
WBCSD: World Business Council for Sustainable Development
WMAC: warm mix asphalt concrete

Chapter 1

INTRODUCTION

1.1 Background

The affluence of societies can be related to the quality and reliability of the infrastructure on which the society is built. From an infrastructure utility perspective, roads are key to the success of all modern societies as they are used to transport people and to distribute consumer goods (Queiroz and Gautam 1992). As roadway infrastructure ages increase, maintenance and rehabilitation are required to ensure that the infrastructure maintains a minimum level of service that is safe for the motoring public and preferably providing an optimized end value of transport utility.

In Canada, most provincial and municipal jurisdictions are facing an infrastructure crisis where a significant amount of infrastructure is in need of rehabilitation. Historically, sufficient funds have not been available to complete the work that is needed to maintain all roadways to a desired level of service (Mirza and Haider 2003).

After World War II, Canada's population increased significantly and continues to increase, resulting in the need for large amounts of new infrastructure to be constructed. In the past, significant funds have been spent on new infrastructure, causing less money to be available for the rehabilitation and maintenance of the existing infrastructure, leading to an infrastructure deficit. Currently many jurisdictions are facing an increasing infrastructure deficit where the funds provided by jurisdictions for rehabilitation and maintenance are not increasing at the same rate that the infrastructure is deteriorating (Mirza and Haider 2003).

In 1987, the Brundtland Commission identified the need for sustainability to be brought to the forefront of the infrastructure profession (Brundtland 1987). The Brundtland Commission indicated that development can be made sustainable by ensuring "*that it meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland 1987).

Further, to achieve the objective of the Brundtland Commission, there must be net positive benefits to the social, environmental and economical aspects of an infrastructure project. Therefore, it is becoming increasingly important to implement sustainable solutions for roadway infrastructure rehabilitation and construction in a more encompassing framework than has traditionally been used in the past.

In 1992, world leaders met in Rio de Janeiro for the Earth Summit where the United Nations Framework Convention on Climate Change (UNFCCC) was created to stop the increase in greenhouse gases (GHGs) in the atmosphere (May and Caron 2009). The UNFCCC adopted a precautionary principle, meaning that it must act on the belief that although it is not certain that climate change is anthropogenic (man-made), action must be taken (May and Caron 2009). This research makes the assumption that anthropogenic GHG generation contributes to climate change even though this assumption is currently being debated (Labohm et al. 2004).

Greenhouse gases are created naturally in the environment through volcanic eruptions, released from oceans and decaying forests (Labohm et al. 2004). There are two issues that are driving climate change – fossil fuel burning and deforestation. Two thirds of man-made GHGs are from the burning of fossil fuels (May and Caron 2009).

Fossil fuels contain different amounts of natural carbon and when they are burned this carbon is released into the atmosphere. Coal releases the most carbon when burned, followed by oil (including gasoline and diesel) and natural gas (May and Caron 2009). For every one million mega joules (MJ) of heat energy that are produced by coal, oil and natural gas, 90.0, 70.5 and

50.2 metric tonnes (t) of carbon dioxide (CO_2) are produced respectively, as shown in Figure 1.1 (Energy Information Administration 1999). Approximately five percent of the CO_2 in the atmosphere is from man-made sources; however, despite this value being small, CO_2 levels in the atmosphere are rising (Environment Canada 2010).

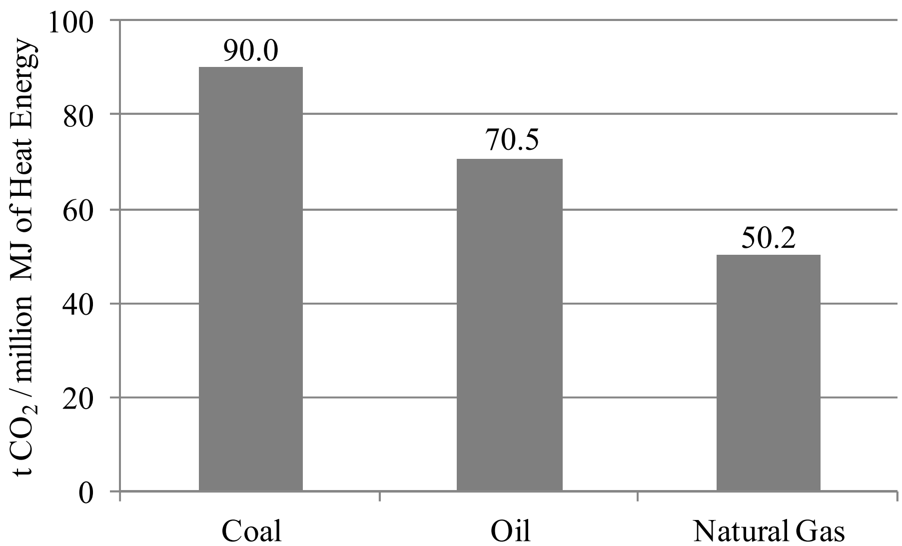

Figure 1.1 CO_2 Emissions per Million MJ of Heat Energy for Coal, Oil and Natural Gas (Reproduced from Energy Information Administration 1999)

The large amount of fossil fuels used in roadway construction and in the production of the materials utilized in road construction results in the creation of significant amounts of GHG emissions. It has been reported that a typical lane-kilometer (lane-km) of constructed road generates between 100 and 500 t of CO_2 (Muench et al. 2010). On average a typical passenger vehicle generates 5.1 t CO_2 equivalents (CO_2e) (US EPA 2012). Comparing these emission rates, the annual emissions generated by approximately 20 to 100 vehicles would be equivalent to the emissions generated for the construction of a lane-km of roadway.

Large amounts of energy are also consumed in roadway construction and in the production of the materials that are utilized in road construction. Muench et al. (2010) report that the construction of a typical lane-km of roadway consumes between 2,000 and 4,000 GJ (gigajoule) of energy. On average a home in Saskatchewan consumes 126 GJ/year of energy (Statistics Canada 2010). Comparing these energy consumption rates the energy used to construct a lane-km of roadway would power between 16 and 32 homes for one year. The amount of energy consumed is an indication of the effort required, fuel consumed and cost of a project.

In 1997, the UNFCCC met in Kyoto and established the Kyoto Protocol which demonstrated a commitment by the countries who entered into the protocol to decrease the amount of their country's GHG emissions produced by a set amount, in a set time (May and Caron 2009). Canada ratified the Kyoto Protocol in 2002, and in doing so, committed to a reduction of 1990 level GHG emissions by six percent by 2012. In December 2011, Canada formally withdrew from the Kyoto Protocol (Environment Canada 2012a). The Copenhagen Accord which was developed in December 2009 addresses issues such as a global temperature target, verifications of reductions, and financing for developing nations (Williams 2010). Canada has committed to the Copenhagen Accord, agreeing to reduce 2005 economy wide greenhouse gas emission levels by 17 percent by 2020 (Environment Canada 2012b and Environment Canada 2012c).

The Kyoto Protocol and the Copenhagen Accord address six GHGs:

- Carbon Dioxide (CO_2);
- Methane (CH_4);
- Nitrous Oxide (N_2O);
- Sulphur Hexafluoride (SF_6);
- Perfluorocarbons (PFCs); and
- Hydrofluorocarbons (HFCs).

Of these gases, SF_6, PFCs and HFCs are fluorinated gases. Based on global warming potential, CO_2, CH_4 and N_2O comprise 77, 14 and eight percent respectively of the GHGs generated while the fluorinated gases comprise only one percent (Bauert et al. 2005). Chlorofluorocarbons (CFCs) are also considered to be GHGs; however, they are governed under the Montreal Protocol and as a result are not included in the Kyoto Protocol (May and Caron 2009). For the purposes of this research, only CO_2, CH_4 and N_2O will be considered.

In an effort to quantify the sustainability of road rehabilitation projects and to distinguish environmental impacts among projects, the construction industry has developed a number of sustainability rating systems. For buildings, the most widely used rating system is LEED (Leadership in Energy and Environmental Design). LEED was developed by the U.S. (United States of America) Green Building Council and is the preferred building rating system by the U.S. General Services Administration (Yudelson 2008). LEED has assisted in making the building industry more aware of the best practices and design principles for buildings that are more environmentally sustainable. As LEED was specifically developed for quantifying the sustainability of buildings, LEED in its present form is not suitable for roadways (Haichert et al. 2009, Foth et al. 2011).

Many roadway rating systems have been or are being developed to measure the sustainability of a roadway and include Greenroads, GreenLITES, the U.S. Federal Highway Administration's (FHWA's) Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), GreenPave and others (Muench et al. 2010, McVoy et al. 2010, FHWA 2012, Proctor 2010). The aforementioned roadway rating systems are used by the industry for more than just a method to measure or distinguish projects from one another. These roadway rating systems can be used as tools to assist in creating baselines, tracking the progress of an agency, encouraging participation, assisting to meet or anticipate new future requirements, rewarding excellence, communicating benefits and goals and developing best practices (FHWA 2012).

In January 2010, version 1.0 of Greenroads was released. Greenroads is a sustainability rating system that evaluates roadway construction projects in a manner similar to the LEED framework used for buildings (Muench et al. 2010). Greenroads and the other roadway rating systems have several inherent limitations within their frameworks. As an example, the achievement of some credits when compared by cost and effort can be highly disproportional. Greenroads is also one of the first roadway environmental analysis frameworks to be developed and as such some of the credits have been included to gain a baseline of the current industry performance (Muench et al. 2010).

Both LEED and Greenroads rating systems award levels of achievement based on the total number of credits that are earned on a project by project basis. These levels of achievement show that some sustainability focused effort has been placed into a project to make it unique amongst other similar projects.

To mitigate the infrastructure crisis, new and innovative methods of road rehabilitation are being developed, particularly in the area of recycling. The goal of typical road rehabilitation methods is to extend the service life of roadways to a performance level equal to that of a new roadway, while minimizing the cost of upgrading the road. As numerous innovative road rehabilitation and recycling technologies have been developed that provide cost effective rehabilitation, there is further need to quantify the sustainable benefits of alternative road rehabilitation methods that address structural and non-structural road rehabilitation.

Portions of the roadway construction industry have identified that reducing the amount of energy required to construct and maintain roads results in reduced construction costs and reduced emissions generated during construction and/or rehabilitation of a roadway (Kuennen 2009). As government policies become more stringent to reduce carbon emissions and the cost of fuel as well as other organic fuels increase, the quantification of energy consumption and carbon generation resulting from roadway construction and rehabilitation will become critical to conduct encompassing evaluations across various road upgrade alternatives.

1.2 Research Goal

The goal of this research was to develop a decision support tool for energy consumption and carbon dioxide equivalent (CO_2e) emissions generated across alternative road construction, maintenance, rehabilitation and reconstruction methods.

1.3 Research Objective

The objective of this research was to develop and validate a probabilistic model that quantifies the amount of energy consumed and CO_2e generated, for typical roadway construction, maintenance, rehabilitation, and reconstruction projects.

1.4 Scope

The scope of this research included material production, hauling and equipment used for placement and removal of materials for typical construction, maintenance, rehabilitation and reconstruction operations of flexible asphalt roadways in Saskatchewan and Alberta. Both conventional and recycling technologies that address structural and non-structural road distresses were considered. The determination of energy consumed and CO_2e generated is completed through the construction of a fundamentals based model constructed in Decision Programming Language (DPL). A list of the various maintenance, rehabilitation and reconstruction methods reviewed in the research and the materials used in the treatments are summarized in Table 1.1.

These treatments and materials capture the majority of treatments and materials used for the construction and preservation of flexible pavement structures.

1.5 Methodology

The model developed herein is intended to be used by roadway managers as an information and decision making tool for comparing alternative and traditional methods of road construction and treatments. The model results, energy consumed and CO_2e emissions are evaluated and compared to published values across various typical road rehabilitation technologies being used in Saskatchewan and Alberta field state conditions.

Table 1.1 Roadway Materials and Treatments Considered in the Model

Maintenance Methods	
	Fog Seal
	Slurry Seal
	Micro Surfacing
	Chip Seal
	Ultra thin overlay (UTO)
Traditional Construction and Rehabilitation Methods	
	Conventional construction of flexible pavements
	Conventional removal and replacement of flexible pavements
	Hot mix asphalt concrete mill and fills
	Hot mix asphalt concrete overlay
Alternative Construction and Rehabilitation Methods	
	In-situ cold in-place recycling (CIPR)
	Use of offsite recycled rubble materials
	Full depth reclamation (FDR) rehabilitation techniques
	Warm mix asphalt concrete (WMAC)
Materials	
	Traditional aggregates
	Recycled Portland cement concrete (PCC) aggregates
	Asphalt cement
	Asphalt emulsion
	Hot mix asphalt concrete (HMAC)
	Portland cement
	Lime

The user will be able to determine the energy used and CO_2e emissions generated due to material processing, hauling and equipment used for the road works in Table 1.1 based upon estimated quantities and equipment usage rates. By determining the energy consumed and CO_2e emissions generated through varying activities related to roadway construction, road managers can identify areas where there is the potential for reductions in the amount of energy consumed and CO_2e generated. To accomplish this, the methodology proposed for this research involves the following elements and tasks.

Element 1: Literature Review

- Task 1: Review of various sustainability definitions used worldwide and their applicability to roadway construction and other works.
- Task 2: Review of the commitment to the reduction of GHGs expressed by Saskatchewan and Canada.
- Task 3: Review of CO_2e generation and climate change, and how it relates to roadway construction.
- Task 4: Review of flexible pavement construction including history and materials used.
- Task 5: Review of current road sustainability frameworks that consider energy consumption and CO_2e generation within their rating frameworks. These sustainability frameworks include Greenroads, GreenLITES, INVEST and GreenPave.
- Task 6: Determine CO_2e emissions for the common GHGs (CO_2, N_2O and CH_4).

Element 2: Fundamental Model Parameters and Calculations

Parameters that have known values are called discrete variables (Park 2007). As there is often uncertainty in numbers, the computational model that is developed uses a discrete probabilistic framework to account for uncertainties in the parameters and inputs used. Each sub-model will be developed in DPL and probabilistic distributions for each individual predictor variable will be encoded based on industry literature as well as local knowledge. Figure 1.2 indicates the inputs and sub-models that will be used to construct the output models.

The following tasks will be completed for the model formulation:

- Task 1: Material Production Sub-model
    - Identify materials produced and needed for each type of road construction and/or treatment considered.
    - For each material determine energy consumption for production.
    - For each material determine the CO_2e generation values for production.
- Task 2: Material Hauling Sub-model
    - Identify volumes and efficiencies of typical hauling vehicles used in road construction.
    - Determine the amount of fuel consumed for hauling.
    - Determine energy consumption values for a unit of fuel consumed.
    - Determine CO_2e generation values for a unit of fuel consumed.
- Task 3: Equipment Usage Sub-model
    - Identify equipment required for each type of road construction and/or treatment considered.
    - Determine a unit productivity rate for each piece of equipment.
    - Determine the fuel usage for each piece of equipment.
    - Determine energy consumption values for a unit of fuel consumed.
    - Determine CO_2e generation values for a unit of fuel consumed.

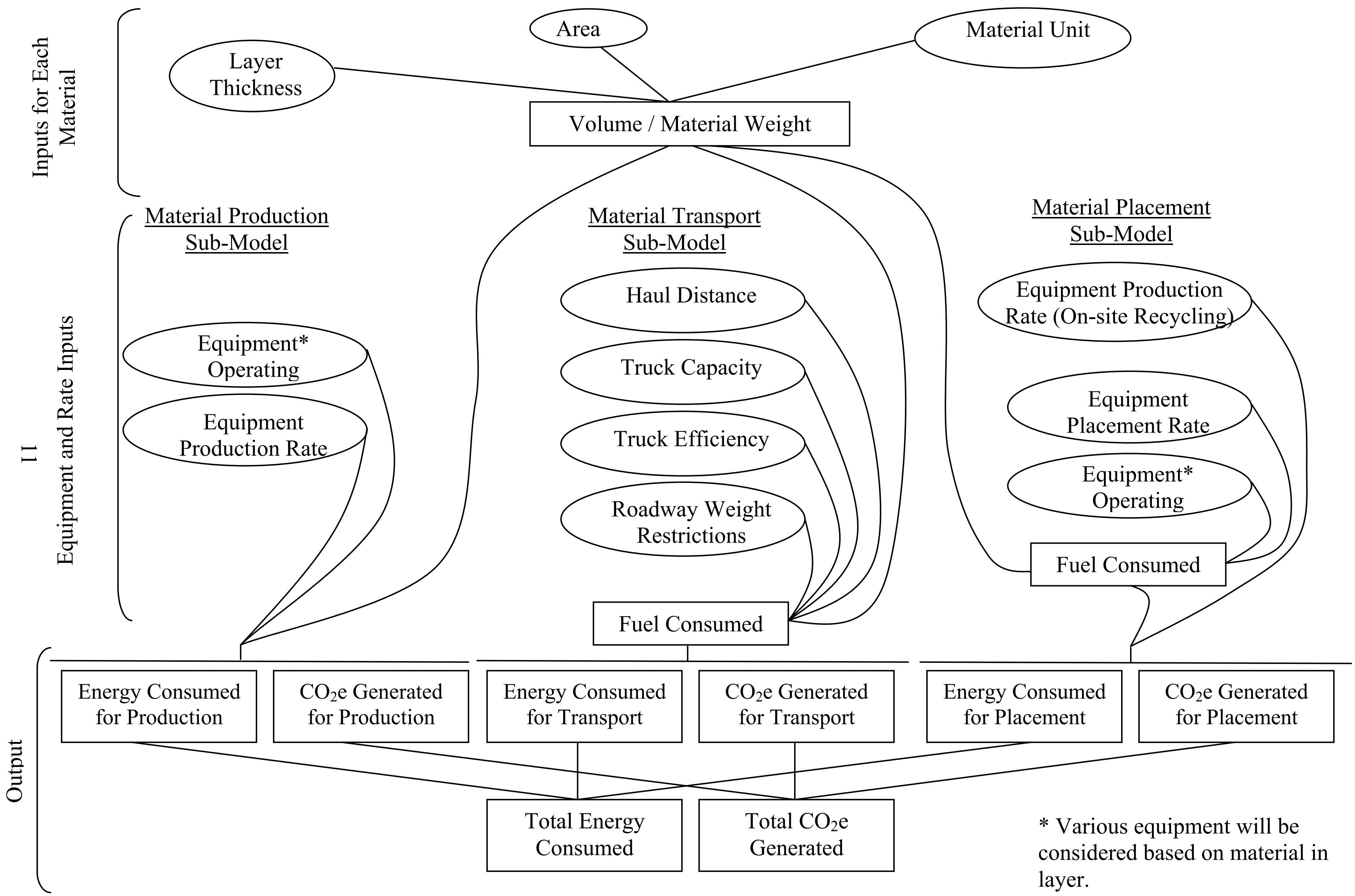

Figure 1.2 Model Formulation Flow Chart

- Task 4: Development of Energy Consumption Output Model.
- Task 5: Development of Carbon Generation Output Model.

Element 3: Computational Model Formulation

- Task 1: Initial Construction
  - Develop a base case study road section for a typical Saskatchewan highway.
  - Determine the energy consumption for the traditional construction of the road section.
  - Determine the CO_2e generation for the traditional construction of the road section.
- Task 2: Maintenance
  - Review maintenance alternatives including fog seal, micro surfacing, slurry seal, chip seal and HMAC overlay for the base case road section.
  - Determine the energy consumed for each maintenance method for the base case road section.
  - Determine the CO_2e generation for each maintenance method for the base case road section.
- Task 3: Rehabilitation
  - Review of roadway rehabilitation techniques, including HMAC mill and fill and cold in-place recycling.
  - Determine the energy consumed for each rehabilitation treatment for the base case road section.
  - Determine the CO_2e generated for each rehabilitation treatment for the base case road section.

- Task 4: Reconstruction
    - Review of reconstruction techniques, including remove and replace with virgin materials, remove and replace with recycled material from off-site and full depth reclamation (FDR).
    - Determine the energy consumed for each reconstruction method for the base case road section.
    - Determine the CO_2e generation for each reconstruction method for the base case road section.

Element 4: Parameter Sensitivity Analysis

- Task 1: Identify the sensitive parameters
    - Develop tornado diagrams in DPL for each treatment.
- Task 2: Sub-model Percentages
    - Determine the percentage that each sub-model contributes to the overall energy consumed.
    - Determine the percentage that each sub-model contributes to the overall CO_2e generated.
    - Determine which sub-model contributes the greatest amount to overall values.
- Task 3: Sub-model Detail
    - Review of the sub-model that contributes the greatest to the overall energy consumption and CO_2e generation values.
- Task 4: Cost of Fuel and Carbon
    - Determine the cost of the energy used.
    - Determine the cost of the CO_2e generated.

Element 5: Model Validation

- Task 1: Determine Published Values
  - Review published values for energy consumption and CO_2e emissions for various roadway treatments.
  - Determine energy consumption and CO_2e emissions for treatments with PaLATE.
- Task 2: Compare Model Values to Published Values

Element 6: Case Studies

- Task 1: Case Study – Traditional Reconstruction Project
  - Collect the required information from a rural roadway project that has been constructed.
  - Determine the amount of energy consumed.
  - Determine the amount of CO_2e generated.
- Task 2: Case Study – Recycled Materials Reconstruction Project
  - Collect the data required for input from a City of Saskatoon Green Streets project that has been completed.
  - Determine the amount of energy consumed.
  - Determine the amount of CO_2e generated.
- Task 3: Case Study – Alternative Structure Analysis
  - Determine the amount of energy consumed and CO_2e emissions generated for a traditional structure for Kenderdine Road.
  - Determine the amount of energy consumed and CO_2e generated for the use of warm mix and recycled asphalt pavement in the asphalt concrete surface coarse.
  - Compare energy consumption and CO_2e generation for each alternative structure.

- Determine the amount of potential carbon credits generated.

- Task 4: Case Study – City of Saskatoon Network Treatment Analysis
  - Determine the amount of energy consumed and CO_2e generated for roadway treatments applied in 2012 with the developed model.
  - Based on the modeled values, determine the amount of energy consumed and CO_2e generated per lane-km.
  - Based on the modeled values, determine the amount of energy consumed and CO_2e generated per 1,000 residents.

1.6 Layout of Thesis

The thesis presented herein consists of eight chapters. Chapter One provides the goal, objective, scope and methodology related to the development of the energy consumption and CO_2e generation model. Chapter Two provides a summary of the literature review on GHG production, how roadway construction and rehabilitation can be viewed as sustainable technologies and what road rating frameworks are currently available.

Chapter Three presents the formulation of the computational model for energy consumption and CO_2e generated within this thesis. The measurements, values and information needed to formulate the framework of the model are outlined. Chapter Three also presents the collected data on the sub-models that compose the final model. These sub-models will quantify the energy consumed and the CO_2e generated for material production, hauling and equipment usage. Probability modeling will be used to account for the uncertainty and variety of values that are collected for the sub-models to determine the final values for energy consumption and CO_2e generation.

Chapter Four presents a case study of one lane-km of roadway for initial construction, maintenance, rehabilitation and reconstruction techniques. The values generated for energy consumption and CO_2e generated are based on a typical rural flexible pavement lane-km of roadway and are compared to published values. Chapter Five provides a detailed analysis of the sensitive parameters within the model. Chapter Six provides a validation of the theoretical model developed in Chapter Three and compares the model values generated from the base case study to published values and values generated from the PaLATE Model.

Chapter Seven presents case studies. The first is a traditional remove and replace project of Range Road 232, a rural roadway in Strathcona County, Alberta. The second is of Kenderdine Road in Saskatoon, Saskatchewan, a project that utilizes recycled materials. The third case study further reviews Kenderdine Road and other applications of green technologies compared to traditional construction methods. The fourth case study quantifies the amount of energy consumed and GHG emissions generated by the City of Saskatoon based on a year of roadway restoration and reconstruction treatments. Chapter Eight presents the summary and conclusions that can be drawn from the outputs of the model.

Chapter 2

LITERATURE REVIEW

This chapter provides a review of the background literature pertaining to the energy and emissions model that will be constructed in this research. The background information includes detailed descriptions of:

- The definition of sustainability;
- Greenhouse gases and emissions;
- Current roadway sustainability frameworks and carbon quantification tools used in the roadway industry;
- Reported carbon generation and energy consumption values; and
- Canada's Carbon Credit System.

2.1 Definition of Infrastructure Sustainability

Many researchers, government agencies, corporate organizations and the general public have recognized the importance of implementing infrastructure sustainability and development. Many definitions, principles and concepts have been developed to assist in communicating the meaning, importance of action, and methods to determine if something is sustainable (Wallace 2005). The World Commission on Environment and Development was established by the United Nations in 1983 and is responsible for identifying and developing ways in which to address critical issues that are related to the global environment and development.

In 1987, the findings of the Brundtland Commission, entitled *Our Common Future*, were released. This report detailed the struggles that were observed by all world citizens with trying to move forward in development and how some development may be considered to be detrimental to the environment and future societal progress (Brundtland 1987). The Brundtland Commission brought the need for sustainability and sustainable development to the forefront of the engineering profession and developed a definition for sustainable development that is often quoted. The Brundtland Commission defines sustainable development as *"[development] that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland 1987).

Although well documented, some have found the concept of sustainability difficult to understand and implement into everyday practices. As a result, a number of principles and concepts have been developed (Wallace 2005). Of these principles the Three Pillars of Sustainability and the Triple Bottom Line are very similar and are often used to define sustainability (Wallace 2005). These concepts are illustrated in Figure 2.1 (Sustainability-ED 2011) and Figure 2.2 (Ernst & Young 2011), respectively.

The United States Federal Highway Administration (FHWA) defines sustainability as "the capacity to endure" and indicates that the goal of sustainability can be described by the Triple Bottom Line including equity, ecology and economy (FHWA 2012). With the FHWA's focus mainly on highways, characteristics of a sustainable highway have been developed that "*satisfy life cycle functional requirements of societal development and economic growth while reducing negative impacts to the environment and consumption of natural resources*" (FHWA 2012).

When examining sustainability from a roadway construction perspective it is important to consider the Triple Bottom Line components of economic, social and environmental benefits that are considered in many of the common definitions, principles and concepts of sustainability. However, one must also consider the technical aspects to ensure that the long term performance of a pavement is maintained (Foth et al. 2011). This concept is shown in Figure 2.3 (Foth et al. 2011).

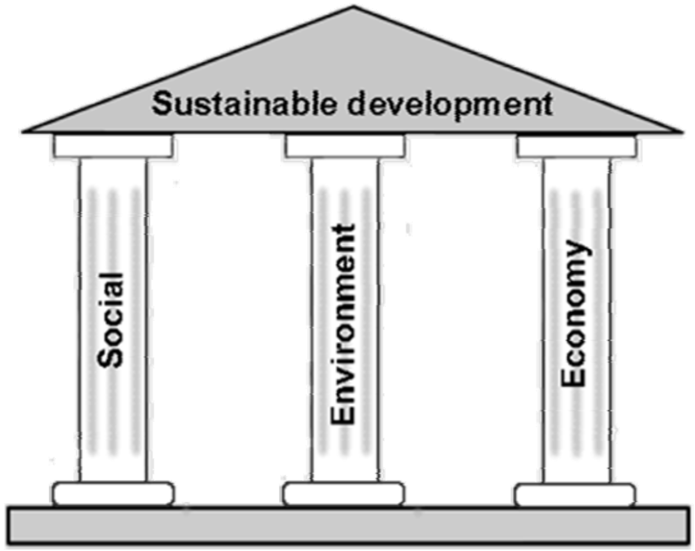

Figure 2.1 Three Pillars of Sustainability (Sustainability-ED 2011)

Figure 2.2 Triple Bottom Line (Ernst & Young 2011)

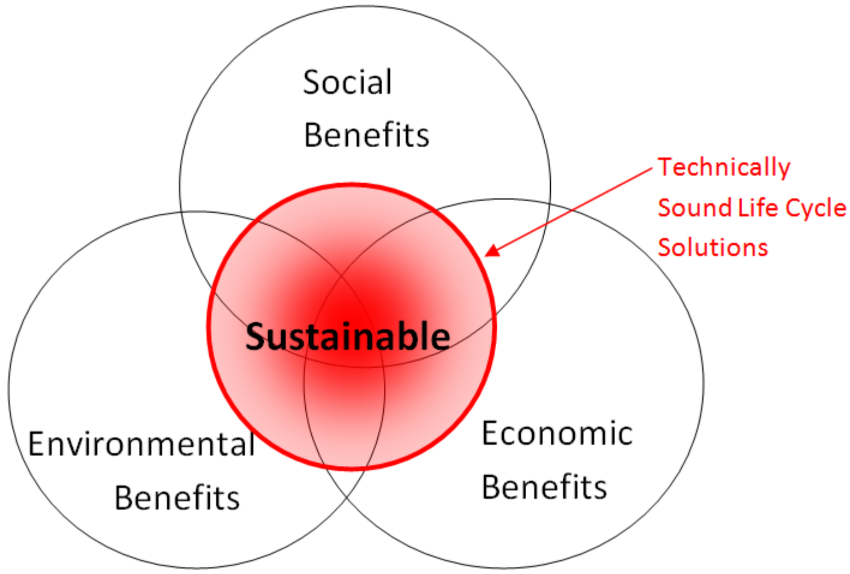

Figure 2.3 Sustainability Diagram (Foth et al. 2011)

The technical aspects of the materials that are being used in the roadway structure as well as the field state conditions must be understood to ensure that the integrity of a roadway may be maintained over the long term. These aspects are of particular concern when recycled materials are being used to construct or rehabilitate a roadway. Using recycled materials should provide a level of service that is similar to or higher than that of a roadway that is constructed with conventional materials (Foth et al. 2011).

2.2 Greenhouse Gases

The Kyoto Protocol regulates those GHGs that are not covered through the Montreal Protocol and include (Environment Canada 2010, May and Caron 2009):

- Carbon Dioxide, CO_2;
- Methane, CH_4;
- Nitrous Oxide, N_2O;

- Sulfur Hexafluoride, SF_6;
- Hydrofluorocarbons, HFCs; and
- Perfluorocarbons, PFCs.

Greenhouse gas emissions can be reported in CO_2 equivalent (CO_2e). CH_4, N_2O, SF_6, HFCs and PFCs can be expressed in CO_2e based on their global warming potential compared to CO_2 (May and Caron 2009). These global warming potentials are illustrated in Figure 2.4 (Environment Canada 2010, May and Caron 2009). A sample calculation for the determination of CO_2e is included in Appendix B.

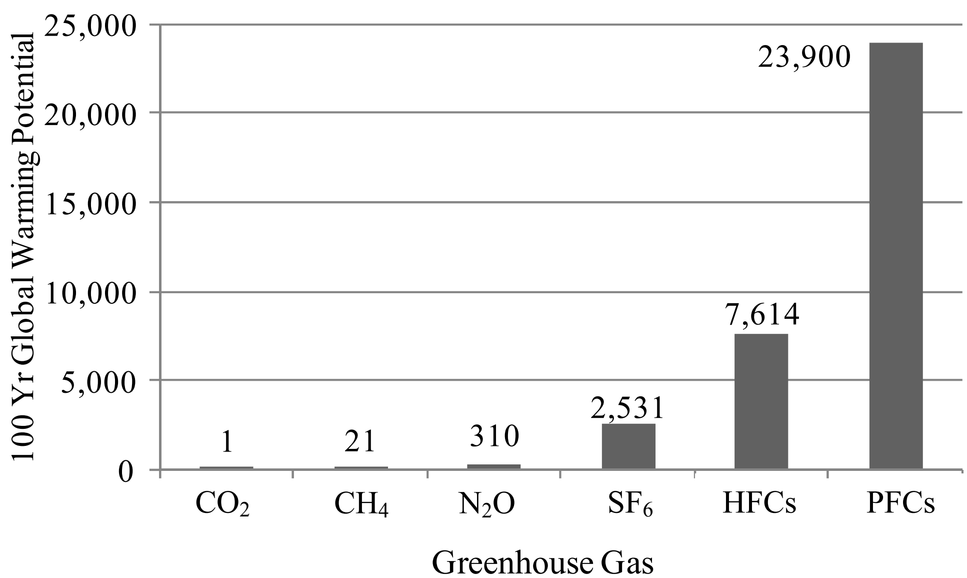

Figure 2.4 CO_2e for Greenhouse Gases (Reproduced from Environment Canada 2010 and May and Caron 2009)

2.2.1 Carbon Dioxide, CO_2

CO_2 is a colourless, odourless and incombustible gas that occurs naturally within the atmosphere. This gas is formed naturally through combustion, respiration, the decomposition of organic materials and reaction of acids with carbonates (Environment Canada 2010). Naturally occurring CO_2 in the atmosphere is regulated through the carbon cycle. Within the environment, there are carbon emitters and carbon absorbers. Ideally, the amount of carbon that is emitted equals the amount of carbon that is absorbed (May and Caron 2009). The amount of CO_2 that is emitted from anthropogenic (man-made) sources is approximately five percent of the amounts that occur naturally. Despite this value being small, CO_2 is accumulating in the atmosphere (Environment Canada 2010). The volume of one metric tonne of carbon is approximately 557 m^3 (cubic meter) (Muench et al. 2010).

2.2.2 Methane, CH_4

CH_4 is a colourless, odourless and combustible gas that occurs naturally within the atmosphere at low concentrations and is created when organic material breaks down when no oxygen is present (Environment Canada 2010). Sources of methane include marshes, digestive processes of animals and the decomposition of organics. Man-made sources include industrial processes, fossil fuel extraction, incomplete combustion and garbage decomposition in landfills (Environment Canada 2010, May and Caron 2009).

2.2.3 Nitrous Oxide, N_2O

N_2O is a gas that is colourless, incombustible, heavier than air and smells sweet. N_2O is naturally released from the oceans and soil dwelling bacteria (Environment Canada 2010). The largest source of N_2O, natural or manmade, is from agricultural fertilizers, which make up 60 percent of the man-made sources and 40 percent overall (May and Caron 2009).

2.2.4 Sulfur Hexafluoride, SF_6

SF_6 is a man-made gas that is colourless, odourless and non-toxic unless it is at an extreme temperature. This gas is used in the electric industry as an insulator, in the magnesium industry to prevent oxidation and also in the electronics industry (Environment Canada 2010).

2.2.5 Hydrofluorocarbons, HFCs

HFCs are a group of thirteen chemical compounds that contain hydrogen, carbon and fluorine that are man-made. These chemicals do not deplete the ozone and as a result they are used in place of ozone depleting substances that are used in fire-extinguishers, refrigeration, foam blowing and semi-conductor manufacturing (Environment Canada 2010).

2.2.6 Perofluorocarbons, PFCs

PFCs are a group of seven chemical compounds that contain carbon and fluorine that are man-made. These chemicals also do not deplete the ozone and are used in place of ozone depleting substances used in semiconductor manufacturing. PFCs are produced during aluminum production, may be used for refrigeration and are used as a solvent in the electronic industry (Environment Canada 2010).

2.3 Greenhouse Gas Emissions

In 1992, world leaders met at the Earth Summit in Rio de Janeiro and formed the United Nations Framework Convention on Climate Change (UNFCCC) to halt the increase in GHG emissions that was being observed in the atmosphere (May and Caron 2009). It has been debated whether climate change is occurring naturally or if it is anthropogenic (Labohm et al. 2004). The UNFCCC adopted a precautionary principle believing that they could not wait for the debate to be resolved and decided that action must be taken to reduce GHG emissions (May and Caron 2009).

In 1997, the Kyoto Protocol was established by the UNFCCC. Those countries that signed the Kyoto Protocol demonstrated a commitment to the reduction of GHG emissions by a set amount. At the Conference of Parties an agreement of a 5.2 percent global reduction of GHG emissions was made (May and Caron 2009). The amount of GHG emissions by gas from Annex

I parties, as defined by the Kyoto Protocol, are summarized in Table 2.1 and Figure 2.5 for 1990 and 2008 respectively (UNFCCC 2010).

To reduce GHG emissions worldwide the Kyoto Protocol established three mechanisms: clean development mechanisms, joint implementation and emissions trading (May and Caron 2009). Clean development mechanisms involve industrialized countries paying for the implementation of clean energy projects in developing countries. Joint implementation involves joint partnerships between developing and industrialized countries to implement GHG reducing technologies (May and Caron 2009). Of these mechanisms, only emissions trading will be discussed in detail.

Table 2.1 Greenhouse Gas Emissions by Gas for Annexed I Parties (UNFCCC 2010)

	CO_2	**CH_4**	**N_20**	**HFCs-PFCs-SF_6**
1990	15.1	2.3	1.3	0.3
2008	14.6	1.9	1.0	0.3

Note: Values are reported in 1000's Tg CO_2e, 1 Tg = 1 x 10^6 t

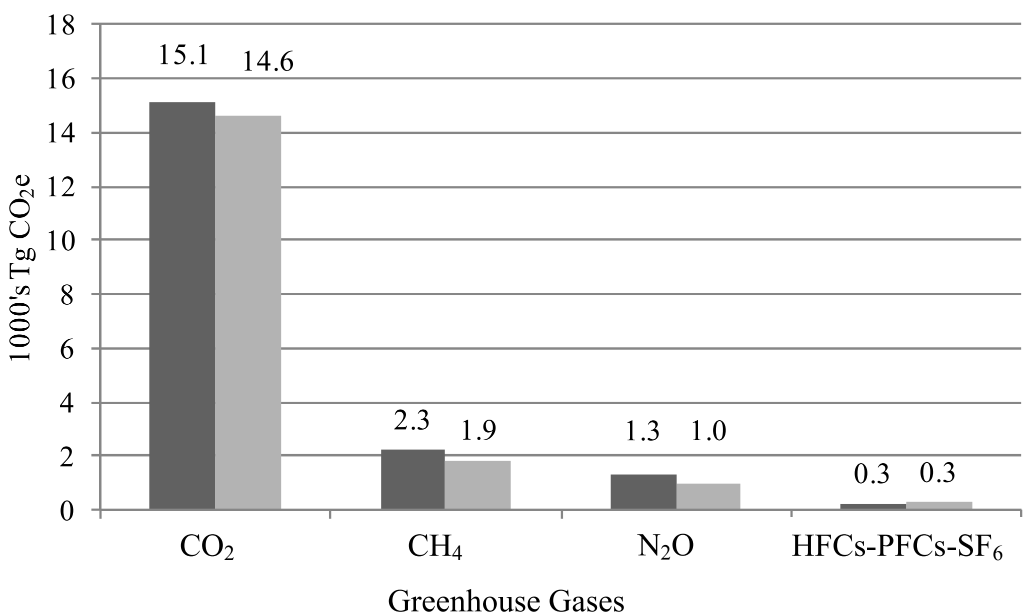

Figure 2.5 GHG Emissions by Gas for Annex I Parties (Reproduced from UNFCCC 2010.)

Canada ratified the Kyoto Protocol in 2002 and committed to a six percent reduction in GHG emissions from 1990 levels between the period of 2008-2012 (May and Caron 2009). In 1990, Canadian GHG emissions were reported at 589 mega tonnes (Mt) CO_2e (Environment Canada 2012b, Environment Canada 2012c). Figure 2.6 shows the reported GHG emissions for Canada since 1990 in five year intervals (Environment Canada 2012c). In 2007 emission levels peaked at 751 Mt CO_2e (Environment Canada 2012c). Based on 2011 emission rates it is estimated that if no government action is taken to reduce emissions, the emissions rates for 2020 will be 850 Mt CO_2e (Environment Canada 2012b).

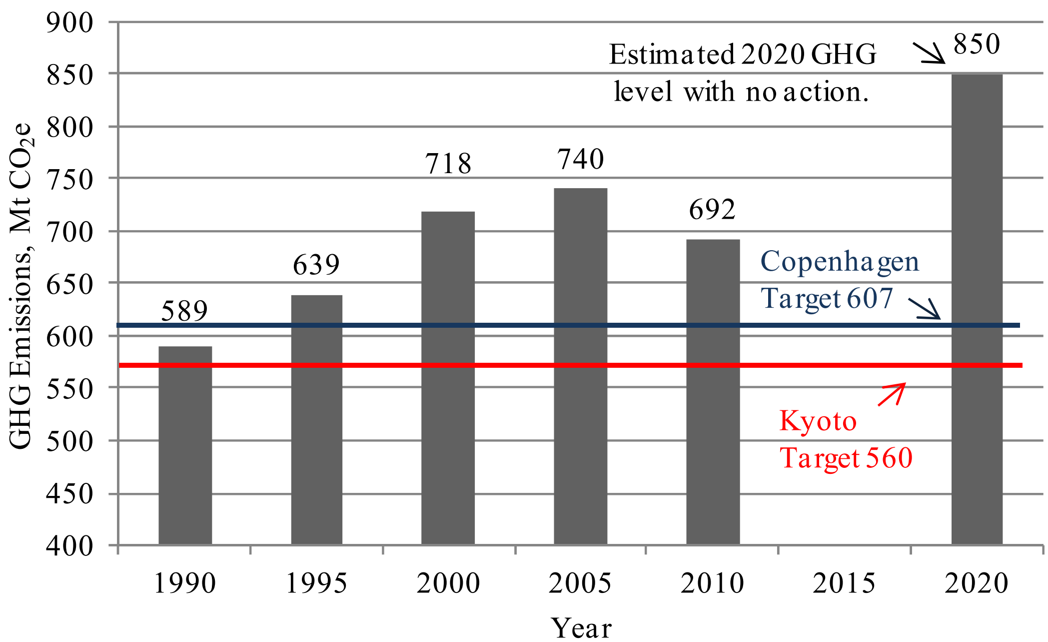

Figure 2.6 GHG Emissions in Canada (Information compiled from Environment Canada 2012b and Environment Canada 2012c.)

Canada reaffirmed its commitment to GHG reduction in December 2009 by committing to a 17 percent reduction of 2005 GHG emissions to 607 Mt by 2020 through the Copenhagen Accord (Environment Canada 2012b, Environment Canada 2012c). The Copenhagen Accord is signed by 140 countries which comprise 85% of global GHG emissions whereas the Kyoto

Protocol is signed by 40 countries that represent only 27 percent of global emissions (Environment Canada 2012b).

On December 15, 2011 Canada formally withdrew from the Kyoto Protocol. Canada withdrew as remaining in the Kyoto Protocol would result in Canada having to purchase a large number of international carbon credits. Instead Canada has chosen to retain the money that would have had to be spent on the carbon credits and invest it domestically (Environment Canada 2012a). The Kyoto Protocol also fails to include the United States, China, Brazil and India, who are responsible for a total of 40 percent of global emissions (Environment Canada 2012b).

The contribution that each GHG makes to the total GHG emissions in Canada is shown in Figure 2.7 (Environment Canada, 2010a). CO_2 is the greatest contributor at 78 percent (Environment Canada 2010).

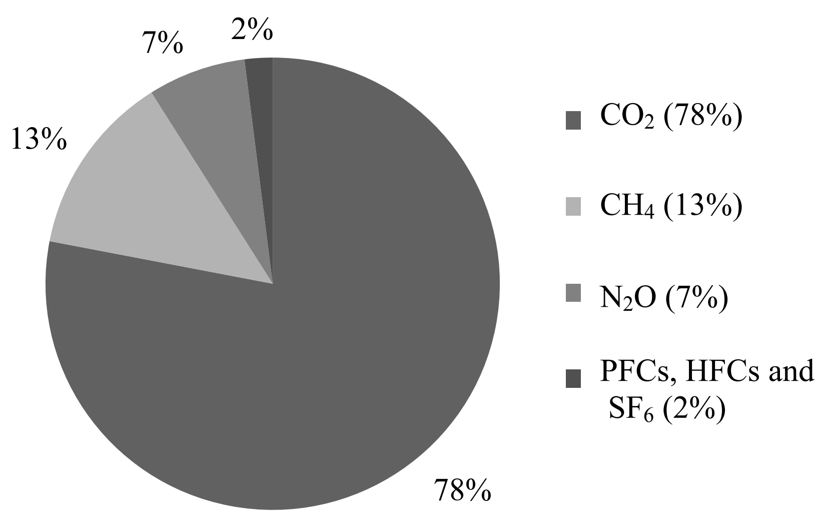

Figure 2.7 Canada's Greenhouse Gas Emissions by Gas Type (Reproduced from Environment Canada 2010.)

Canada's GHG emissions are approximately 1.5 percent of total global GHG emissions. In 2010 Canada emitted 20.3 t of GHGs per person, making it one of the highest per capita emitters globally (Environment Canada 2012b). Canada's high emissions rate can be attributed to the large size of the country, the colder climate which requires more energy for heating and its resource based economy (Environment Canada 2010). Canada's GHG emissions by source are shown in Figure 2.8 (Environment Canada 2010). It is also reported that 73 percent of all GHG emissions in 2008 resulted from the burning of fossil fuels (Environment Canada 2010).

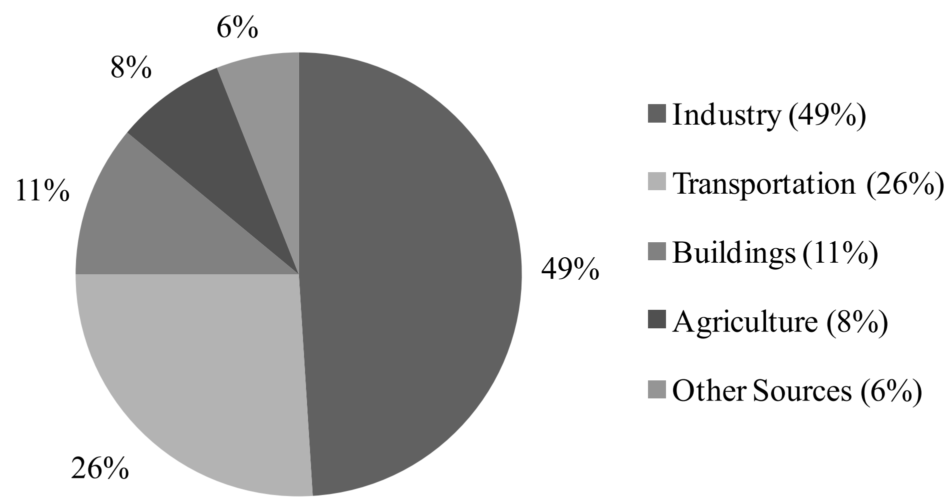

Figure 2.8 Canada Greenhouse Gas Emission Sources (Reproduced from Environment Canada 2010.)

In 2010, Saskatchewan generated 10.5 percent, or 73 Mt, of Canada's GHGs emitted and is the province with the highest per capita GHG emissions at 69.8 t/person, 6.4 t/person higher than Alberta, the next highest province (Environment Canada 2012b). This higher per capita value may be attributed to various reasons including having a low population, a resource based economy, extreme climate in the winter and summer as well as the generation of electricity from the burning of fossil fuels and the need to transport goods large distances over land to reach markets (Climate Change Saskatchewan 2007, Environment Canada 2010).

Saskatchewan has set a GHG emissions reduction target of 20 percent from the 2006 emission level to be achieved by 2020. The Saskatchewan Ministry of Environment has introduced Bill 126: *The Management and Reduction of Greenhouse Gases Act* to the Legislative Assembly on December 1, 2009. The Act has 11 parts including sections on regulated emitters, GHG emission reduction programs, enforcement and offences (Saskatchewan Ministry of the Environment 2010).

2.4 Current Roadway Construction Sustainability Analysis Frameworks

In the pursuit of improved sustainability, road agencies and organizations have developed roadway sustainability rating systems to compare projects. There are many reasons why an agency may choose to use a rating system on a project including: baselines and tracking, encouraging participation, assisting with meeting or anticipating new future requirements, rewarding excellence, communicating benefits and goals and developing best practices (FHWA 2012, Muench et al. 2010).

A review of four of the readily available rating systems is provided in this literature review and includes:

- Greenroads;
- GreenLITES;
- INVEST; and
- GreenPave.

2.4.1 Greenroads

Version 1.0 of Greenroads was released in January 2010 and its purpose and use is described as "*a sustainability performance metric for roadways that awards points for more sustainable practices*" (Muench et al. 2010). Greenroads is a voluntary metric that may be used by any agency and works to incorporate all aspects of roadway development including planning, design, construction, maintenance and management.

Greenroads consists of seven categories which include Project Requirements, Environment & Water, Access and Equity, Construction Activities, Materials and Resources, Pavement Technologies and Custom Credits (Muench et al. 2010). The Project Requirement section has eleven requirements that must be met to achieve any type of Greenroad certification and includes a lifecycle inventory. The goal of the lifecycle inventory is to allow an agency to "*incorporate energy and emissions information into the decision-making process for design alternatives*" (Muench et al. 2010). In the remaining categories there are 39 credits where 118 points may be achieved.

The metric structure of Greenroads is very similar to the LEED system for buildings. To achieve a project that is Greenroads certified the agency must submit an application, pay the fees and complete and submit the required documentation for each credit that may apply to the project for third party verification. Four levels of certification are available based on the points achieved. The four levels are (Muench et al. 2010):

- Certified (32 - 42 points);
- Silver (43 - 53 points);
- Gold (54 – 63 points); and
- Evergreen (64 or higher points).

2.4.2 GreenLITES

The GreenLITES (Green Leadership In Transportation and Environmental Sustainability) certification program was developed by the New York State Department of Transportation (NYSDOT) to assist in integrating sustainability principles into transportation projects. It is also used as a tool to align the sustainability efforts by the department in the areas of planning, design, construction and maintenance operations over the long term. The program was developed following the structure of the LEED certification program and Greenroads (McVoy et al. 2010).

GreenLITES is different from the LEED and Greenroads systems in that it is a self certification program rather than being third party certified. Self certification allows GreenLITES to be used by the NYSDOT to not only measure performance but to recognize good practices and identify areas that require improvement. Credits for GreenLITES can be earned in five categories: Sustainable Sites, Water Quality, Materials and Resources, Energy and Atmosphere and Innovation/Unlisted. The four levels of certification that may be achieved through GreenLITES are (NYSDOT 2008):

- Certified (15 – 29 points);
- Silver (30 – 44 points);
- Gold (45 – 59 points); and
- Evergreen (60 points or higher).

One of the sustainability goals that NYSDOT has identified is to "*promote energy efficiency in support of lower costs, and reductions in energy usage and greenhouse gas emissions*" (McVoy et al. 2010). Within the categories available to achieve points the Energy and Atmosphere category addresses this goal; however, there is no specific credit that can be achieved for quantifying the energy consumption or CO_2e generation for roadway construction.

2.4.3 INVEST

The FHWA released version 1.0 of its Infrastructure Voluntary Evaluation Sustainability Tool, INVEST October 2012. This self certification tool is available on the world wide web and includes a collection of best practices to allow users to integrate sustainability into every day practice. The FHWA administration has no future plans to make this tool a requirement to receive future financial funding or that it must be used by an agency for any type of compliance or regulations (FHWA 2012). With this tool there are three categories – System Planning, Project Development and Operations & Maintenance – where 16, 30 and 15 credits for totals of 160, 117 and 150 points may be earned in each respective category. Four levels of achievement may be reached for each category as summarized in Table 2.2.

Table 2.2 Achievement Levels for INVEST (FHWA 2012)

Category	**System Planning**	**Project Development**	**Operations & Maintenance**
Bronze	48	35	45
Silver	64	47	60
Gold	80	59	75
Platinum	96	70	90
Total	160	117	150

2.4.4 GreenPave

GreenPave is currently under development by Ontario's Ministry of Transportation (MTO) and it differs from the other roadway rating systems in that it focuses only on the pavement and not the entire road right-of-way. This rating system was modeled after the Greenroads and GreenLITES rating systems but is tailored to Ontario. There are four certifications that may be awarded in GreenPave which are (Proctor 2010):

- Bronze (7-10 points);
- Silver (11-14 points);
- Gold (15-19 points); and
- Trillium (20-35 points).

2.5 Current Energy and Carbon Quantification Frameworks

One of the project requirements for Greenroads is a lifecycle inventory based on energy used and emissions generated (Muench et al. 2010). The goal of conducting the life cycle inventory is to incorporate consumed energy and emissions derived from different pavement alternatives into the decision-making process (Muench et al. 2010). For a project to receive a rating with Greenroads, a lifecycle inventory must be completed. There is no target to be achieved or points awarded for either energy consumption or carbon generation reduction through the use of alternative pavements. Greenroads suggests that in order to achieve the Lifecycle Inventory Project requirement the PaLATE "Pavement Lifecycle Assessment Tool for Environmental and Economic Effects" tool should be used (Muench et al. 2010).

A number of energy consumption and carbon quantification frameworks have been developed. Some are available for free while others are available commercially, resulting in limited information on the methods of calculation. Other programs that have been developed to calculate energy consumption and/or GHG generation are ÉcologicieL, developed by Colas (Dorchies 2008) and CHANGER (Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads), developed by the International Road Federation (IRF) (IRF 2010). These programs assist in making informed decisions and provide emission generation and cost information for roadway construction projects and rehabilitation.

2.5.1 PaLATE

PaLATE is a lifecycle analysis tool that evaluates the use of different types of material in the maintenance and construction of roadways. The environmental components that are estimated by this tool are energy consumption, emissions of CO_2, NO_x (mono-nitrogen oxides), PM_{10} (particulate matter 10), SO_2 (sulfur dioxide), CO (carbon monoxide) and leachate releases. These values are reported for construction, maintenance and total amounts over the life of the project for material production, transportation and equipment processes (Horvath 2003). The PaLATE framework is available for free on the world wide web and is run within Microsoft Excel.

The PaLATE v2.2 program has been modified by Greenroads and may be used for the lifecycle credits in Greenroads and GreenPave. Greenroads has indicated there are a number of limitations to the PaLATE tool to tailor the model to a specific project. These limitations include limited information on modes of transportation available, equipment rates and material densities. Truck and rail emissions included in the model only account for CO_2 emissions and are based upon European values (PaLATE 2011).

2.5.2 ÉcologicieL

ÉcologicieL is a tool that was developed by the Colas group to quantify energy and GHG emissions of various pavement structures. The program considers all aspects of road construction, including the extraction of materials, material manufacturing, placement of materials and maintenance of the roadway. The values for the varying aspects of construction used for this model are collected from published sources (Chappat and Bilal 2003).

2.5.3 CHANGER

CHANGER is available for purchase through the IRF. The program is broken into two modules: preconstruction and pavements. The preconstruction module takes into account land clearing and any cut and fill work that is required before the construction of the road structure may begin. The pavement module considers material production, material transport and the machines used to place the material. Maintenance procedures are under development (IRF 2011).

2.6 Reported Carbon Generation and Energy Consumption Values

Greenroads reviewed 35 assessments for energy consumption. The median value per lane-km determined from these assessments is 3.17 terra joules (TJ) (Muench et al. 2010). A typical range for the amount of energy used to construct a lane-km of roadway is between 2 and 4 TJ (Muench et al. 2010). The carbon generation and energy consumption values will vary from each project depending upon the pavement structure and materials that are used.

For CO_2 generated through roadway construction projects, 31 assessments were reviewed and the amount of CO_2 generated through roadway construction is reported. From these assessments the median value per lane-km was 243 t (Muench et al. 2010). A typical range of CO_2 emissions for a roadway is determined to be between 100 and 500 t/lane-km (Muench et al. 2010).

Greenroads also reviews the processes involved in construction and maintenance of roadways, including material production, material transportation, maintenance and initial construction, and how the amount of energy consumption and CO_2 generation are distributed. Material production uses the greatest amount of energy at 75 percent and CO_2 generation at 60 to 70 percent. Material transportation accounts for 20 percent of the energy consumption and 10 percent of CO_2 emissions. Maintenance accounts for 25 percent and 10 to 20 percent for energy consumption and CO_2 generation respectively. The actual construction of the roadway contributes the least to the overall totals for energy consumption and CO_2 generation at less than five percent (Muench et al. 2010).

2.7 Roadway Rehabilitation and Construction in Canada

Canada is a large country with a population that is widely dispersed and is dependent upon the roadway system to maintain the standard of living to which citizens have become accustomed. Canada's roadway network has over 1.4 million two lane equivalent kilometers of roadways, resulting in more kilometers of roadway per person than any other nation (Statistics Canada 2009).

Governments have recognized the importance of the roadways within Canada and have spent \$25.1 billion by all levels of government on roadways in 2008, which is 71 percent of the total amount spent on transportation (Statistics Canada 2009). At the provincial, territorial and local government level 78 percent of \$30.9 billion spent on transportation was directed to highways and roads. This amount increased by 21.8 percent from 2007, and 87.3 percent from 2000 spending (Statistics Canada 2009). With the amount of money that is being directed into roadway infrastructure across Canada it is important that this money is utilized in a way to maximize benefits for users.

2.7.1 Pavement Management Systems

All infrastructure at some time will require maintenance, rehabilitation, retrofit, reconstruction or abandonment (Smith 2009). After World War II, there was an increase in Canada's population and as a result there was a need for new municipal infrastructure to be constructed. With the increase of new infrastructure being required there was less money available for maintenance and rehabilitation, resulting in an infrastructure deficit. As Canada's infrastructure continues to age and deteriorate, there are not enough funds available to conduct the needed maintenance and rehabilitation that is required to extend the infrastructure life without requiring complete replacement (Mirza and Haider 2003). With limited funds available, agencies must pick and choose which pieces of infrastructure require immediate attention and which can wait.

Most agencies within Canada have pavement management systems in place to evaluate the ongoing condition of roadway networks. These systems are critical to the asset management of roadways to ensure that a minimum level of service and safety is maintained for residents. Tasks within a pavement management system include optimal pavement planning, programming, design, construction, maintenance and evaluation. One of the benefits of pavement management systems is that they ensure that public funds are spent cost effectively based on informed decision making (TAC 1997).

The treatment or work plan that is chosen for a roadway will depend on a number of factors including the pavement type, pavement condition, expected traffic, environment, budget and other constraints (TAC 1997). With pavements, if maintenance and preservation treatments are conducted at the right time, the life of a pavement can be extended; however, if maintenance and preservation treatments do not occur at that time, reconstruction may be required at a significantly higher cost. From an economic perspective it is often more cost effective to conduct preservation maintenance in lieu of reconstruction (Smith 2009, TAC 1997).

2.7.2 Roadway Maintenance and Rehabilitation Methods

Pavement preservation through pavement maintenance strategies is an important aspect of roadway management that can postpone the need for roadway rehabilitation or reconstruction. By conducting regular maintenance such as minor crack sealing, pothole repair, minor drainage improvements and localized spray patching, the need for major maintenance such as deep depth patching, thin overlay, mill and fill, micro surfacing and slurry and chip sealing can be delayed. Major maintenance typically is more expensive than regular maintenance; however, it will generally also improve the structural condition and the surface of the roadway. Major maintenance may extend the expected service life of the roadway by five to ten years (TAC 1997).

Pavement maintenance must be completed prior to a pavement developing too many distresses. If a treatment is applied when too many stresses are present the treatment will not extend the service life of the pavement and as a result the money should not be spent on a treatment. Rather a complete rehabilitation or reconstruction of the roadway may be required. This work may include the removal of the existing roadway to the subgrade and replacement with virgin or recycled materials and in-place recycling.

2.8 Canada's Carbon Credit Offset System

Canada's Offset System for Carbon Credits has been established to encourage cost-effective methods of GHG reduction that are not covered by other federal incentives or regulations for reduction. The system is regulated through Environment Canada under the Environmental Protection Act 1999 section 322 as a voluntary program. This is the proposed market where carbon credits may be sold at a national level (Environment Canada 2009). This system has been developed based on the following five principles (Environment Canada 2009):

- There are net environmental benefits with GHG reduction;
- GHG reductions are in Canada;
- The scope of a project should be maximized so that the system can cover many project types over various sectors;

- A simple administrative system that is cost-effective and practical to minimize the burden of the participant but to ensure the integrity of the system is maintained; and
- Experience of previous projects should be built upon.

For a project to receive offset credits, proponents must complete the five steps as summarized in Figure 2.9.

Step 1: Creation of a Quantification Protocol

↓

Step 2: Registration of the Project

↓

Step 3: Implementation of the Registered Project and Monitoring of Data

↓

Step 4: Reporting and Verification of Reductions from the Registered Project

↓

Step 5: Certification of Reductions and Issuance of Offset Credits

Figure 2.9 Steps for Achieving Canada's Carbon Offset Credits (Reproduced from Environment Canada 2009.)

For the registration of offset projects in Canada there are six eligibility criteria that must be reviewed for a project which are described in Table 2.3. Many of these eligibility criteria are addressed during the development of the Quantification Protocol.

There are two types of carbon markets where carbon credits may be sold: the Voluntary Carbon Market and the Compliance Carbon Market. The Voluntary Carbon Markets may be used by those parties who may choose to purchase carbon credits on a voluntary basis rather than a required basis. The Compliance Market is used by those parties that are required to purchase credits under government regulated programs as strict review processes must be implemented to ensure the creditability of the credits whereas with the voluntary markets these review processes are not required (Carlson et al. 2009).

Table 2.3 Eligibility Criteria for Generation of Carbon Credits

Criteria	Description
Scope	The project must take place in Canada and reduce one or more of the six GHGs.
Real	After accounting for all of the GHG sources, sinks and reservoirs within a project, the Proponent must show specific and identifiable action for which the reduction occurs.
Incremental	Any credits that are applied for must be in addition to the regulatory requirements and other climate change incentives.
Quantifiable	GHGs must be able to be quantified.
Verifiable	A third party verifier must review the GHG reduction claims of the project.
Unique	The GHG reduction can only be used once for offset credits.

2.9 Summary

Globally many groups have acknowledged the importance of infrastructure and societal sustainability. To achieve sustainability in roadways, environmental, social, and economic benefits must be achieved while maintaining technically sound lifecycle solutions. There has been an increase in the atmospheric amount of GHGs and governments have taken steps to halt and reduce the amount of GHGs that are being emitted. Canada committed to the reduction of GHG emissions by agreeing to the Copenhagen Accord. To encourage the reduction of carbon generation within Canadian industry, the Government of Canada has set up the Canadian Carbon Credit Offset System.

Within the construction industry, rating systems have been developed to encourage sustainable development and to rate a project's level of sustainability. A number of rating systems have been developed for roadways including Greenroads, GreenLITES, INVEST and GreenPave. All of these rating systems award credits for reviewing the amount of carbon generated and energy consumed during the construction or rehabilitation of a roadway. Understanding the amount of carbon generated and energy consumed from alternative methods of roadway rehabilitation and construction allows more sustainable choices to be achieved.

The model that is constructed in this research takes a fundamental approach to its construction and covers a range of values so that any maintenance, rehabilitation and/or reconstruction treatment within a range of design parameters can be estimated.

Chapter 3

FUNDAMENTAL MODEL PARAMETERS AND CALCULATIONS

The model constructed in this research requires information from the user about the physical characteristics of the roadway and treatment that is applied. Values and calculations that relate to the materials, equipment and transportation that are used, which are not influenced by the user, are also required for the model. This chapter reviews those values and formulas which are the fundamental parameters and calculations that construct the model. The input required by the user and generation of values from the model are discussed in Chapter Four.

The model is comprised of three sub-models for material production, the equipment used and the transport of the materials for construction, maintenance, rehabilitation and reconstruction of flexible pavement structure roadways. The processes that are used for the production of each material are detailed and the energy consumed and GHG emissions generated for each process are indicated. For the placement or removal of the materials the various types of equipment used are detailed. For the transport sub-model the type of truck, hauling capacity and truck fuel efficiency are discussed.

3.1 Flexible Pavement Structures

An asphalt pavement structure is a pavement that has a surface or wearing coarse that is constructed of asphalt. Asphalt pavements are also referred to as flexible pavements (Asphalt Institute 2007). Flexible pavements generally consist of a layered system including the subgrade, subbase, base and asphalt layers. A typical cross-section of a conventional flexible pavement structure is shown in Figure 3.1 (Asphalt Institute 2007).

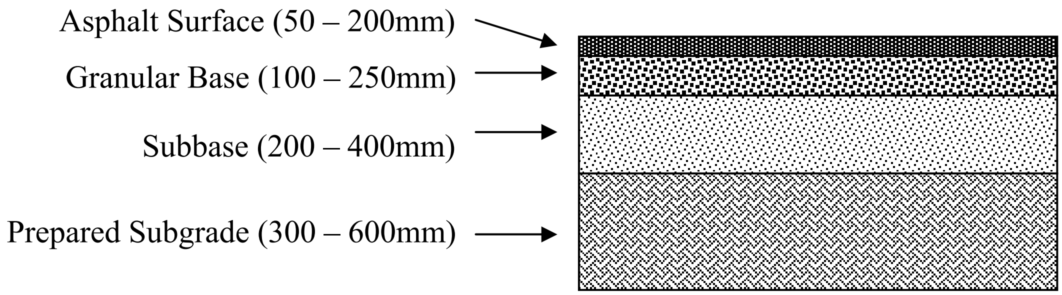

Figure 3.1 Typical Conventional Flexible Pavement Structure Composition and Layer Thickness (Reproduced from Asphalt Institute 2007.)

Within a flexible asphalt pavement structure, the subgrade is the foundation (TAC 1997). The subgrade typically consists of native material; however, when the grade line of the road needs to be raised imported material is typically used. The material properties and characteristics of the subgrade impact the long term performance of the road and as a result it is important to ensure that the subgrade is designed properly (TAC 1997). This model only considers the preparation of the subgrade once it has been brought to grade. The earthworks required to bring the subgrade to grade will not be considered.

The subbase layer is the first layer of the pavement structure on top of the subgrade which includes processed aggregate. The aggregate used in this layer is typically of higher quality relative to the subgrade material. The purpose of the subbase is to dissipate the traffic loads from the above layers to the subgrade and provide a buffer between the subgrade and the pavement structure above. The subbase layer is also used to transmit moisture and to protect the subgrade from frost (TAC 1997).

The granular base layer is a layer of processed aggregate that is placed on top of the prepared subbase. The purpose of the granular base layer is to transfer the traffic induced stresses from the above wearing course to the deeper structure further down and to direct water away from the surface layers (TAC 1997).

In conventional pavement structures the asphalt provides a smooth riding surface for users, an all-weather proof surface and typically only a minimal amount of structural support (Asphalt Institute 2007). Hot mix asphalt concrete (HMAC) is traditionally comprised of asphalt binder and granular aggregates; however, various types of asphalt mixes have been developed to meet the various *in situ* field state conditions that are experienced by road agencies and based on the local source aggregate materials that are available.

3.2 Material Quantities

To determine the amount of energy consumed and carbon generated in the construction of a roadway, the quantities of each material in the pavement structure must be known. The in-place compacted volume of each material in the pavement structure is determined by multiplying the area of the pavement by the average thickness of the material layer. The weight of the material can then be determined by multiplying the volume by the compacted in-place unit density of the material.

$$Total\ Weight\ Material\ =\ Area\ of\ Material * Thickness * Compacted\ Unit\ Density$$

Equation 3.1

The average compacted unit weight for all types of aggregates and HMAC used in the model are indicated in Table 3.1 (NRC 2005).

Table 3.1 Compacted Unit Densities for Aggregates and Asphalt Concrete

Material	Compacted Unit Density (t/m^3)
Asphalt Concrete Overlay	2.42
Asphalt Concrete Base	2.42
Virgin Granular Base Course	2.36
Recycled Base Course	2.01
Virgin Subbase	2.24
Recycled Subbase	1.91

3.3 Material Production Sub-model

The materials that compose the layers of a flexible pavement must be produced to meet specifications as set out by an agency (City of Saskatoon 2009, City of Edmonton 2009). Some of the layers that are included are composed of more than one material. Table A.1 in Appendix A lists all of the layers that may compose a flexible pavement structure. For each layer the materials that are considered in the model for production are indicated. The production of materials considered in the model described in further detail are:

- Traditional Aggregates;
- Recycled Portland Cement Concrete (PCC) Aggregates;
- Asphalt Cement, Polymer Modified Asphalt Cement and Asphalt Emulsion;
- HMAC (plant operations);
- Portland Cement; and
- Lime.

3.3.1 Aggregates (Traditional and Recycled)

Sources of aggregates can be divided into three groups – pit or bank-run materials, quarried, and synthetic and lightweight aggregates. Pit or bank-run materials are found in loose or unconsolidated alluvial deposits extracted without drilling or blasting. Quarried aggregates are natural aggregates that are produced from natural solid rock through crushing. Quarried aggregates will have more crushed faces compared to the pit or bank-run materials because of the crushing process (Asphalt Institute 2007). In Saskatchewan aggregates generally come from quarries.

The steps required to produce a quarried aggregate that may be used in roadway construction involve extracting, crushing, screening, washing, handling and stockpiling. When a location has been identified for a quarry, the first step is to remove the overburden material to access the rock deposit. Once the overburden material has been removed, drilling and blasting will be conducted to remove the rock. The rock will then be transported to a location for further processing.

Similar crushing processes are used for virgin and recycled aggregates. There are two main types of crushers – compression and impact. Compression crushers include jaw, cone, gyratory and roller. These crushers fracture the rock by squeezing the material between the crusher surfaces. With impact crushers the rock particles are impacted with crusher surfaces or other rocks, causing them to shatter (Asphalt Institute 2007). Berthelot et al. (2010) found that an impact crusher produced superior end products compared to a jaw and cone crusher.

The material characteristics including particle size and shape as well as the amount of fines generated through crushing will depend on feedstock materials, the type of crusher and the rate at which material is fed into the crusher. If the crushing process does not generate a material that is within the required gradation specifications for a certain material, the material will be required to be screened and run through the crusher again (Asphalt Institute 2007). Screening is completed to separate the aggregate by size.

3.3.2 Energy Consumption and Greenhouse Gas Emissions

The amount of energy that is required to extract and process one tonne of aggregate is summarized in Table 3.2 (Athena Institute 2006). The Athena Institute indicates that processing required for subbase is less than that of granular base course, and that only 25 percent of the energy required for processing granular base course is needed for subbase. The value included in the table for subbase processing is 25 percent of the average of the production of coarse and fine aggregates (Athena Institute 2006).

GHG emissions generated from the production of one tonne of aggregate are summarized in Table 3.3 (Athena Institute 2006). A sample calculation for CO_2e is included in Appendix B. The total amount of GHG emissions generated are proportioned based on the extraction energy and the average of the production of the coarse and fine aggregate production. The subbase values, similar to the energy production values, are one quarter of the processing production values.

Table 3.2 Energy Consumption for Aggregate Production (Athena Institute 2006)

	Coarse	**Fine**	**Subbase**
Extraction GJ/t (Diesel)	0.027	0.027	0.027
Processing GJ/t (Electric)	0.0108	0.0324	0.0054

Table 3.3 Greenhouse Gas Emissions for Aggregate Production (Athena Institute 2006)

Process	**CO_2**	**CH_4**	**N_2O**	**CO_2e**
	kg/t aggregate produced			
Extraction and Processing	7.965	0.007	~0.000	8.130
Extraction	4.425	0.004	~0.000	4.517
Processing (Avg Fine and Coarse)	3.540	0.003	~0.000	3.613
Processing Subbase	0.885	0.001	~0.000	0.903

3.3.3 Asphalt Cement, Polymer Modified Asphalt Cement and Asphalt Emulsion

Asphalt cement is a dark brown to black cementitous material and contains mainly bitumens that occur naturally or may be obtained through petroleum processing (Asphalt Institute 2007). During the processing of crude oil, the oil is separated into several fractions by high temperature distillation. The heavier fraction of the crude oil is turned into asphalt. The lighter fractions are turned into various types of fuel (Asphalt Institute 1998). To achieve asphalt cements with varying grades to meet various *in situ* conditions a refinery will mix crude from various sources (Asphalt Institute 1998).

The most common practice to produce polymer modified binders (PMBs) is to pre-blend the asphalt binder and the polymer at the refinery or terminal. Depending on the type of polymer, mixing may be completed by a mixing kettle while some may require shearing milling or other special mixing methods. The use of various PMBs have been found to prevent pavement deformation, rutting, fatigue and cold temperature cracking (Asphalt Institute 2007).

Asphalt emulsion production involves further processing of hot asphalt cement by combining it with an emulsifying agent in water and mechanically separating the bitumen into droplets. The advantages of asphalt emulsions are that the viscosity is considerably lower than asphalt cement and as a result it can be applied at lower temperatures. Asphalt emulsions are also compatible with binders such as cement and lime and can be diluted with water (James 2006).

3.3.4 Energy Consumption and Greenhouse Gas Emissions

Eurobitume (European Bitumen Association) conducted a lifecycle analysis for the production of asphalt cement from extraction of the raw bitumen to the time the asphalt cement leaves the production plant. The processes that were considered are the extraction of oil, transportation to the refinery, production and storage of the finished product at the refinery.

Transportation to the asphalt plant is not included. This analysis was conducted based on the most recent information available from European oil producers and refineries. Raw crude oil, when refined, can be processed into many different end products. The values determined by Eurobitume are proportioned to represent the amount of energy consumed and GHGs generated by just the materials that compose the asphalt cement end product. As such, the values for extraction and transport have been divided by the mass balance at the refinery based on relative economic values (Eurobitume 2011). The energy consumption values and emissions generated for asphalt cement, PMB and asphalt emulsion production are determined. The internal energy of the materials will not be considered.

The energy consumed and CO_2e emissions generated for the transportation of the oil from its source to the refinery is assumed to be transported by pipeline for a distance of 100 km. The summary of values for the energy consumed for the production of one tonne of asphalt cement is included in Table 3.4 (Eurobitume 2011).

CO_2 is generated from the flaring and combustion of fuels for the production of energy in the manufacturing process. CO_2e emission values determined for the production of asphalt cement are summarized in Table 3.5 (Eurobitume 2011). Transport values are based on the amount of diesel used to generate the electricity needed to move oil through a pipeline to a refinery. Refer to Appendix B for this calculation.

Table 3.4 Energy Consumption for Asphalt Cement Production (Eurobitume 2011)

	Unit	**Crude Oil Extraction**	**Transport***	**Refinery**	**Storage**	**Total**
Energy	MJ/t	1030	11.2	510	100	1651.2

* Refer to Appendix B for the detailed calculation of the value.

Table 3.5 Greenhouse Gas Emissions from Asphalt Cement Production (Eurobitume 2011)*

	Unit	Crude Oil Extraction	Transport+	Refinery	Storage	Total
CO_2	kg/t	99.135	0.799	37.2	7.831	144.965
CH_4	kg/t	0.548	~0.000	0.025	0.060	0.633
CO_2e	kg/t	110.643	0.799	37.725	9.091	158.258

* No values for N_20 provided (assumed to be negligible).

+ Refer to Appendix B for the detailed calculation of the value.

Eurobitume reviewed the energy consumed and GHG emissions that are associated with the production of the most commonly used PMB, styrene butadiene styrene (SBS). On average, the PMB is composed of 96.5 percent asphalt cement and 3.5 percent SBS by weight. The amount of energy consumed for the production of asphalt cement is based on the total values presented in Table 3.6. The value for production and transport of the SBS are calculated based on the fuel used as shown in Appendix B. The GHG emissions associated with the production of one tonne of a PMB are summarized in Table 3.7.

Table 3.6 Energy Consumption for PMA Production (Eurobitume 2011)

	Unit	Asphalt Cement	SBS (Production & Transport)*	PMB Milling	Total
Energy	MJ/t	1593.4	2377.8	72.0	4043.2

* Refer to Appendix B for the detailed calculation of the value.

Table 3.7 Greenhouse Gas Emissions for PMA Production (Eurobitume 2011)*

	Unit	Asphalt Cement	SBS (Production & Transport)	PMB Milling	Total
CO_2	kg/t	139.891	117.719	10.056	267.656
CH_4	kg/t	0.611	0.574	0.018	1.203
CO_2e	kg/t	152.72	129.773	10.424	292.919

* No values for N_20 provided (assumed to be negligible).

Eurobitume also reviewed the energy consumed and GHG emissions that were associated with the production of 1.524 t of emulsion from one tonne of residual asphalt cement. A cationic emulsion formula for the most common emulsion used in Europe was considered. By mass, the formula is 65 percent asphalt cement, 0.3 percent emulsifier and hydrochloric acid (HCl) and 34.4 percent water. The energy consumption values and CO_2e emissions associated with the production of 1.54 t emulsion (one tonne residual asphalt cement) are summarized in Table 3.8 and Table 3.9. The values included for the energy consumed during the production and transport of the emulsifier and HCl are calculated based on the fuel consumed (Eurobitume 2011). Refer to Appendix B for these calculations.

Table 3.8 Energy Consumption for Asphalt Emulsion Production (Eurobitume 2011)

	Unit	**Asphalt Cement**	**Emulsifier***	**HCl***	**Hot Water**	**Emulsion Milling**	**Total**
Energy	MJ/t	1651.2	76.2	48.8	74	111	1961.2

* Refer to Appendix B for the detailed calculation of the value.

Table 3.9 Greenhouse Gas Emissions from Asphalt Emulsion Production (Eurobitume 2011)*

	Unit	**Asphalt Cement**	**Emulsifier**	**HCl**	**Hot Water**	**Emulsion Milling**	**Total**
CO_2	kg/t	144.965	4.602	3.985	5.459	15.455	174.466
CH_4	kg/t	0.633	0.006	0.008	0.004	0.003	0.653
CO_2e	kg/t	158.258	4.728	4.147	5.537	15.514	188.183

* No values for N_20 provided (assumed to be negligible).

3.3.5 Hot Mix Asphalt Concrete (HMAC)

For the production of HMAC there are two types of plant facilities / production processes that are used: batch facilities and drum-mix facilities. Batch facilities were initially used for HMAC production and were popular until the 1970s, when drum-mix facilities were introduced.

In North America 80 percent of the HMAC that is produced is from drum-mix facilities (Asphalt Institute 2007). Two pieces of equipment that are similar in both facilities that consume large amounts of energy are the storage unit for the asphalt cement and the aggregate dryer.

Batch facilities produce HMAC in batches. A typical layout of a batch facility is included in Figure 3.2 (Asphalt Institute 1998). The aggregates are first portioned from the cold feed bins onto a conveyor belt, which takes them to the dryer. Once the aggregates are dried and heated they are placed into the batch tower to be screened by size and placed in hot bins. From the hot bins the aggregates are portioned by weight and the asphalt cement is weighed. The aggregates are first placed into the pug mill and mixed before the asphalt cement is added. Mixing continues until the aggregate has been thoroughly coated with the asphalt cement. Mixing usually takes between 25 – 45 seconds (Asphalt Institute 2007).

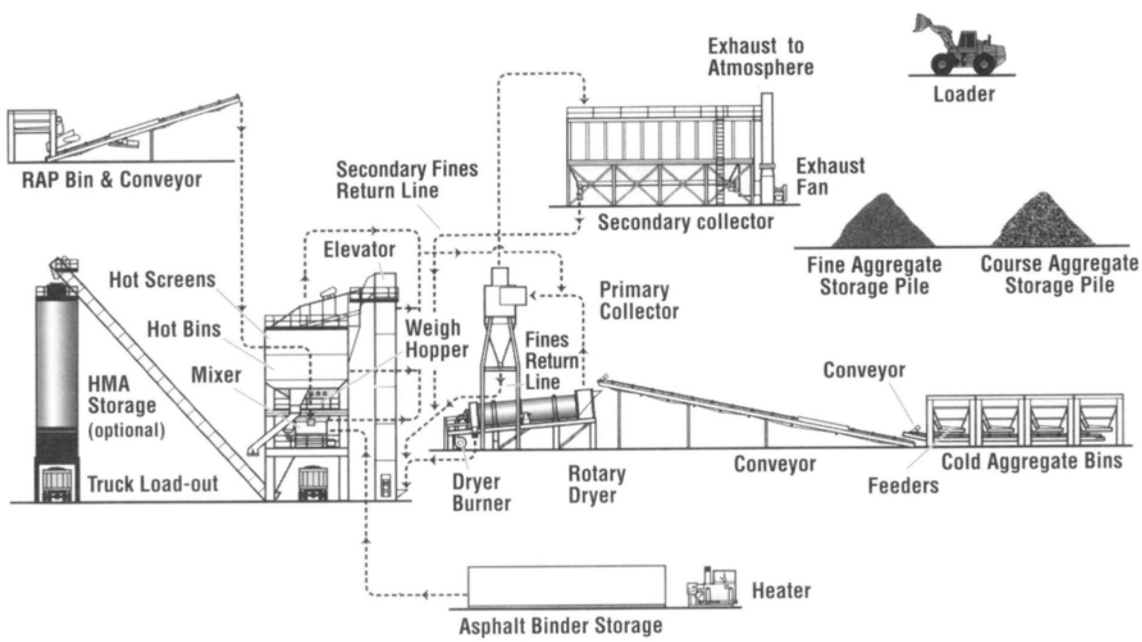

Figure 3.2 Typical Batch Facility (Asphalt Institute 1998)

Drum-mix facilities have a continuous flow of HMAC production as long as materials are available. A typical layout of a drum-mix facility is included in Figure 3.3 (Asphalt Institute

1998). The aggregates are proportioned directly from the cold feed bins. The aggregates then enter the drum to be dried and heated. Based on the weight of the proportioned aggregate the amount of asphalt cement required is weighed out. Drum-mix plants can either have one drum that dries/heats the aggregate and mixes in the asphalt cement or the dryer and the mixing drum can be separate (Asphalt Institute 2007).

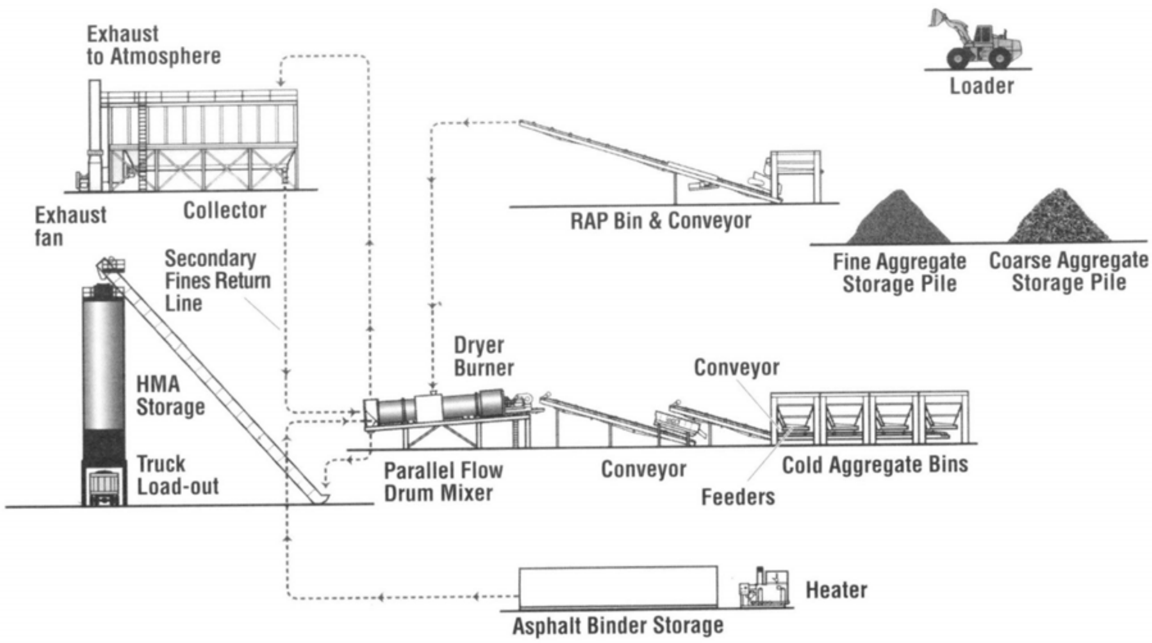

Figure 3.3 Typical Drum-Mix Facility (Asphalt Institute 1998)

For the aggregate and asphalt cement to be properly mixed, a specified mixing temperature must be maintained. The aggregate is dried and heated within the dryer and the asphalt cement must be heated prior to it being mixed with the aggregate. At batch and drum-mix plants, the asphalt cement is stored in insulated and heated tanks (Asphalt Institute 2007).

Dryers consist of a burner and a fan at one end of the dryer that create a hot gas stream that heats and dries the aggregate. The dryer is inclined and it rotates, allowing the aggregate to be picked up and dropped through the gas stream. The typical retention time of material in the dryer is three to five minutes but this depends upon the dryer size, length, incline and flight configuration (Asphalt Institute 2007). There are two types of dryers: parallel and counter flow, based on the movement of the aggregate in comparison to the direction of the gas stream (Asphalt Institute 1998).

Significant amounts of energy are used to heat an asphalt mix to the temperature that is required to be met for hot mixes. In Europe warm mix technologies have been used for a number of years. These technologies allow mixing of the binder and aggregate to occur at temperatures that are up to 30 percent less than hot mixes reducing the amount of energy that is required and the emissions that are being emitted (Asphalt Institute 2007). The technologies that are utilized for warm mixes include: organic additives, foaming technologies, bituminous emulsions, chemical additives and mixing process modifications (Croteau 2008).

Cold mixes are unheated mineral aggregates mixed with cutback or emulsified asphalts which are divided into two groups: plant mix and mixed-in-place (Asphalt Institute 1989).

3.3.6 Energy Consumption and Greenhouse Gas Emissions

Table 3.10 summarizes the information that was gathered from seven Canadian asphalt plants on the amount of energy used to mix one tonne of asphalt concrete (NRC 2005). There is no distinction in the value for whether a batch of drum-mix plant is used. The US Environmental Protection Agency (US EPA) has developed CO_2 and CH_4 emission factors for batch and drum-mix asphalt plants based on collected information from over 350 plants. The values are summarized in Table 3.11 (US EPA 1995). The values for CO_2 may be used for dryers fueled by natural gas, propane, butane, coal, fuel oil or waste oil (RTI International 2004).

Table 3.10 Energy Consumed for Asphalt Concrete Production (NRC 2005)

	Low	**Average**	**High**
Energy MJ/t	356	406	443

Table 3.11 Greenhouse Gas Emissions for Asphalt Concrete Production (US EPA 1995)*

Plant Type	**CO_2**		**CH_4**	
	Average	**Std. Dev.**	**Average**	**Std. Dev.**
Batch Mix (kg/t)	18.5	11	0.004	Unavailable
Drum-Mix (kg/t)	16.5	6.5	0.006	Unavailable

* No information available for N_20 (assumed to be negligible).

3.3.7 Portland Cement

The first step required to produce Portland cement is to extract the required raw materials which may include limestone, shale, chalk, clay and sand. The raw materials are then crushed, ground and monitored to ensure the proper proportions of materials are present. The material is then preheated to 260°C before it goes into the rotary kiln where the material is heated to 1,450°C and a product called clinker is produced. The clinker material is cooled and mixed with gypsum and potentially other industrial byproduct materials such as fly ash; it is then ground, resulting in the production of Portland cement (WBCSD and IEA 2009, Cardarelli 2008). In flexible pavement roadways Portland cement is used as a stabilizing agent.

3.3.8 Energy Consumption and Greenhouse Gas Emissions

Electricity and fuel costs are almost 40 percent of the cost of manufacturing cement. The age and type of kiln used are the main factors influencing the efficiency of cement production. In Canada, 55 percent of the Portland cement produced comes from plants that were built after 1980. The modernization of Canadian plants continued, and between 1990 and 2008 there was a 16 percent reduction in energy consumption (CAC 2010).

Published information on the amount of energy consumed through the production of Portland cement was collected from two sources – The Cement Association of Canada (CAC) and The World Business Council for Sustainable Development (WBCSD). The energy consumption rates are summarized in Table 3.12 (CAC 2010, WBCSD and IEA 2009). Electrical energy is typically used for the grinding of the materials.

Table 3.12 Energy Consumption for Cement Production (WBCSD and IEA 2009)

	CAC		**WBCSD**
	2006	**2008**	**2006**
Clinker to Cement Ratio (%)	85	83	79
Thermal Energy Efficiency (GJ/t clinker)	3.882	3.883	4.200
Electrical Energy Efficiency (GJ/t cement)	0.474	0.484	0.400
Electrical Energy Efficiency (kWh/t cement)	132	134	111
Overall Energy Efficiency (GJ/t cement)	3.785	3.704	3.718*

* Calculated based on clinker to cement ratio.

It is estimated that the production of Portland cement accounts for approximately five percent of the world's man-made GHGs. CO_2 is the primary pollutant that is generated and Figure 3.4 shows the proportions of CO_2 that are generated for various production steps (WBCSD 2005).

Published information on the amount of CO_2 generated through the production of Portland cement was also collected from the CAC and the WBCSD. The emission rates for production of Portland cement are summarized in Table 3.13 (CAC 2010, WBCSD and IEA 2009).

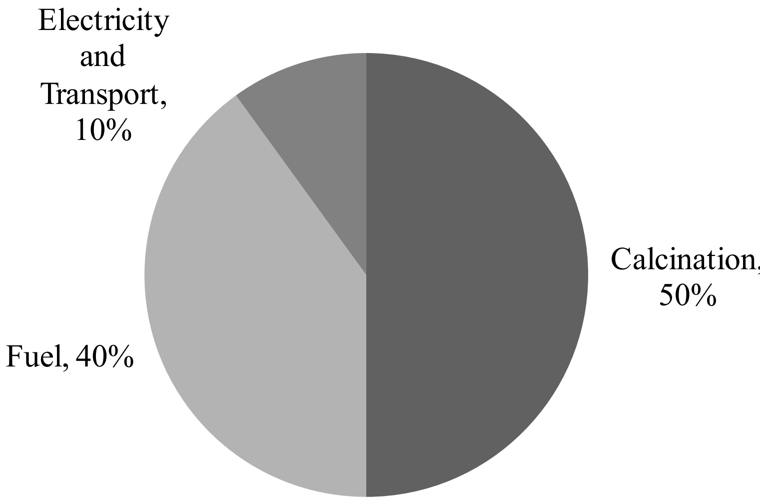

Figure 3.4 Distribution of CO_2 Emissions in Portland Cement Production (Reproduced from WBCSD 2005.)

Table 3.13 Greenhouse Gas Emissions for Portland Cement Production (CAC 2010, WBCSD and IEA 2009)

	2006	**2008**
	CO_2 Emissions (kg CO_2 / tonne cement)	
CAC	769	732
WBCSD	800	NA

3.3.9 Lime

Similar to the production of cement, lime manufacturing involves the extraction of raw materials including limestone, dolomite, aragonite, chalk, choral, marble and sea shells. After the material is extracted, it goes through crushing and screening prior to entering the kiln. In the kiln, the material is heated until it is calcinated. Through the manufacturing of lime, CO_2 is produced through the chemical reaction that occurs to create the lime and from the fuel that is required to heat the kiln. A rotary kiln is used in 90 percent of the plants producing lime in the United States (US EPA 1995). In roadways lime may be used as a stabilizing agent and as an anti-stripping agent in HMAC (Boynton 1980).

3.3.10 Energy Consumption and Greenhouse Gas Emissions

The manufacturing of lime is energy intensive and approximately half of the costs are due to the fuel that is consumed during production (Bes 2006). It is reported that the energy usage for kilns can range from 3.6 to 7.5 GJ/t of lime produced for vertical double shaft kilns and non-preheated long rotary kilns respectively (Meier et al. 2006).

The GHG emissions generated through the manufacturing of lime are separated into two categories: those from the chemical reaction that occur in the process of making the lime and the emissions generated through the combustion of the fuel that is required. For the production of lime from dolomitic and calcitic limestone the chemical process accounts for 915 kg/t and 785 kg/t respectively (Davis 2000). For a coal fired rotary kiln, the total CO_2 emissions are 1600 kg/t of lime produced (Davis 2000).

3.4 Material Hauling Sub-model

The material hauling sub-model accounts for material hauling to production facilities, to site for placement or from site for disposal. A number of material transport related factors are considered for each transport link. These include haul distance, truck capacity, truck efficiency and road weight restrictions. The various transport links of the materials considered in the model are summarized in Figure 3.5.

3.4.1 Truck Capacity

Truck capacities vary depending on a number of factors including: the size of the truck trailer, the maximum weight that the truck can hold, the allowable weights, and the dimensions of the roadway upon which is being travelled. For the purposes of this study two types of trucks are considered: a typical smaller medium duty end dump truck with two or three axles and a typical heavy duty larger truck with six or eight axles. Refer to Figure 3.6 and Figure 3.7 for pictures of the trucks typically used for hauling. The capacities of these trucks used for this model are summarized in Table 3.14.

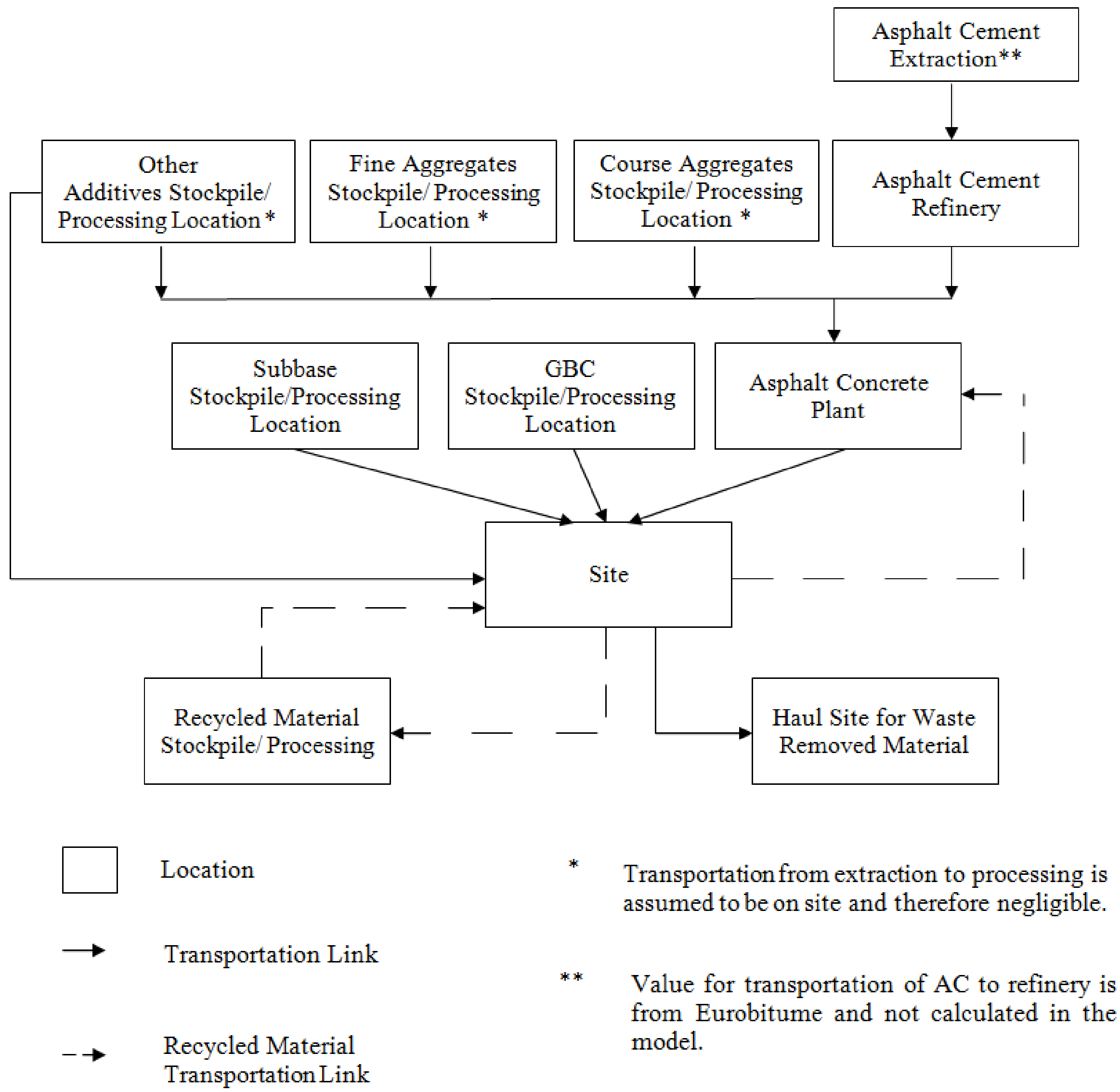

Figure 3.5 Material Transport Sub-model Framework

Figure 3.6 Typical Three Axle Haul Truck (Courtesy Dr. C. Berthelot)

Figure 3.7 Eight Axle Haul Truck (Courtesy Dr. C. Berthelot)

Table 3.14 Typical Capacities of Small and Large Haul Trucks Considered

Truck	Axle	Haul Weight (t)
Small (Medium Duty)	3	10
Large (Heavy Duty)	6	25
	8	40

3.4.2 Road Weight Restrictions

Government agencies in the spring may reduce the weight limits that are allowed on the roadway networks to protect their infrastructure. When weight restrictions are imposed on trucks the amount of material that may be transported in each load may need to be less than the full volume of the truck. Road weight restrictions increase the amount of energy that is consumed and the amount of CO_2e emissions generated for a construction project.

3.4.3 Truck Fuel Efficiency

There are many factors that influence the fuel efficiency of trucks including environmental and road characteristics as well as vehicle configuration and loading. For this model, average fuel efficiencies as indicated in Table 3.15 will be used as determined by Natural Resources Canada (2006).

Table 3.15 Average Fuel Efficiencies for Medium and Heavy Duty Trucks (NRC 2006)

Truck	Fuel	Average Fuel Efficiency (l/100km)
Medium Duty	Diesel	21.6
Heavy Duty	Diesel	39.5

3.4.4 Fuel Consumption

The generic form of the calculation to determine the amount of fuel consumed from the transportation of materials is:

$$Total\ Fuel = \sum_{Material\ Type}^{n} Truck\ Trips \times km\ Travelled \times Truck\ Fuel\ Efficiency \div Road\ Weight\ Restriction$$

Equation 3.2

where:

Truck Trips	=	the total amount of material hauled divided by the truck capacity
km Travelled	=	the number of kilometers travelled from load to unload site (if the truck goes back to the load site empty the round trip distance should be entered)
Truck Fuel Efficiency	=	fuel efficiency of the truck, l/100km
Road Weight Restriction	=	the decimal percent of the allowed primary weight capacity allowed on the roadway

3.4.5 Energy Consumption and Greenhouse Gas Emissions

The amount of energy consumed by the trucks used for hauling is determined by using the heat content of the type of fuel consumed by a truck. The heat content of fuel is based on a number of parameters that include the chemical constituents, the impurities of fuel and the temperature and climatic conditions (Davis 2011). The average value for the heat content of diesel used in this model is 37.3 MJ/l (Davis 2011). Depending on the parameters affecting the heat content of the fuel, the difference between the high and low values can be between five to eight percent (Davis 2011).

To quantify the CO_2e emissions generated from the transportation of materials, the emission factors based on the amount of fuel consumed in Table 3.16 are used (Environment Canada 2008).

Table 3.16 Greenhouse Gas Emissions Factors for Trucks (Environment Canada 2008)

Fuel	Greenhouse Gas (g/l)			
	CO_2	CH_4	N_2O	CO_2e
Diesel	2,663	0.12	0.082	2,691

3.5 Equipment Usage Sub-model

The equipment usage sub-model was constructed based on typical equipment usage rates and the fuel efficiency of each piece of equipment required for construction of the specific pavement structure. In 1990, the US EPA instituted a tiered system to reduce the emissions from non-highway diesel engines. The system consists of four tiers and the final tier is to be implemented from 2012 to 2015. Canada began regulating the emissions from non-highway diesel engines in 2000. The Canadian Off-Road Compression-Ignition Engine Emission Standards were released in 2006, which brought the Canadian engine standards similar to those of the U.S. (BCRBHCA 2011). Typical equipment that is used for various roadway construction, maintenance and rehabilitation treatment is listed in Table A.2 in Appendix A and is described briefly in the following sub-sections.

3.5.1 Soil Stabilization Equipment

Stabilization is often done when preparing the subgrade of a roadway to provide a good stiff foundation. Only cement stabilization will be considered in this work. The equipment required for cement stabilization includes a spreader to distribute the cement evenly and a mixer to mix the cement into the subgrade.

Prior to the subbase or granular base being placed, the cement stabilized subgrade must meet minimum compaction specifications which are achieved with the use of compaction equipment as discussed in the following section.

3.5.2 Compaction Equipment

Compaction of materials is important to roadway construction and the long term performance of a roadway. Compaction improves soil properties to reduce settlement, increase strength, improve bearing capacity, control volume changes and lower permeability (Peurifoy et al. 2006). Compaction is achieved through the application of energy through impact, pressure, vibration and kneading of a material. Impact is achieved through a sharp blow, pressure through a static weight, vibration through shaking and kneading through manipulation/rearranging (Peurifoy et al. 2006).

The types of compaction equipment that are typically used for road construction include self propelled static steel-wheel, pneumatic-tire and vibratory rollers. Sheepsfoot rollers are also used to compact earth fill materials or to aerate soils that are above their optimum moisture content. Refer to Figure 3.8 and Figure 3.9 (Simpson 2006) for pictures of a steel-wheel compactor and a pneumatic-tire roller.

3.5.3 Motor Grader

A motor grader is used for a number of tasks within a construction site, including rough and fine grading, bank and back sloping, ripping and scarifing (Day and Benjamin 1991). Refer to Figure 3.10 for a picture of a typical motor grader.

Figure 3.8 Steel-Wheel Roller (Courtesy Dr. C. Berthelot)

Figure 3.9 Pneumatic-Tire Roller (Simpson 2006)

Figure 3.10 Motor Grader (Courtesy Dr. C. Berthelot)

3.5.4 Asphalt Paving Equipment

Prior to placing HMAC on a granular base, a prime coat is often applied. It is an emulsion which is used to protect the granular base layer from construction equipment, it provides waterproofing and assists in bonding the HMAC to the granular base. A tack coat, which is either hot asphalt cement or an emulsion, is applied prior to the placement of a new layer of HMAC on an existing layer of HMAC. The tack cost is used to bond the two layers of asphalt together. Prime and tack coats are sprayed using an asphalt distributor. The distributor consists of a truck or trailer with an insulated tank and heating system to keep the asphalt hot. The distributor releases the asphalt through a spray bar to evenly coat the existing pavement surface (Asphalt Institute 2007). A typical distributor is shown in Figure 3.11.

Asphalt pavers are comprised of three main parts – the material handling system, the screed and the tractor (Asphalt Institute 2007). The hopper is part of the material handling system and is where the HMAC is transferred from a truck, pickup machine or a material transfer device. From the hopper the HMAC is moved by augers to the screed. The screed controls the thickness and cross section of the HMAC that is being placed. The paver is powered by either a tractor or rubber tire mounted system (Peurifoy et al. 2006). A typical asphalt paver is shown in Figure 3.12.

After the HMAC has been placed with the asphalt paver, compaction of the HMAC must be completed. This is conducted with vibratory steel wheel and pneumatic rollers as described in section 3.5.2.

Figure 3.11 Asphalt Distributor (Courtesy Dr. C. Berthelot)

Figure 3.12 Asphalt Paver (Caterpillar 2012)

3.5.5 In-Place Recycling Equipment

There are a number of benefits to in-place recycling including the reuse of materials which not only reduces the amount of virgin aggregate required but also reduces the impact that hauling material in and out of the site has on the surrounding roadways. Two types of cold in-place recycling will be reviewed including cold in-place recycling and full depth reclamation. Hot in-place recycling is also used within the industry but is not reviewed and is considered out of scope of this work.

3.5.5.1 Cold in-Place Recycling (CIPR)

Cold in-place recycling (CIPR) can be used to address pavement distresses such as transverse, fatigue and reflection cracking. The first step is to mill the existing asphalt to a specified depth between 50 to 125 mm. If necessary, the material is screened, crushed and aggregate is added, followed by the material being mixed with an asphalt emulsion and other additives such as cement or lime. Depending on the project, single-unit, two-unit or multi-unit trains can be used for CIPR. A single-unit train mills the asphalt, sizes the reclaimed asphalt pavement (RAP) and blends at the cutting head. A two-unit train is comprised of a milling machine and a pugmill mixer-paver that mixes the millings, emulsion and other additives. The multi-train consists of a milling machine, portable screener, crusher and pugmill. The advantage of the multi-train is that the crushing and screening provide a better gradation and improved final product (Asphalt Institute 2007). Figure 3.13 shows a CIPR multi-train system (Hot-Mix Magazine 2012).

The material produced through the train can either be placed in a windrow or it can be placed by a traditional paver, but without heat. After the material is placed on the roadway it is compacted with the equipment described in Section 3.5.2. As CIPR is a mix that has a high air-void content, a wearing course of HMAC is added (Asphalt Institute 2007).

Figure 3.13 Cold In-Place Multi-Train System (Hot-Mix Magazine 2012)

3.5.5.2 Full Depth Reclamation (FDR)

The process of full depth reclamation (FDR) uses the existing pavement materials on-site by pulverizing the entire asphalt pavement layer and a portion of the underlying granular layer. From the pulverized material, a stabilized base layer is constructed through mechanical, asphalt and/or chemical stabilization. An FDR reclaimer that is used to pulverize the material in-place is shown in Figure 3.14.

Figure 3.14 Full Depth Reclamation Reclaimer (Courtesy Dr. C. Berthelot)

Multiple passes with the reclaimer are required to mix the material. A grader is also needed to spread and fine grade the pulverized material. Compaction of the material is achieved with pneumatic or steel-wheel rollers. A wearing course of HMAC is also added (Asphalt Institute 2007).

3.5.6 Asphalt Surface Treatments

Asphalt surface treatments are long lasting, easy to place and economical. They add life to a roadway surface by providing a waterproof seal and help to resist wear from traffic. Before any work is started, an examination of the surface should be completed to determine if any major repairs are required for the existing pavement structure; these repairs should be completed prior to a surface treatment being placed. The surface should also be cleaned, typically with a street sweeper, prior to the placement of the surface treatment so that the asphalt emulsion can bond to the existing pavement (Asphalt Institute 2007).

Spray applied seals that are considered in the model are fog seals and rejuvenators. A fog seal involves the application of a slow setting emulsion which is able to flow into cracks and surface voids. Rejuvenators are used to rejuvenate the maltenes in the asphalt cement. Maltenes are the liquid fraction of asphalt cement, which oxidize over time making an asphalt dry and brittle. Rejuvenators can be used for maintenance purposes like a fog seal but are also used in recycling processes to restore the asphalt binder (Asphalt Institute 2007).

Chip seals involve the spray application of asphalt and then the application of a uniform sized aggregate that is raked in and compacted. The application of a chip seal protects the underlying pavement structure from weathering and provides skid resistance for vehicles. Multiple layers of chip seal can be applied (Asphalt Institute 2007). Figure 3.15 shows a roadway surface where a chip seal has been applied.

Slurry seals are composed of well-graded fine aggregate, emulsified asphalt and a mineral filler if required and are used for preventative and corrective maintenance. The machine that is used for the placement of a slurry seal is a self-contained continuous flow mixing unit that mixes the aggregate, mineral filler and emulsion to a designated amount within a mixing chamber and then is discharged into the spreader box for placement. Rolling the slurry seal with a pneumatic roller will improve durability but only in places of high wear (Asphalt Institute 2007). Figure 3.16 shows a roadway surface where a slurry seal has been applied.

Micro surfacing is similar to a slurry seal except that a stiffer polymer modified binder rather than an emulsified asphalt is used. With a stiffer mix the thickness of the layer that is placed can be up to 75 mm. Figure 3.17 shows a roadway surface where a micro surface has been applied.

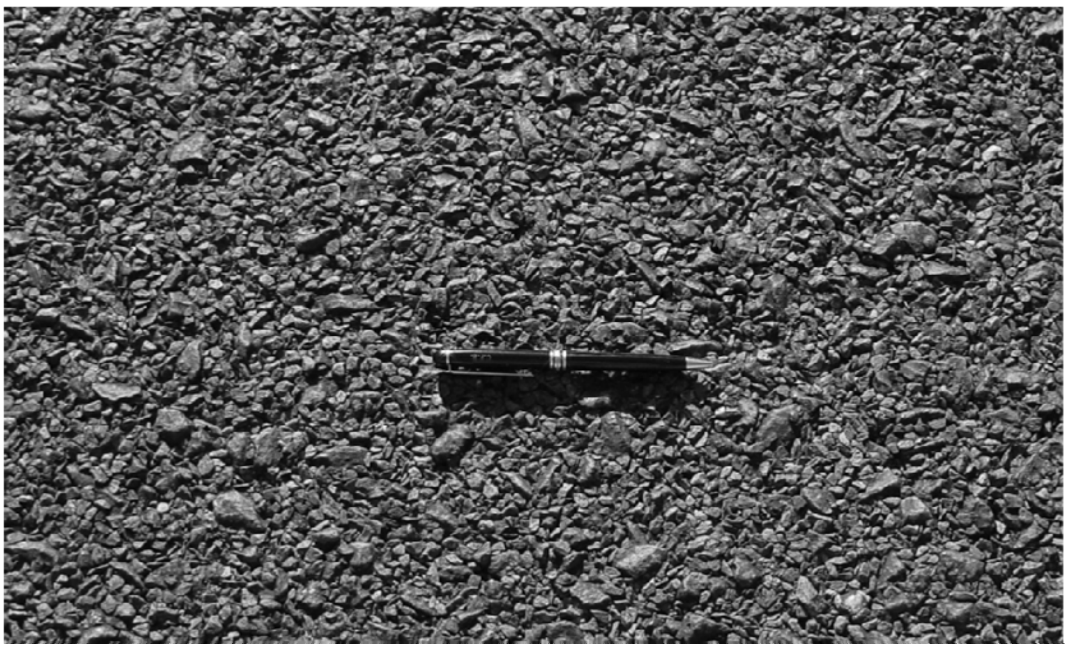

Figure 3.15 Chip Seal (Courtesy Dr. C. Berthelot)

Figure 3.16 Slurry Seal

Figure 3.17 Micro Surface (Courtesy Dr. C. Berthelot)

3.5.6.1 Equipment Used for Asphalt Surface Treatments

An asphalt distributor is required for surface treatments as described in section 3.5.4. For chip seal, an aggregate spreader is also required. There are three types of spreaders available: a tailgate spreader, mechanical spreader and a self propelled spreader. Specialized equipment is required for slurry seal and micro surfacing placement.

3.5.7 Removal Equipment

Milling or grinding of an asphalt surface is completed when a layer of the wearing asphalt surface pavement coarse is removed. A milling machine consists of a rotating drum with carbide teeth and removes asphalt as the teeth strike the pavement (Roberts et al. 1996). A milling machine is shown in Figure 3.18 (Performance Paving 2012).

Figure 3.18 Milling Machine (Performance Paving 2012)

These machines have a considerable amount of control in the longitudinal and transverse directions. The material that is generated through the milling process can be collected and reused in future mixes (Roberts et al. 1996).

In some cases where the entire pavement structure must be removed first, the asphalt pavement will be broken up, loaded into a truck and hauled off site. The granular base coarse and any other material below the asphalt will be removed, loaded and hauled off site.

3.5.8 Placement Rates

The rate at which a pavement structure can be constructed is dependent upon many variables including the equipment being used, the operator and the site conditions. The placement rate per day, based on eight hours of work, used in this model is summarized by layer type in Table A.3 in Appendix A.

3.5.9 Equipment Fuel Efficiency

The fuel efficiency of any piece of equipment depends on many factors including the condition of the equipment, engine size, the operator, load factor, the design of the equipment and the environmental conditions (FAO 1992). To estimate the fuel efficiency of a piece of equipment the following equation can be used (FAO 1992, USACE 2009):

$$EFE = \frac{HP \times HPF \times FC}{FW}$$

Equation 3.3

where:

EFE	=	equipment efficiency, l/hr
HP	=	rated horsepower of the engine, hp
HPF	=	horsepower factor which represents the average percent of full-rated horsepower that is used by the engine under average working conditions
FC	=	fuel consumption, kg/bhp-hr
FW	=	weight of fuel, kg/l

Note: The sum of the product of HP x HPF for the equipment used in each treatment layer is entered into the model. The values entered for each layer of treatment are summarized in Table A.4 in Appendix A.

The US Army Corp of Engineers has determined average values for horsepower factor (HPF) for various types of equipment that are used in the equation above. For the equipment that will be used in this model the values are summarized in Table A.2 in Appendix A. The values for average fuel consumption and unit weight for diesel are summarized in Table 3.17 (FAO 1992).

Table 3.17 Weight and Fuel Consumption Values (FAO 1992)

Fuel	**Weight (FW) kg/l**	**Fuel Consumption kg/bhp-hr**
Diesel	0.84	0.17

The equation to determine the total amount of fuel consumed for material placement is:

$$Total\ Fuel = \sum\nolimits_{Layer} \frac{Material\ Quantity}{Placement\ Rate} \times EFE$$

Equation 3.4

where:

Material Quantity	=	total quantity of material placed in layer
Placement Rate	=	rate at which the equipment can place material
EFE	=	equipment fuel efficiency

3.5.10 Energy Consumption and Greenhouse Gas Emissions

The amount of energy consumed will be based on the heat content of the type of fuel consumed and the amount of fuel that is consumed by the respective piece of equipment that is being used. The heat content of diesel fuel is 37.3 MJ/l as described in section 3.4.5.

To quantify the GHG emissions generated from the placement of materials the emission factors based on the amount of fuel consumed in Table 3.18 are used (CCAR 2009).

Table 3.18 Greenhouse Gas Emissions Factors for Construction Equipment (CCAR 2009)

Fuel	**Greenhouse Gas (g/l)**			
	CO_2	**CH_4**	**N_2O**	**CO_2e**
Diesel	2,682	0.38	0.069	2,712

3.6 Summary

This chapter summarized the key parameters that are used to construct the material production, material transport and equipment usage sub-models. The values presented within this chapter for energy consumption and GHG emissions generated are the basis of the model. The values that are independent and may be required to be adjusted based on the pavement structure, material composition and material location that are required to be determined by the user are described in Chapter Four. A summary of the values detailed in this chapter are included in Table 4.2 to Table 4.5 in Chapter Four.

Chapter 4

COMPUTATIONAL MODEL FORMULATION

This chapter discusses the methods used to formulate the model based on the parameters and calculations described in Chapter Three to determine the energy consumed and CO_2e emissions generated through alternative methods of roadway maintenance, rehabilitation and reconstruction. The inputs required by the user and the generation of values from the model are discussed in this chapter. A base case study that reviews the construction of a lane-km of a typical Saskatchewan highway is used to generate values that are used as inputs.

The values collected for model inputs as described in Chapter Three are summarized, and low and high values for each parameter are assigned. The values determined for the energy consumed and CO_2e emissions from this model are compared to published values in Chapter Six.

The initial validation case study begins with the quantification of the initial construction of a pavement structure with virgin materials. Then, various maintenance, rehabilitation and reconstruction options as listed in Table 4.1 are evaluated for the same area.

The designs that are used to compare the alternative methods of maintenance, rehabilitation and reconstruction are assumed to have comparable strength and performance. The testing and analysis of the materials used are considered out of scope of this work.

Table 4.1 Roadway Maintenance, Rehabilitation and Reconstruction Methods

Category	Work
Maintenance	
	Fog Seal Slurry Seal Micro Surfacing Chip Seal 25mm Ultra Thin HMAC Overlay (UTO)
Rehabilitation	
	Mill and Fill Cold in-Place Recycling (CIPR)
Reconstruction	
	Full Depth Reclamation (FDR) Remove and Replace with Virgin Materials (R&R Virgin) Remove and Replace with Off-Site Recycled Materials (R&R Recycled)

4.1 Model Variables

The model created is based on a discrete probabilistic framework and developed in the program Decision Programming Language (DPL). DPL is a program that provides an interface for users to develop influence diagrams and enter values with a range of values and varying probabilities. The influence diagrams of the energy consumption sub-models for materials production, placement and transport are included in Appendix C. The values presented in Chapter Three are used for the average/most likely (Avg/ML) value for the model. When the low and high values were not indicated in Chapter Three for parameters, low and high values were assumed. All of the variables entered into the model are summarized in Table 4.2 to Table 4.5. Table 4.2 summarizes the compacted densities of materials and the unit weight of asphalt emulsion, Table 4.3 includes model information for trucks and fuel and Table 4.4 and Table 4.5 summarize the energy consumption and CO_2e variables respectively for material production. For truck capacity it is assumed that all trucks will always be loaded to the maximum allowable weight.

The model input information for equipment was discussed in Chapter Three and is included in Appendix A. The design information for each layer or treatment is indicated in each case study.

The Avg/ML values for a material production, placement or transport rate variable were assigned based on published values. The low and high values were assumed to be above or below the Avg/ML value by five percent except for when other information was available, as was the case with GHG emissions for Portland cement and HMAC production. For truck fuel efficiency, five percent of the Avg/ML values was used for the low values and 25 percent for the high values.

For the design parameters of each treatment, a range of values was found in the literature for the amount of materials recommended. The low and high values were determined based on these ranges and the Avg/ML values were determined as the average of the high and low values. The probability distribution used for all of the variables was assumed to be 0.3 for the low and high values and 0.4 for the Avg/ML.

Table 4.2 Unit Densities Model Variables

Material	Unit	Low	Avg /ML	High
Asphalt Concrete Overlay	t/m^3	2.39	2.42	2.45
Asphalt Concrete Base	t/m^3	2.39	2.42	2.45
Virgin Granular Base Course	t/m^3	2.33	2.36	2.40
Recycled Base Course	t/m^3	1.91	2.01	2.11
Virgin Subbase	t/m^3	2.21	2.24	2.28
Recycled Subbase	t/m^3	1.81	1.91	2.00
Asphalt Emulsion	kg/l	0.90	1.00	1.10

Table 4.3 Truck and Fuel Model Variables

Variable	Unit	Low	Avg /ML	High
Truck Capacity				
Medium Duty - 3 Axel	t	-	-	10
Heavy Duty - 6 Axel	t	-	-	25
Heavy Duty - 8 Axel	t	-	-	40
Fuel Efficiency				
Medium Duty - Diesel	l/100km	20.5	21.6	27.0
Heavy Duty - Diesel	l/100km	37.5	39.5	49.4
Diesel Fuel				
Weight	kg/l	-	0.84	-
Fuel Consumption	kg/bhp-hr	-	0.17	-

Table 4.4 Energy Consumption Model Variables

Material / Process	Unit	Low	Avg/ML	High
Aggregates				
Extraction	GJ/t	0.026	0.027	0.028
Production - Coarse	GJ/t	0.010	0.011	0.011
Production - Fine	GJ/t	0.031	0.032	0.034
Production - Subbase	GJ/t	0.005	0.005	0.006
Asphalt				
Cement	GJ/t	1.569	1.651	1.734
PMB	GJ/t	3.841	4.043	4.245
Emulsion	GJ/t	1.863	1.961	2.059
Asphalt Concrete Plants				
Batch	GJ/t	0.356	0.406	0.443
Drum	GJ/t	0.356	0.406	0.443
Cement				
Production	GJ/t	3.704	3.745	3.785
Lime				
Production	GJ/t	3.600	5.550	7.500
Fuel				
Diesel	MJ/l	35.9	37.3	38.7

Table 4.5 CO_2e Generation Model Variables

Material / Process	Unit	Low	Avg/ML	High
			CO_2e	
Aggregates				
Production	kg/t	7.723	8.130	8.536
Asphalt Cement				
Cement	kg/t	150.345	158.258	166.171
PMB	kg/t	277.267	291.860	306.453
Emulsion	kg/t	178.790	188.200	197.610
Asphalt Concrete Plants				
Batch	kg/t	7.574	18.578	29.578
Drum	kg/t	10.120	16.626	23.126
Cement				
Production	kg/t	732.000	769.000	800.000
Lime				
Production	kg/t	1520.000	1600.000	1680.000
Fuel				
Trucks - Diesel	kg/l	2.556	2.691	2.825
Construction - Diesel	kg/l	2.576	2.711	2.847

4.2 User Required Model Inputs

The model requires inputs from the user. These inputs include layer information, material composition, material volumes, and hauling information. Material composition information that is required includes the RAP content when applicable and the asphalt cement plant type. Finally, the number of kilometers for material transport between locations is required.

4.3 Validation Case Study

4.3.1 Initial Construction

For this initial construction case study, the pavement structure used is a typical structure used for a Saskatchewan highway as shown in Figure 4.1 and the area considered is a lane-km (3,700 m^2). The cement application rate for the cement stabilized subgrade is 10 kg/m^2 and to be conservative, the production of the asphalt concrete is assumed to be for a batch plant. Transport distances for the materials are summarized in Table 4.6. The design parameters that are used for virgin ACO, ACB and GBC are included in Table 4.7.

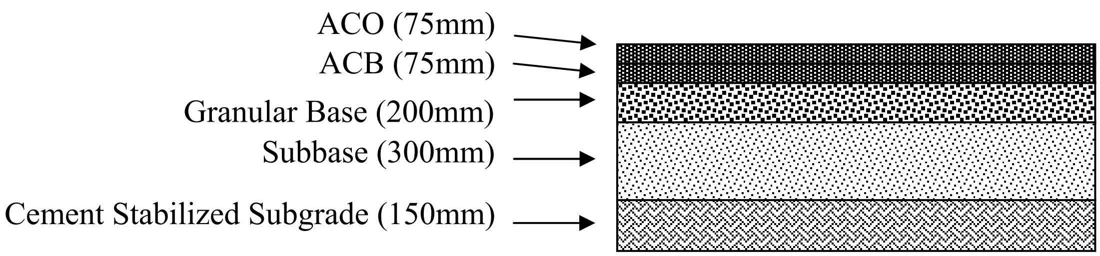

Figure 4.1 Typical Lane Kilometer Cross Section

Table 4.6 Model User Inputs for Hauling Information

From	To	km*	Truck-Axle
Transport to Production / Stockpile Locations			
Aggregate Source	Asphalt Concrete Plant	100	6
Asphalt Cement Refinery	Asphalt Concrete Plant	250	8
Lime Source	Asphalt Concrete Plant	250	6
Aggregate Source	Aggregate Supplier	100	8
Cement Source	Cement Supplier	500	6
Transport to Site			
Asphalt Concrete Plant	Site	50	3
Aggregate Supplier	Site	50	6
Cement Supplier	Site	50	6

* kms round trip.

Table 4.7 Design Values for ACO, ACB and GBC (City of Edmonton 2011, SMHI 2011)

Material		Unit	Low	Avg/ML	High
ACO					
	Asphalt Cement	% Weight	5.5	6.0	6.5
	Lime*	% of Dry Aggregate	0.5	1.0	1.5
	Coarse Aggregate	% Aggregate	30	40	50
ACB					
	Asphalt Cement	% Weight	4.5	5.0	5.5
	Coarse Aggregate	% Aggregate	40	50	60
GBC					
	Coarse Aggregate	% Aggregate	25	45	65

Fine Aggregate calculated by (1 - % Course Aggregate Weight).
* Not included in all cases.

The expected value for the amount of energy consumed from the material production, on site equipment and transportation based on the model and user parameters are summarized in Table 4.8. The model values for the energy consumed for each sub- model are shown in Figure 4.2 and for the CO_2e emissions generated from the material production, equipment and transportation for the initial construction of one lane-km of the structure are shown in Figure 4.3. The bars included on all of the figures represent the low and high values that were determined for each sub-model. A sample calculation of the initial construction base case is provided in Appendix B for the Avg/ML values.

Table 4.8 Initial Construction Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	970.8	1038.0	1087.7	78.7	93.4	108.2
On Site Equipment	366.4	403.9	468.7	26.6	29.3	34.0
Transport	409.8	428.6	522.2	29.4	30.9	37.7
Total	1803.3	1870.4	1964.0	137.6	152.4	167.2

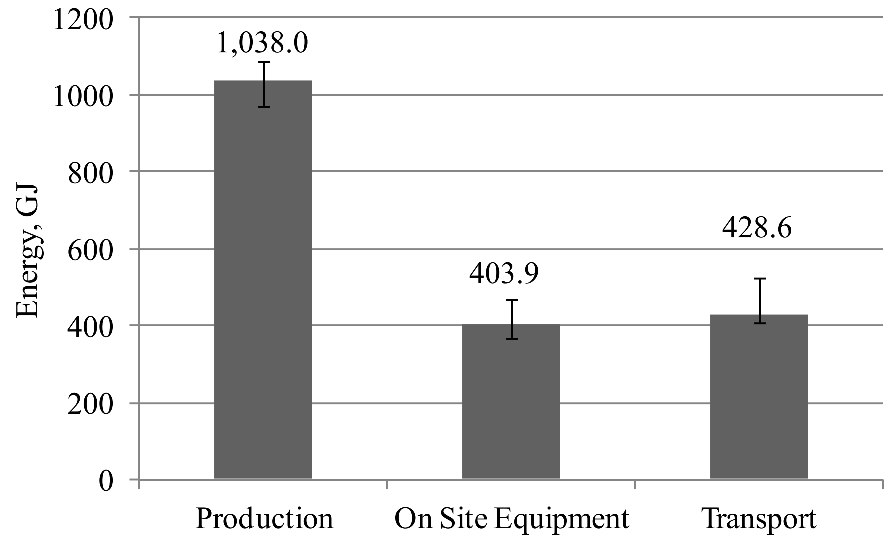

Figure 4.2 Initial Construction Energy Consumption

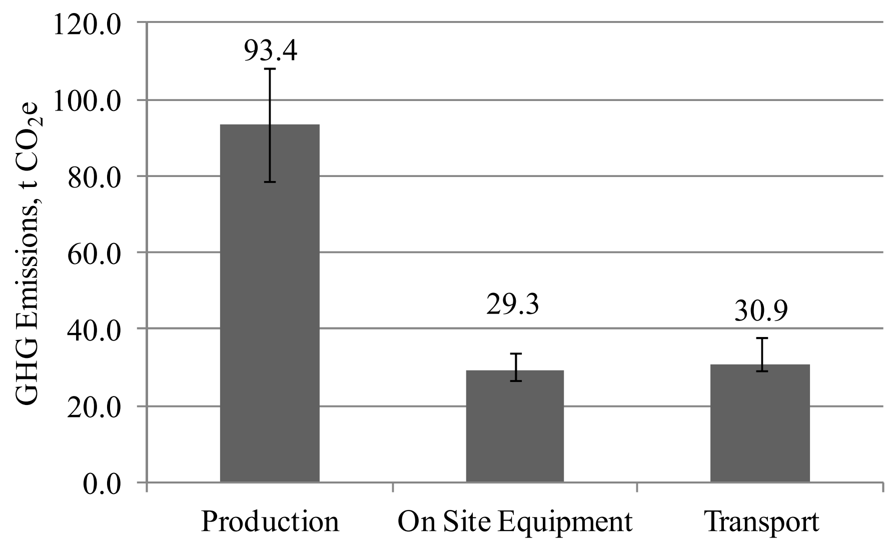

Figure 4.3 Initial Construction GHG Emissions

4.3.2 Flexible Pavement Maintenance Treatments

The maintenance works that will be considered include a fog seal, slurry seal, micro surfacing, ultra thin HMAC overlay and single, double, and triple chip seals. The design parameters used for each are summarized in Table 4.9.

Table 4.9 Maintenance Treatment Design Parameters (Asphalt Institute 2007, ISSA 2010)

Treatment	Material	Low	Average	High	Unit
Fog Seal					
	Emulsion	0.45	0.575	0.7	l/m^2
Slurry Seal					
	Asphalt Cement*	7.5	10.5	13.5	%
	Aggregate Mixture Application*	5.5	6.75	8.0	kg/m^2
Micro Surfacing					
	Aggregate	5.4	10.85	16.3	kg/m^2
	Portland Cement (mineral filler)*	1.5	2.25	3.0	%
	Asphalt Binder*	5.5	7.5	9.5	%
Chip Seal (Single)					
	Aggregate	5.0	16.0	27.0	kg/m^2
	Asphalt	0.5	1.6	2.7	l/m^2
25mm Ultra Thin HMAC Overlay					
	Refer to Table 4.7				

* Based on weight of dry aggregate.

Based on one lane-km, the values for energy consumption and CO_2e emissions for the various maintenance treatments are determined and summarized in the following tables and figures.

Table 4.10 Fog Seal Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	3.3	4.2	5.1	0.3	0.4	0.5
On Site Equipment	0.7	0.9	1.1	0.1	0.1	0.1
Transport	0.2	0.3	0.3	0.0	0.0	0.0
Total	4.2	5.4	6.5	0.4	0.5	0.6

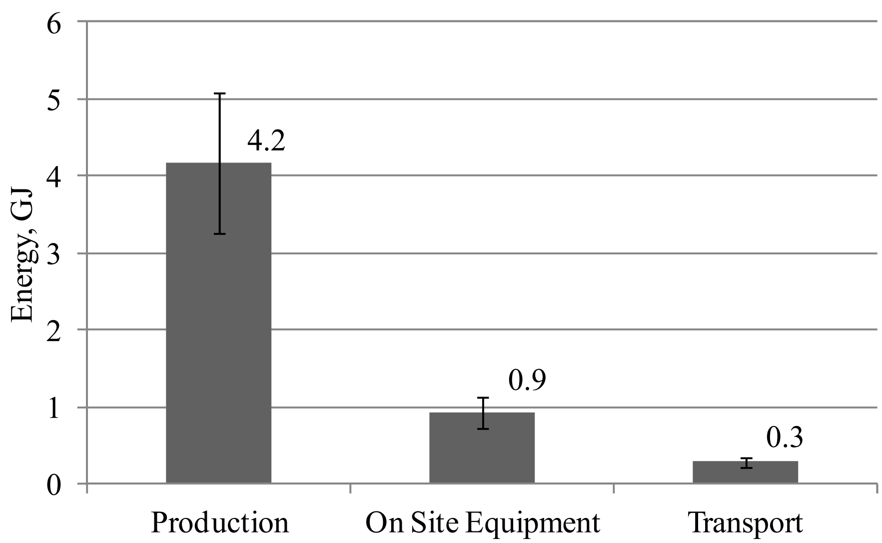

Figure 4.4 Fog Seal Energy Consumption

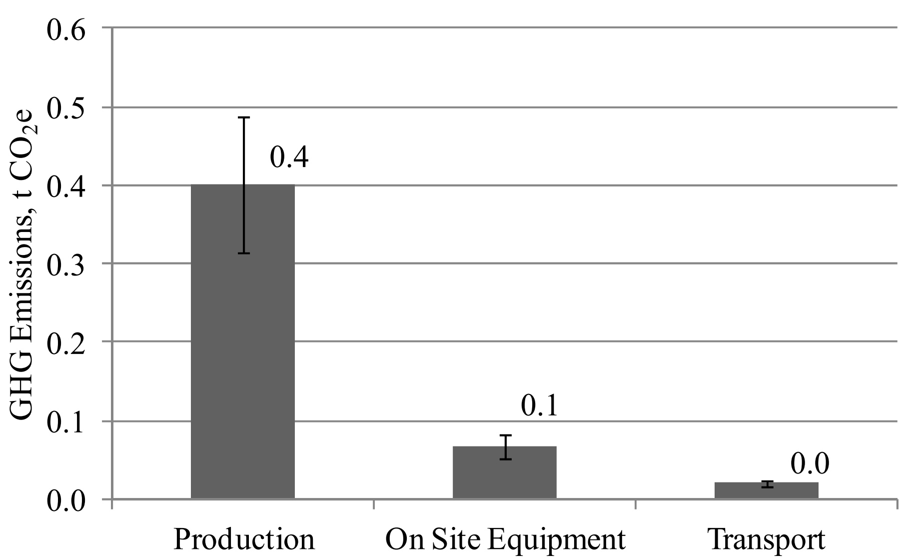

Figure 4.5 Fog Seal GHG Emissions

Table 4.11 Slurry Seal Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	5.2	6.6	8.1	0.6	0.7	0.8
On Site Equipment	5.6	6.9	9.3	0.4	0.5	0.7
Transport	1.4	1.8	2.1	0.1	0.1	0.2
Total	13.8	15.3	17.7	1.2	1.3	1.5

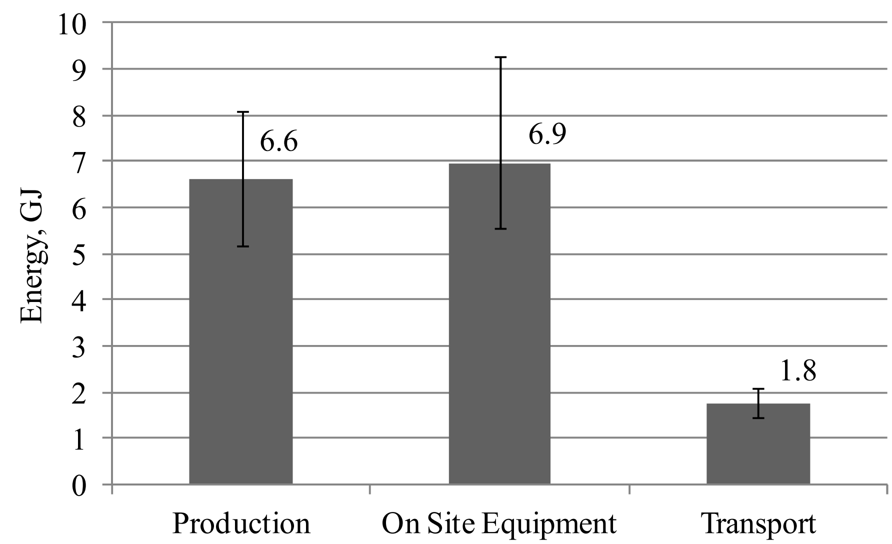

Figure 4.6 Slurry Seal Energy Consumption

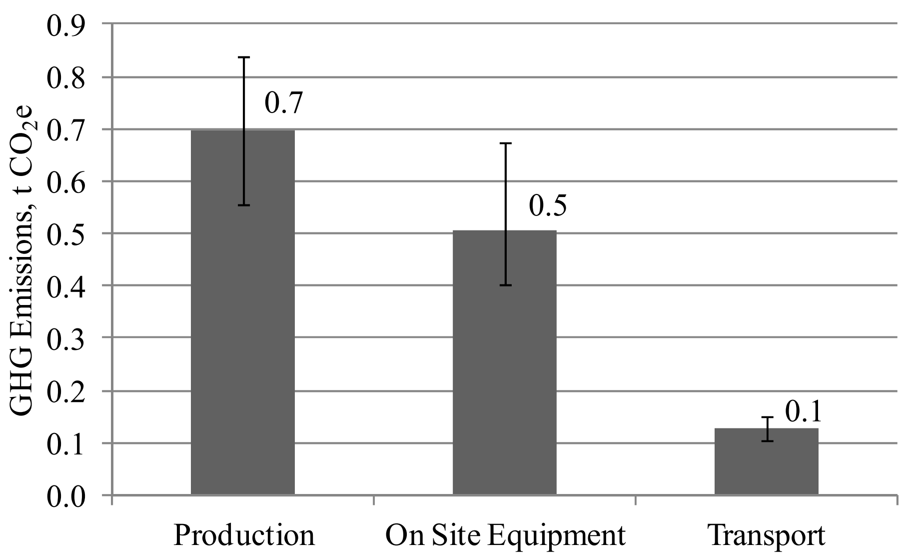

Figure 4.7 Slurry Seal GHG Emissions

Table 4.12 Micro Surfacing Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	7.2	14.6	21.9	0.9	1.9	2.8
On Site Equipment	5.3	6.6	8.8	0.4	0.5	0.6
Transport	1.5	3.0	4.4	0.1	0.2	0.3
Total	15.3	24.2	33.0	1.5	2.6	3.6

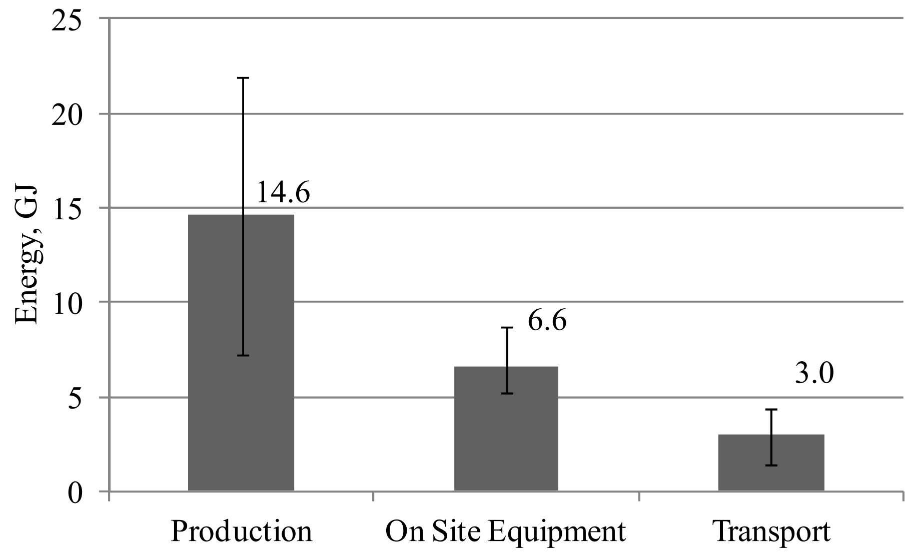

Figure 4.8 Micro Surfacing Energy Consumption

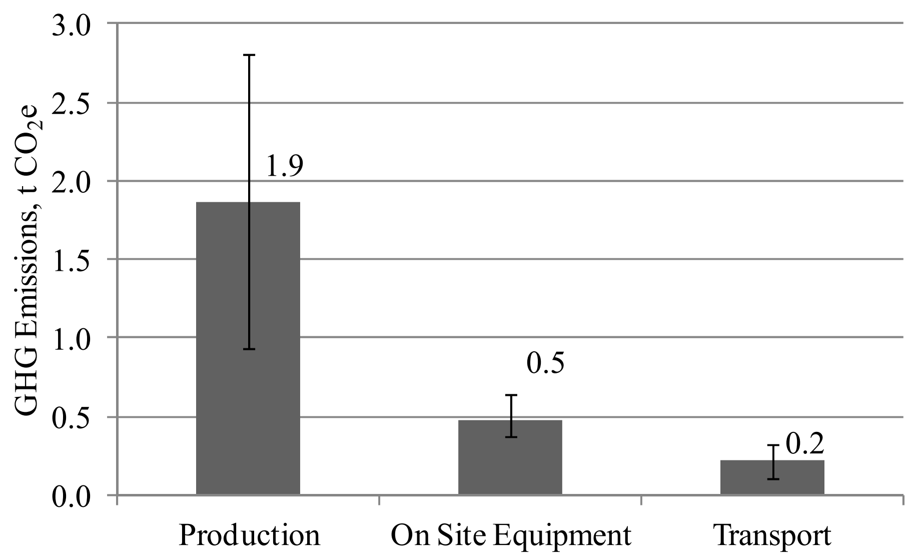

Figure 4.9 Micro Surfacing GHG Emissions

Table 4.13 Chip Seal Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	6.5	14.5	22.5	0.8	1.6	2.4
On Site Equipment	11.0	14.6	22.0	0.8	1.1	1.6
Transport	1.5	4.2	6.9	0.1	0.3	0.5
Total	25.1	33.3	41.4	2.2	3.0	3.7

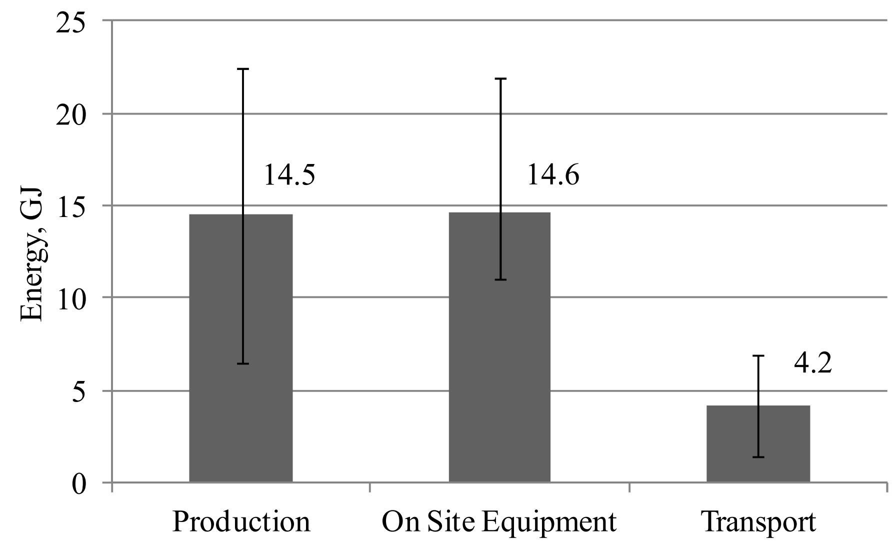

Figure 4.10 Chip Seal Energy Consumption

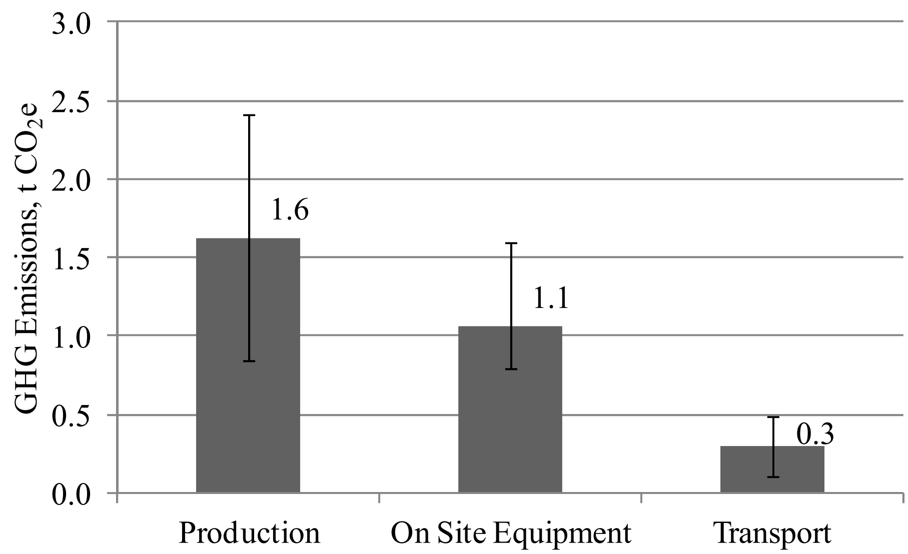

Figure 4.11 Chip Seal GHG Emissions

Table 4.14 Ultra Thin Overlay Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	115.8	127.0	135.3	5.5	8.0	10.5
On Site Equipment	6.0	6.8	8.1	0.1	0.1	0.2
Transport	34.0	35.3	41.9	2.4	2.5	3.0
Total	158.0	169.2	177.5	8.5	11.0	13.5

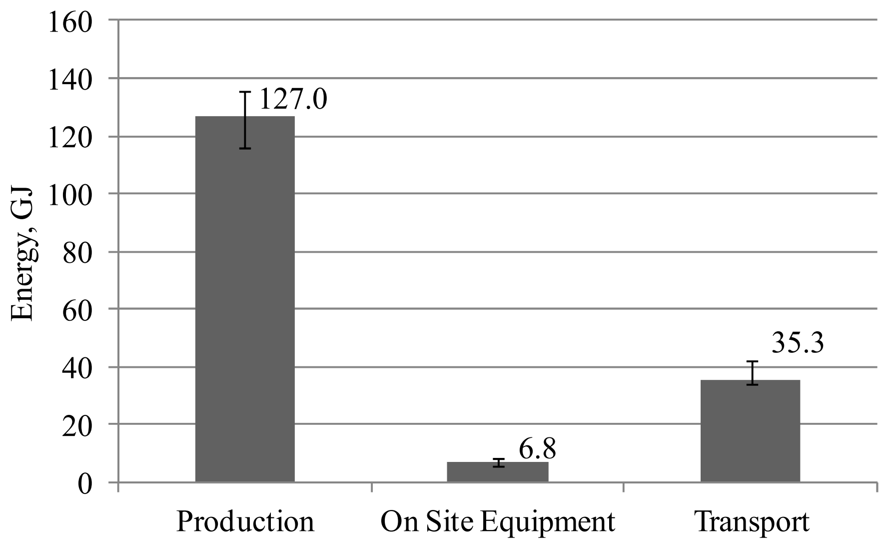

Figure 4.12 Ultra Thin Overlay Energy Consumption

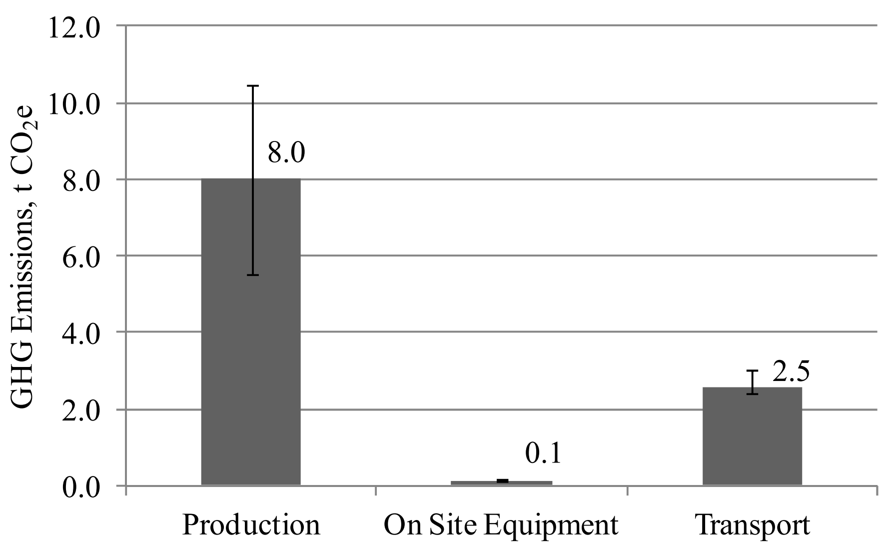

Figure 4.13 Ultra Thin Overlay GHG Emissions

Figure 4.14 and Figure 4.15 summarize the total amount of energy consumed and CO_2e emissions generated from the model for each maintenance treatment.

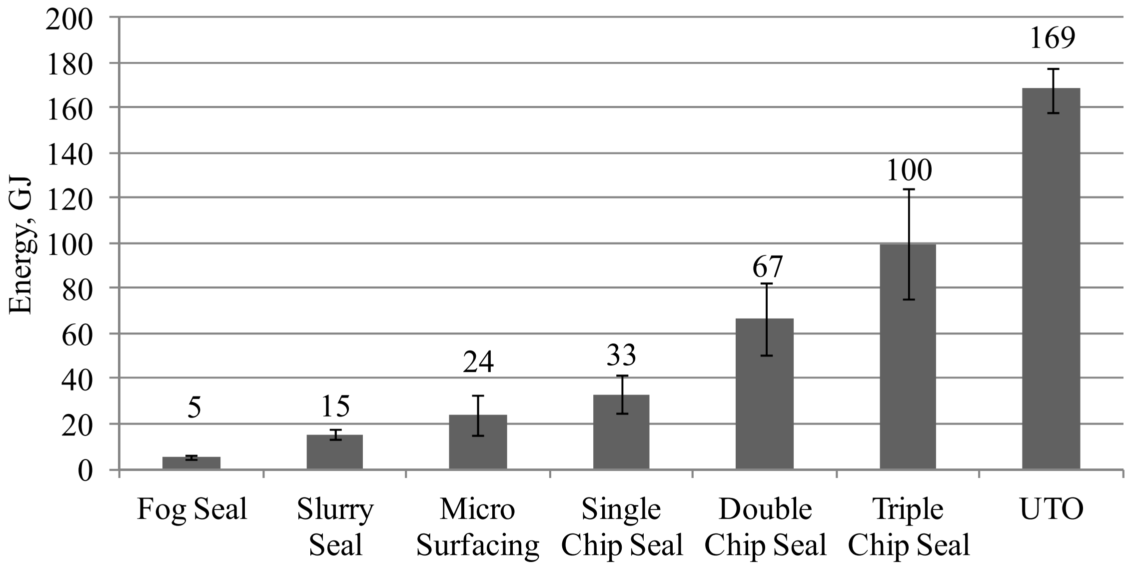

Figure 4.14 Summary Energy Consumption for Maintenance Treatments

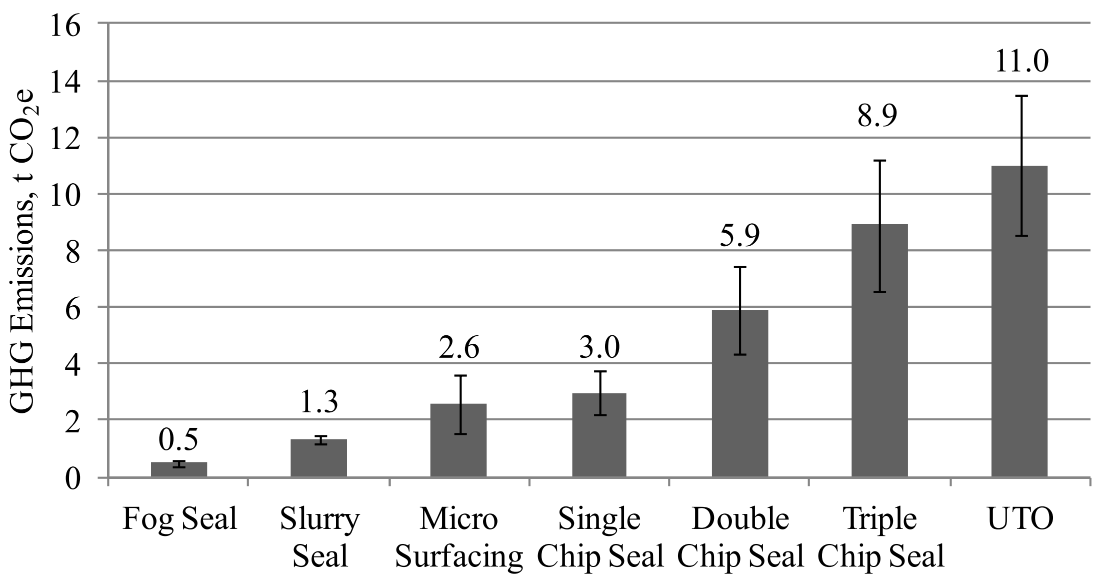

Figure 4.15 Summary GHG Emissions for Maintenance Treatments

Figure 4.14 and Figure 4.15 show that as aggregate is added to a treatment the amount of energy consumed and GHGs emitted increases. The order of increasing magnitude of the treatments is the same for both energy consumption and CO_2e emissions generated.

4.3.3 Rehabilitation and Reconstruction

The rehabilitation works that will be considered include a mill and fill and cold in-place recycling (CIPR). The design parameters used for each are summarized in Table 4.15. The reconstruction works that will be considered include full depth reclamation, removal and replacement of an existing roadway with virgin materials and removal and replacement of an existing roadway with recycled materials. The design parameters used for each are summarized in Table 4.16.

Table 4.15 Rehabilitation Design Parameters (Asphalt Institute 2007, FCM/NRC 2005)

Method	Unit	Low	Avg / ML	High
Mill and Fill				
Mill Depth	mm	-	50	-
HMAC Placement	mm	-	100	-
Tack Coat	l/m^2	0.20	0.45	0.70
Cold in-Place Recycling				
Recycle Depth	mm	-	150	-
Asphalt Emulsion	%	0.00	0.75	1.50
Portland Cement	%	0.00	1.50	3.00
HMAC Overlay	mm	-	50	-

Table 4.16 Reconstruction Design Parameters (FCM/NRC 2005)

Method	Unit	Low	Avg / Most Likely	High
Full Depth Reclamation				
Recycle Depth	mm	-	300	-
Asphalt Emulsion	%	2.00	2.75	3.50
Cement	%	1.00	2.00	3.00
Aggregate	%	0.00	2.50	5.00
HMAC Overlay	mm	-	50	-
Remove and Replace Virgin				
Remove Asphalt Concrete	mm	-	150	-
Further Excavation	mm	-	500	-
Replacement Structure	Structure as in section 4.3.1			
Remove and Replace Recycled				
Remove Asphalt Concrete	mm	-	150	-
Further Excavation	mm	-	500	-
Asphalt Concrete Overlay	mm	-	75	-
Asphalt Concrete Base	mm	-	75	-
Recycled PCC Base	mm	-	200	-
Recycled PCC Subbase	mm	-	300	-
RAP Content in Asphalt	%	-	10	-

Based on a lane-km, the values for energy consumption and GHG emissions for the various rehabilitation and reconstruction treatments are evaluated and summarized in the following tables and figures.

Table 4.17 Mill and Fill Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	453.5	498.2	531.4	22.4	32.3	42.1
On Site Equipment	36.9	62.8	88.7	2.7	4.6	6.4
Transport	96.1	99.9	113.5	7.2	7.5	8.5
Total	616.1	660.9	694.0	34.3	44.1	54.0

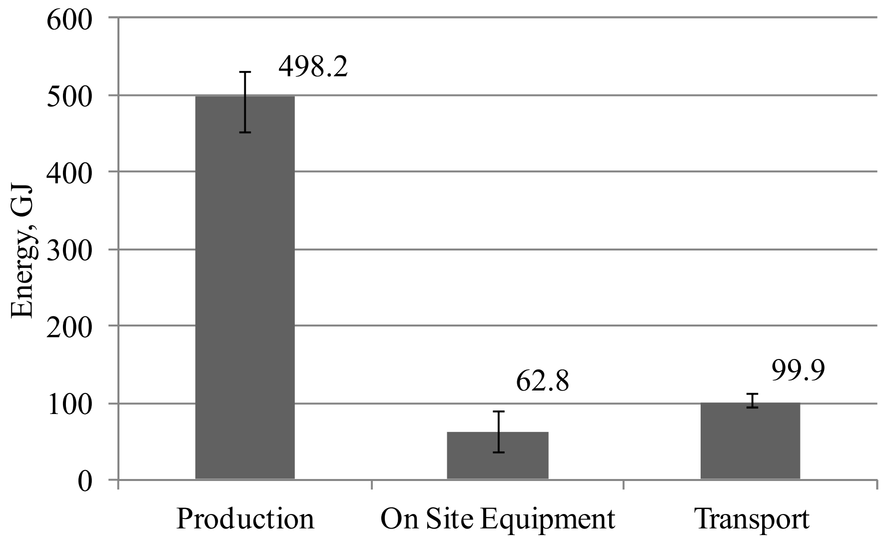

Figure 4.16 Mill and Fill Energy Consumption

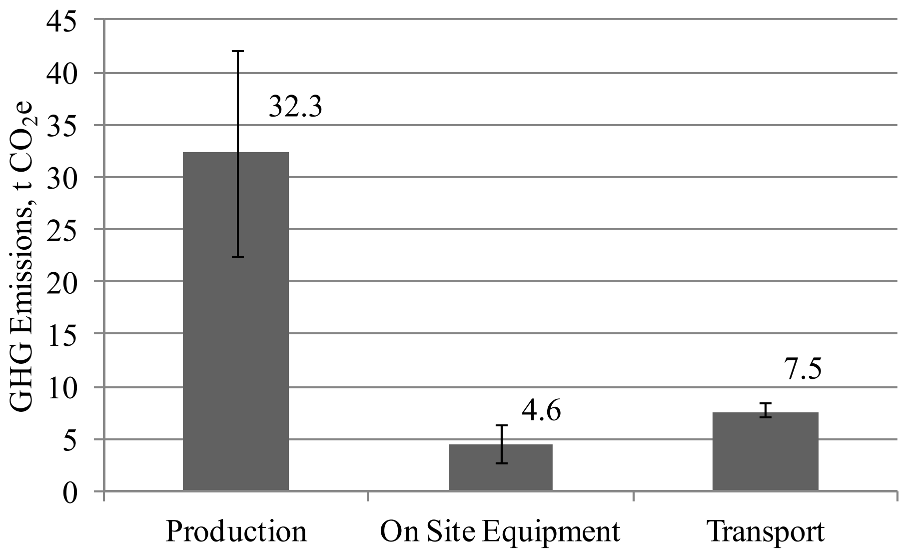

Figure 4.17 Mill and Fill GHG Emissions

In the design of the CIPR and FDR treatments, a 50 mm overlay of ACO is included after the treatment is completed. The energy consumed and CO_2e emissions generated from the placement of a 50 mm overlay have been determined and are summarized in Table 4.18. The energy consumption and GHG emission values for the CIPR are shown in Table 4.19 and the total values for the CIPR treatment and 50 mm overlay are shown in Table 4.20, Figure 4.18 and Figure 4.19.

Table 4.18 Overlay (50 mm) Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	228.4	250.7	267.3	11.1	16.0	20.9
On Site Equipment	9.6	12.1	14.5	0.2	0.3	0.3
Transport	67.8	70.4	82.5	4.8	5.1	6.0
Total	310.8	333.2	349.8	16.7	21.7	26.6

Table 4.19 Cold in-Place Recycling Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	2.0	64.1	126.3	1.6	14.5	27.4
On Site Equipment	11.8	15.6	19.5	0.9	1.1	1.4
Transport	1.0	4.6	8.2	0.1	0.3	0.6
Total	15.6	84.3	150.1	2.8	16.0	29.1

Table 4.20 Cold in-Place Recycling and 50 mm Overlay Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	230.3	314.9	393.6	12.6	30.5	48.3
On Site Equipment	21.4	27.6	34.0	1.1	1.4	1.8
Transport	68.8	75.0	90.7	4.9	5.4	6.6
Total	326.4	417.5	499.9	19.5	37.6	55.7

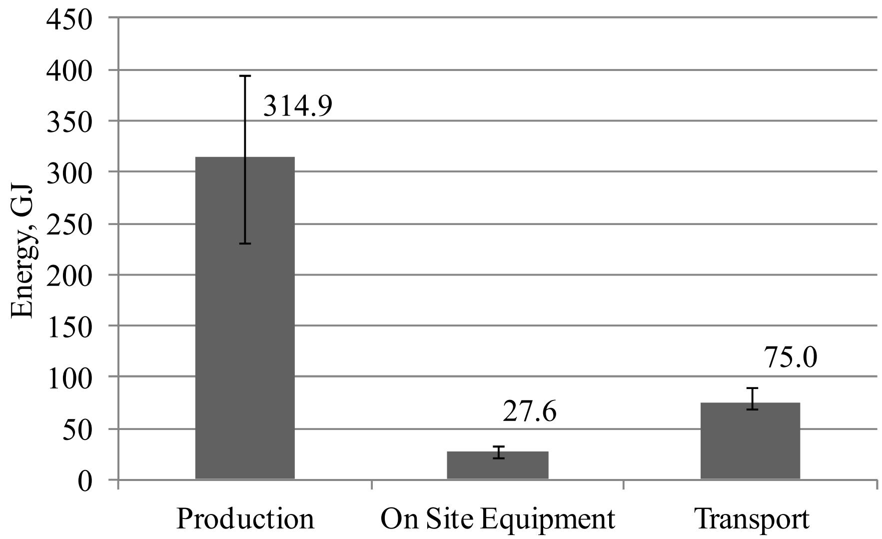

Figure 4.18 Cold in-Place Recycling Energy Consumption

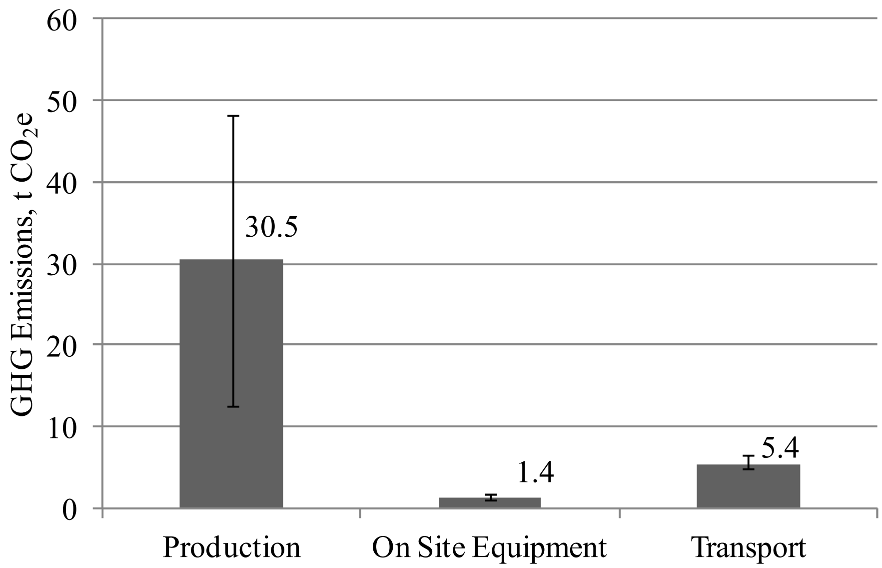

Figure 4.19 Cold in-Place Recycling GHG Emissions

Table 4.21 Full Depth Reclamation Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	100.7	243.2	480.6	31.0	59.2	106.1
On Site Equipment	38.7	72.8	106.7	2.8	5.3	7.8
Transport	11.8	20.0	33.7	0.8	1.4	2.4
Total	185.4	336.1	587.2	37.2	65.9	113.8

Table 4.22 Full Depth Reclamation and 50 mm Overlay Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	329.1	494.0	748.0	42.1	75.2	127.0
On Site Equipment	48.3	84.9	121.2	3.0	5.6	8.1
Transport	79.6	90.4	116.2	5.7	6.5	8.4
Total	496.2	669.3	936.9	53.9	87.6	140.4

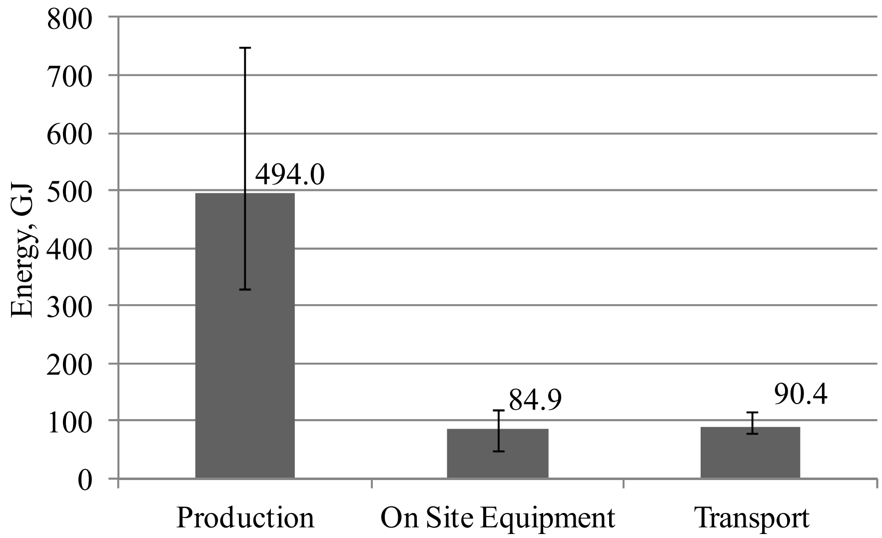

Figure 4.20 Full Depth Reclamation Energy Consumption

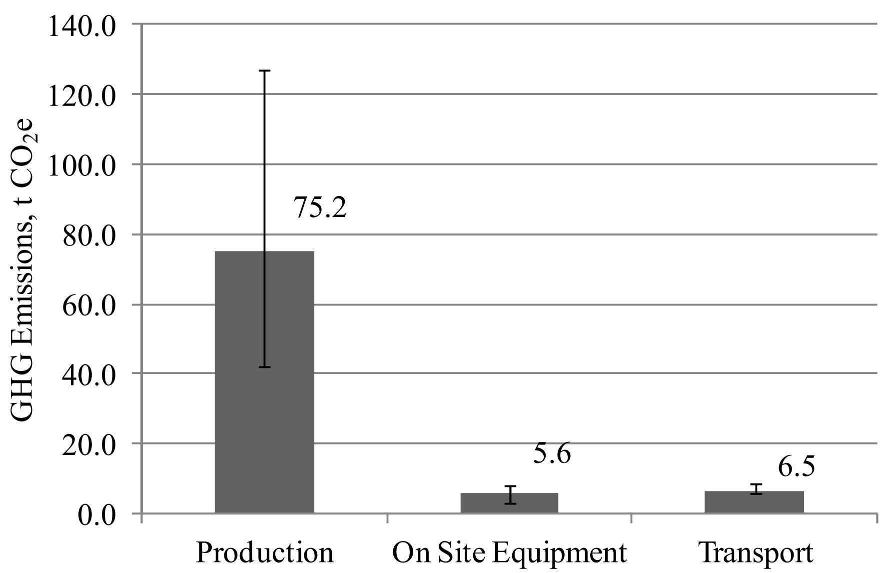

Figure 4.21 Full Depth Reclamation GHG Emissions

To determine the amount of energy consumed and GHGs generated for the removal and replacement of one lane-km of roadway with virgin materials, the values for removal as included in Table 4.23 are added to those for the initial construction as indicated in Table 4.8.

The total energy consumed and GHG emissions for the removal and replacement for a lane-km of roadway with virgin materials from the model are summarized in Table 4.24. The values determined for each sub-model are also summarized in Figure 4.22 and Figure 4.23 respectively.

Table 4.23 Removed Values for Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	N/A	N/A	N/A	N/A	N/A	N/A
On Site Equipment	81.6	140.5	199.4	8.9	10.2	14.5
Transport	175.9	182.8	214.9	12.5	13.2	15.5
Total	264.4	323.3	382.2	19.1	23.4	27.7

Table 4.24 Remove and Replace with Virgin Materials Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	970.8	1038.0	1087.7	78.7	93.4	108.2
On Site Equipment	448.0	544.4	668.1	35.5	39.5	48.5
Transport	585.7	611.3	737.1	41.9	44.1	53.2
Total	2067.7	2193.7	2346.2	156.7	175.8	194.8

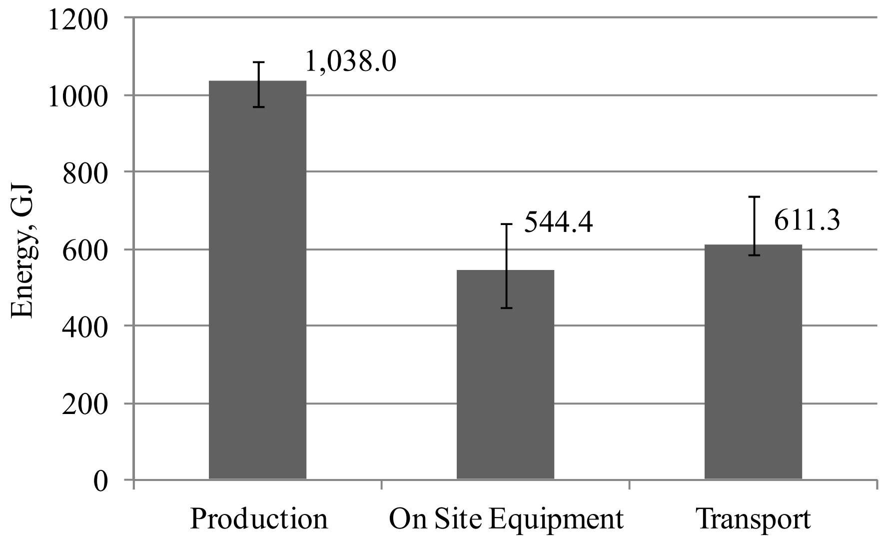

Figure 4.22 Remove and Replace with Virgin Materials Energy Consumption

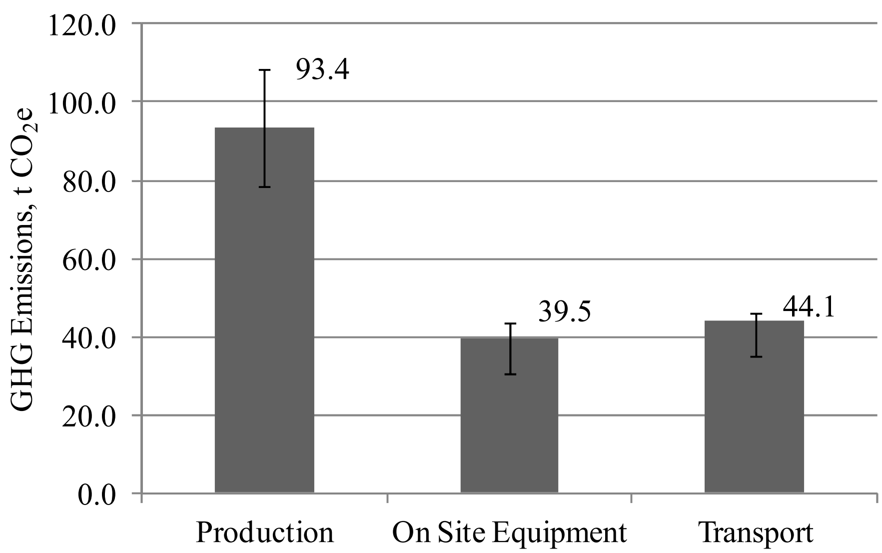

Figure 4.23 Remove and Replace with Virgin Materials GHG Emissions

To determine the amount of energy consumed and GHGs generated for the removal and replacement of a lane-km of roadway with recycled materials, the values for removal as included in Table 4.23 are added to those for construction with recycled materials as indicated in Table 4.25 and totaled in Table 4.26. The sub-model values for energy consumed and CO_2e emissions are summarized in Figure 4.24 and Figure 4.25 respectively.

Figure 4.26 and Figure 4.27 show all of the values for the amount of energy consumed and GHGs generated for the Avg/ML input parameters from the model for each rehabilitation and reconstruction treatment.

The order of increasing magnitude for treatments for GHG emissions follows the order for energy consumption. A reduction in the energy consumed and GHG emissions with the use of recycled materials compared to virgin materials is observed.

Table 4.25 Recycled Structure Values for Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	701.3	768.4	818.1	73.9	88.7	103.5
On Site Equipment	338.3	419.9	481.6	24.7	27.4	31.9
Transport	236.6	246.2	294.2	16.9	17.8	21.2
Total	1367.4	1434.5	1496.3	118.2	133.0	147.8

Table 4.26 Total Remove and Replace with Recycled Structure Values for Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			**GHG Emissions (t CO_2e)**		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	701.3	768.4	818.1	73.9	88.7	103.5
On Site Equipment	419.9	560.4	681.1	33.6	37.6	46.4
Transport	412.5	429.0	509.1	29.4	30.9	36.7
Total	1631.7	1757.8	1878.5	137.3	156.4	175.5

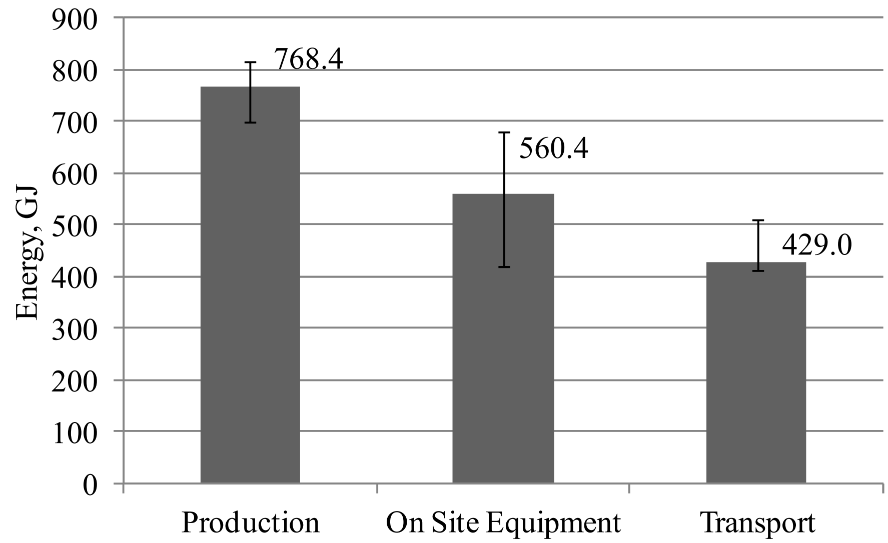

Figure 4.24 Remove and Replace with Recycled Materials Energy Consumption

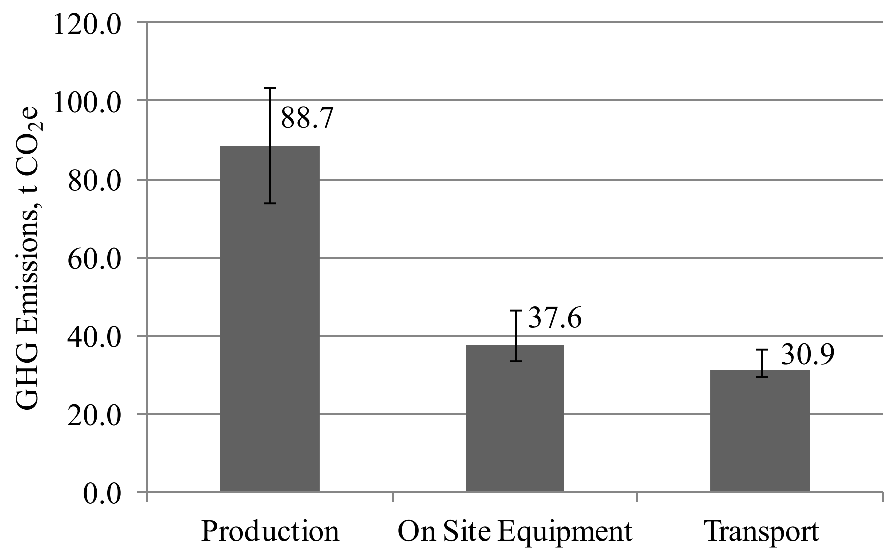

Figure 4.25 Remove and Replace with Recycled Materials GHG Emissions

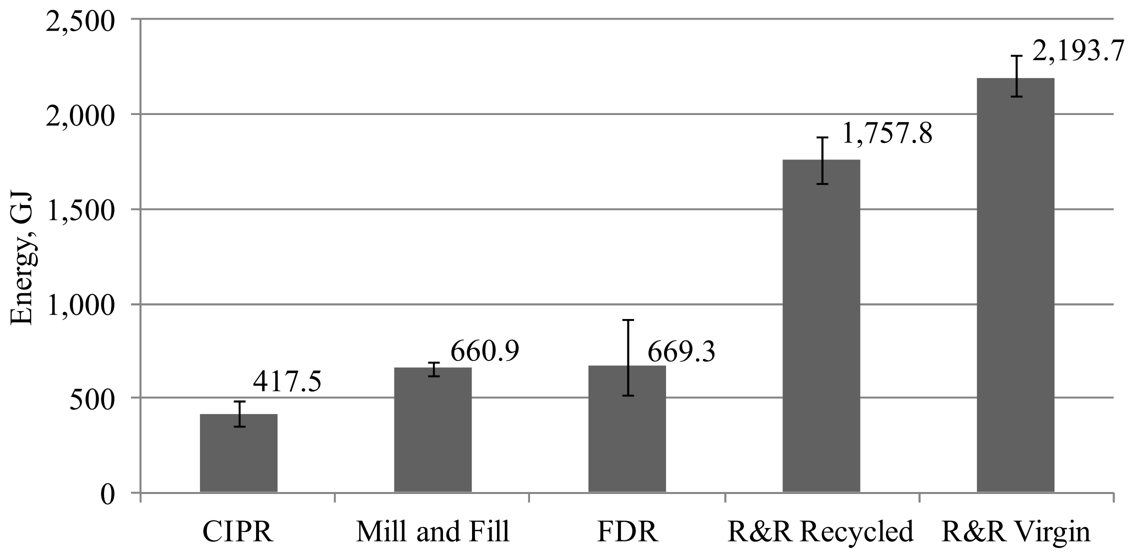

Figure 4.26 Summary Energy Consumption for Rehabilitation and Reconstruction Treatments

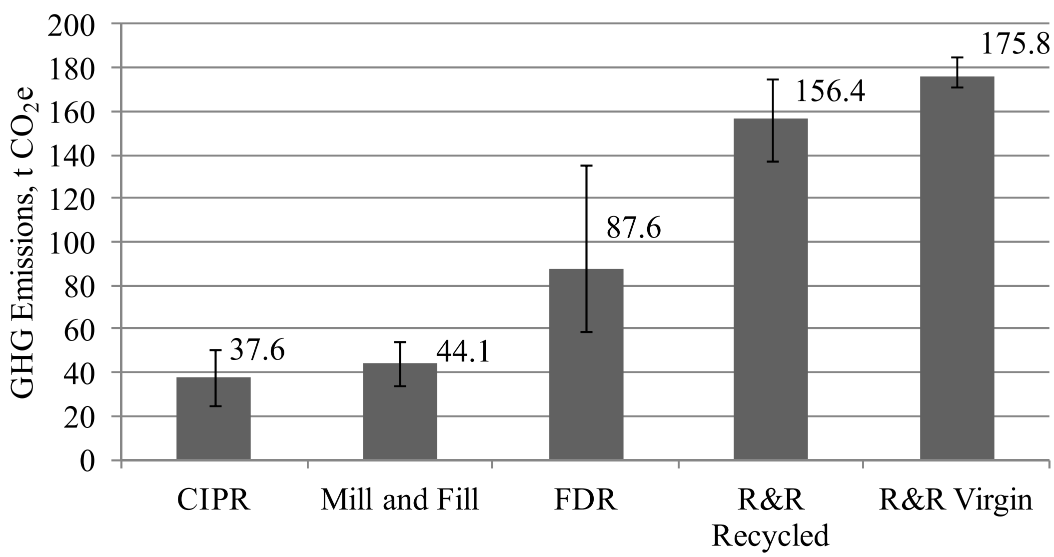

Figure 4.27 Summary GHG Emissions for Rehabilitation and Reconstruction Treatments

4.4 Summary

This chapter summarized the input values for the model for material production, transportation and placement as well as the variable input values that are required by the user to determine the amount of energy consumed and GHG emissions generated through each treatment. The initial construction for the roadway consumed 1,870 GJ of energy and emitted 152.4 t CO_2e which in volume is approximately 85,000 m^3. The volume of material placed for initial construction is 2,960 m^3 which is a ratio of 30 m^3 of CO_2 to one cubic meter of material in the pavement structure.

For maintenance treatments the order from least to greatest energy consumption and GHG emission generation was found to be fog seal, slurry seal, micro surfacing, single, double and triple chip seal and UTO. For rehabilitation and reconstruction the order from least to greatest energy consumption and GHG emissions generated was found to be CIPR, mill and fill, FDR, remove and replace with recycled materials and remove and replace with virgin materials. The values determined by the model are compared to published and other modeled values in Chapter Six.

Chapter 5

MODEL SENSITIVE PARAMETER ANALYSIS

Further analysis was completed based on the models that were developed in Chapter 4. This analysis includes the evaluation of the sensitive parameters, sub-model percentages, review of material production for each pavement layer and asphalt concrete and the cost of energy and emission outputs.

5.1 Sensitive Parameters

As a probabilistic model is developed, a range of values that represent the total expected amount of energy consumed or CO_2e generated based on the variance of input parameters is determined. For each treatment a tornado diagram was developed in DPL to determine the sensitive parameters. Figure 5.1 is the tornado diagram that was generated for the amount of energy consumed in the base case roadway as described in Section 4.3.

The tornado diagram shows the parameter with the greatest sensitivity to the model at the top, with the largest bandwidth, followed by the remaining parameters in decreasing order of sensitivity (Clemen and Reilly 2001). In Figure 5.1 the most sensitive parameter is the energy that is consumed from the production of HMAC followed by the placement rate of the subbase materials. The list of parameters then continues with the least sensitive parameter being the placement rate of the tack coat.

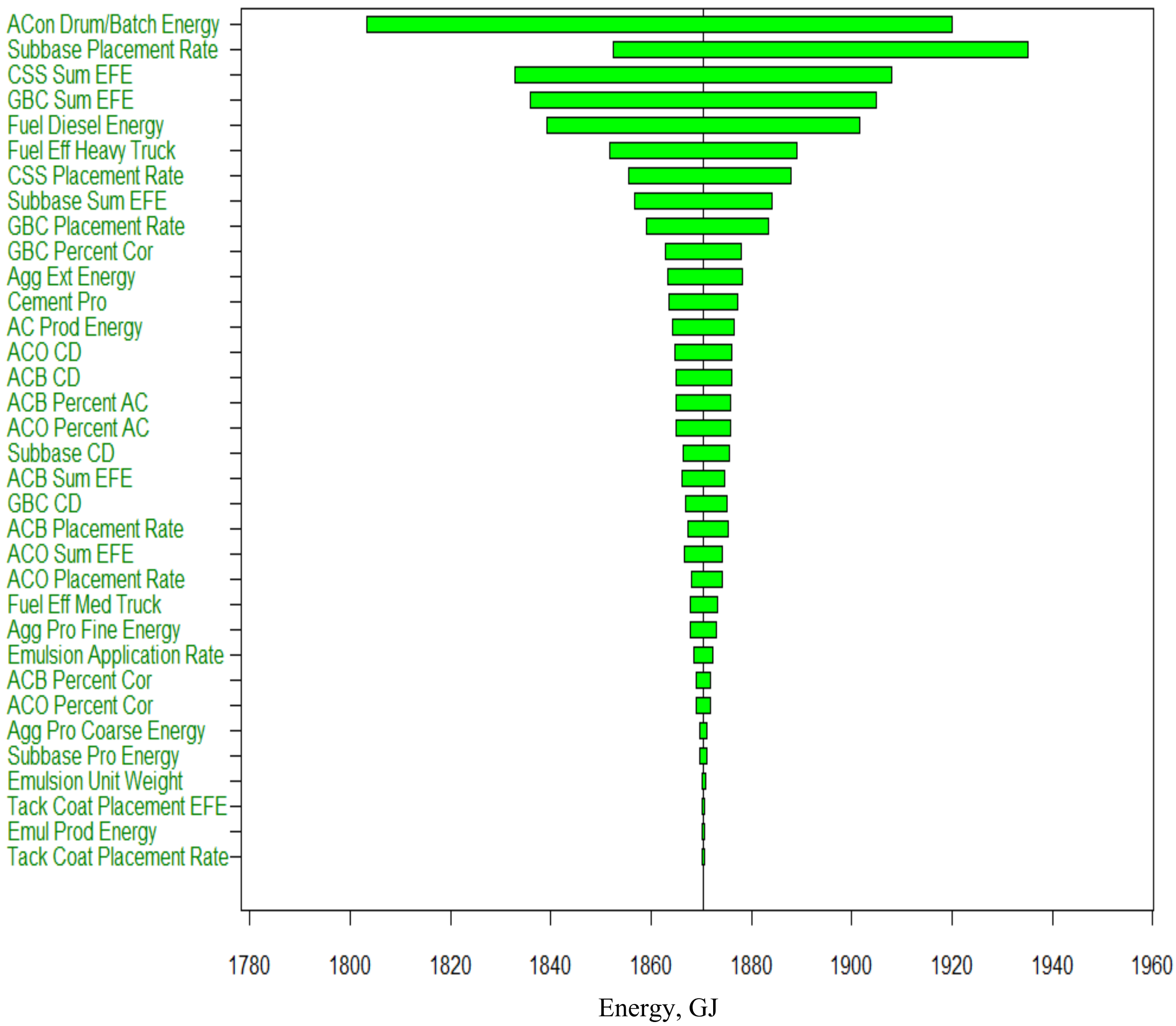

Figure 5.1 Tornado Diagram Initial Construction

To determine the relative impact of a sensitive parameter on an expected value, the following calculation was completed for each parameter. Refer to Appendix B for a sample calculation.

$$\%\ of\ Expected\ Value = \frac{High\ Value - Low\ Value}{Expected\ Value} \times 100$$

Equation 5.1

Table 5.1 and Table 5.2 indicate the sensitive parameters for energy consumption and GHG emissions for maintenance treatments. For each treatment any parameters that had greater than a ten percent range of the expected value are included in these tables and for the treatments that have no parameters with sensitivity greater than ten percent, the most sensitive parameter is indicated.

Table 5.1 Energy Consumption Sensitive Parameters for Maintenance Treatments

Parameter	Low (GJ)	High (GJ)	Difference (GJ)	EV (GJ)	% of EV
Fog Seal					
Seal Placement EFE	13.1	19.0	5.8	15.3	37.9
Seal Placement Rate	13.1	17.5	4.3	15.3	28.3
Emulsion Application Rate	14.4	16.3	1.9	15.3	12.6
Slurry Seal					
Seal Placement Rate	13.9	17.7	3.7	15.3	24.2
Aggregate Application	13.8	16.9	3.1	15.3	20.3
% Asphalt Emulsion by Aggregate Weight	13.8	16.8	3.0	15.3	19.6
Seal Placement EFE	14.2	16.4	2.2	15.3	14.4
Micro Surfacing					
Aggregate Application	15.3	33.0	17.7	24.2	72.9
% PMB by Aggregate Weight	21.0	27.5	6.6	24.2	27.1
Micro Surfacing Rate	22.9	26.4	3.5	24.2	14.4
Micro Surfacing EFE	23.0	25.5	2.6	24.2	10.6
Chip Seal					
Emulsion Application Rate	25.1	41.4	16.3	33.3	48.9
Seal Placement Rate	29.6	40.6	11.0	33.3	33.0
Aggregate Application	28.6	38.0	9.4	33.3	28.1
Seal Placement EFE	30.8	35.8	5.0	33.3	14.9
25mm UTO					
ACon* Drum/Batch Energy	158.0	177.5	19.5	169.2	11.5

* Asphalt Concrete (ACon)

Table 5.2 GHG Emissions Sensitive Parameters for Maintenance Treatments

Parameter	Low (GJ)	High (GJ)	Difference (GJ)	EV (GJ)	% of EV
Fog Seal					
Seal Placement EFE	1.1	1.5	0.4	1.2	34.8
Seal Placement Rate	1.1	1.4	0.3	1.2	26.0
Emulsion Application Rate	1.1	1.3	0.2	1.2	15.1
Slurry Seal					
% Asphalt Emulsion by Aggregate Weight	0.6	0.8	0.3	0.7	40.5
Aggregate Application	0.6	0.8	0.3	0.7	37.0
Micro Surfacing					
Aggregate Application	1.5	3.6	2.1	2.6	81.8
%PMB by Aggregate Weight	2.3	2.8	0.5	2.6	18.4
Cement Application Rate	2.3	2.8	0.5	2.6	17.7
Micro Surfacing Rate	2.5	2.7	0.3	2.6	9.9
Micro Surfacing EFE	2.5	2.7	0.2	2.6	7.3
Chip Seal					
Emulsion Application Rate	2.2	3.7	1.6	3.0	52.5
Aggregate Application	2.4	3.5	1.1	3.0	35.5
Seal Placement Rate	2.7	3.5	0.8	3.0	27.0
Seal Placement EFE	2.8	3.1	0.4	3.0	12.2
25mm UTO					
ACon Batch GHG	8.5	13.5	4.9	11.0	44.8

Through the review of the sensitive parameters for energy consumption there are four key parameters that are observed across the treatments – the equipment efficiency (EFE) value, the placement rate of the treatment, the aggregate application rate and the rate of the asphalt cement/emulsion or polymer modified binder. The UTO is the exception with one sensitive parameter: the energy for the asphalt concrete production energy. Figure 5.2 shows the identified four sensitive parameters for the applicable treatments.

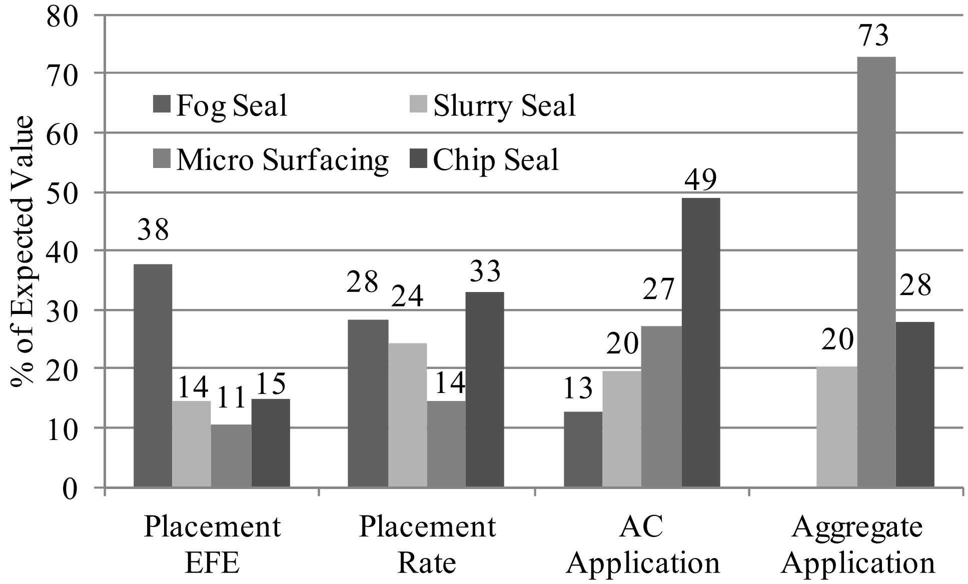

Figure 5.2 Energy Consumption Sensitive Parameters for Maintenance Treatments

Similar to the energy consumption sensitive parameters the same four sensitive parameters are observed for CO_2e emissions – the equipment EFE value, the placement rate of the treatment, the aggregate application rate and the rate of the asphalt cement/emulsion or polymer modified binder. For the UTO the sensitive parameter is the GHG emissions related to the asphalt concrete plant. Also added to the sensitive parameters is the application of Portland cement to the micro surfacing mix.

For rehabilitation and reconstruction treatments, the energy consumption and GHG emission sensitive parameters are summarized in Table 5.3 and Table 5.4.

Table 5.3 Energy Consumption Sensitive Parameters for Rehabilitation and Reconstruction Treatments

Parameter	**Low**	**High**	**Difference**	**EV**	**% of EV**
	GJ				
Mill and Fill					
ACon Drum/Batch Energy	616.1	694.0	77.9	660.9	11.8
CIPR*					
Cement Application Rate	24.4	234.8	210.5	129.6	162.4
FDR*					
Cement Application Rate	185.4	587.2	401.8	336.1	119.6
FDR EFE	301.9	369.9	68.0	336.1	20.2
Initial Construction					
ACon Drum/Batch Energy	1803.3	1920.1	116.9	1870.4	6.2
Recycled Construction					
ACon Drum/Batch Energy	1367.4	1484.2	116.9	1434.5	8.1

* CIPR and FDR values do not include 50mm overlay.

Table 5.4 GHG Emissions Sensitive Parameters for Rehabilitation and Reconstruction Treatments

Parameter	**Low**	**High**	**Difference**	**EV**	**% of EV**
	GJ				
Mill and Fill					
ACon Batch GHG	34.3	54.0	19.7	44.1	44.7
CIPR*					
Cement Application Rate	2.8	29.1	26.3	16.0	165.1
FDR*					
Cement Application Rate	37.2	83.8	46.7	63.0	74.1
Initial Construction					
ACon Batch GHG	137.6	167.2	29.6	152.4	19.4
Recycled Construction					
ACon Batch GHG	118.2	147.8	29.6	133.0	22.2

* CIPR and FDR values do not include 50mm overlay.

From the various rehabilitation and reconstruction treatments that were modeled, two key sensitive parameters were observed for energy consumption – the asphalt concrete plant energy and the cement application rate. These sensitive parameters are shown in Figure 5.3.

Similar to the sensitive parameters for the energy consumption, there are two key sensitive parameters for the GHG emissions model – the emissions from the production of the HMAC and the rate at which Portland cement is added. These sensitive parameters are shown in Figure 5.4.

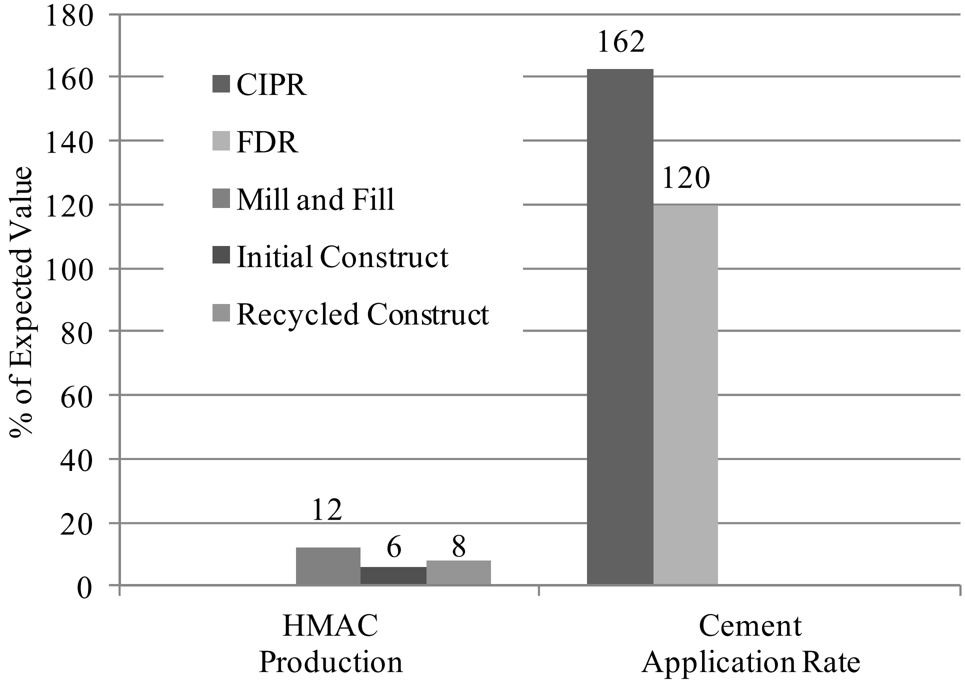

Figure 5.3 Energy Consumption Sensitive Parameters for Rehabilitation and Reconstruction Treatments

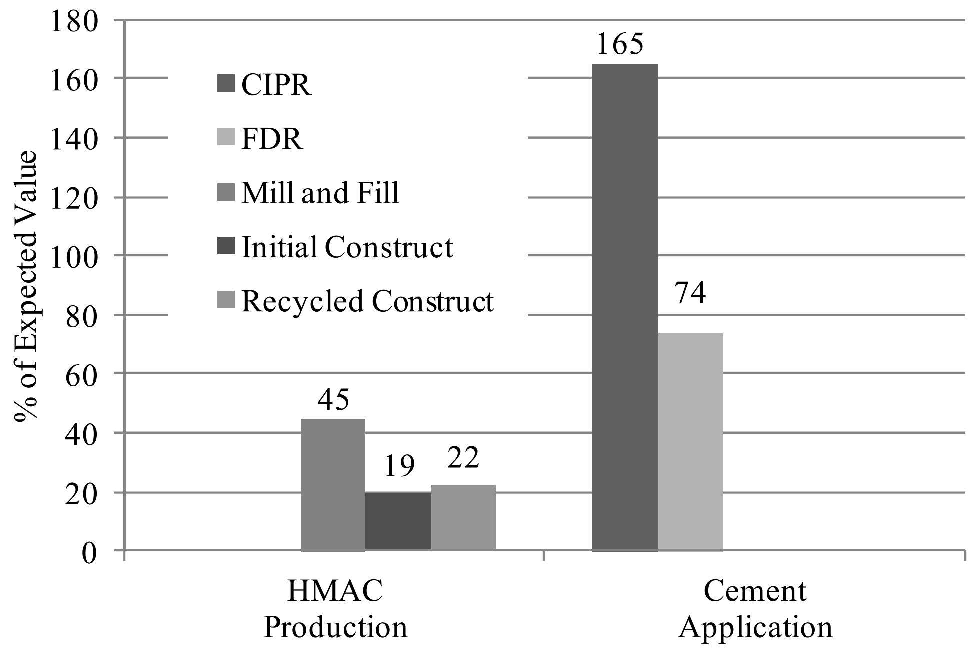

Figure 5.4 GHG Emissions Sensitive Parameters for Rehabilitation and Reconstruction Treatments

5.2 Sub-model Percentages

The expected values for each sub-model were determined allowing the percentage that each model activity contributes to the overall energy consumed and CO_2e emissions generated to be determined. These values are summarized in Table 5.5 and illustrated in Figure 5.5 and Figure 5.6 for energy consumption. For GHG emissions these values are summarized in Table 5.6 and illustrated in Figure 5.7 and Figure 5.8.

Table 5.5 Energy Consumption Sub-model Percentages

	Energy Consumption (%)		
	Production	**Equipment**	**Transport**
Fog Seal	78	17	5
Slurry Seal	43	45	11
Micro Surfacing	60	27	12
Chip Seal	44	44	13
Ultra Thin Overlay	75	4	21
Mill and Fill	75	10	15
CIPR	75	7	18
FDR	74	13	14
R & R Virgin	47	25	28
R & R Recycled	44	32	24

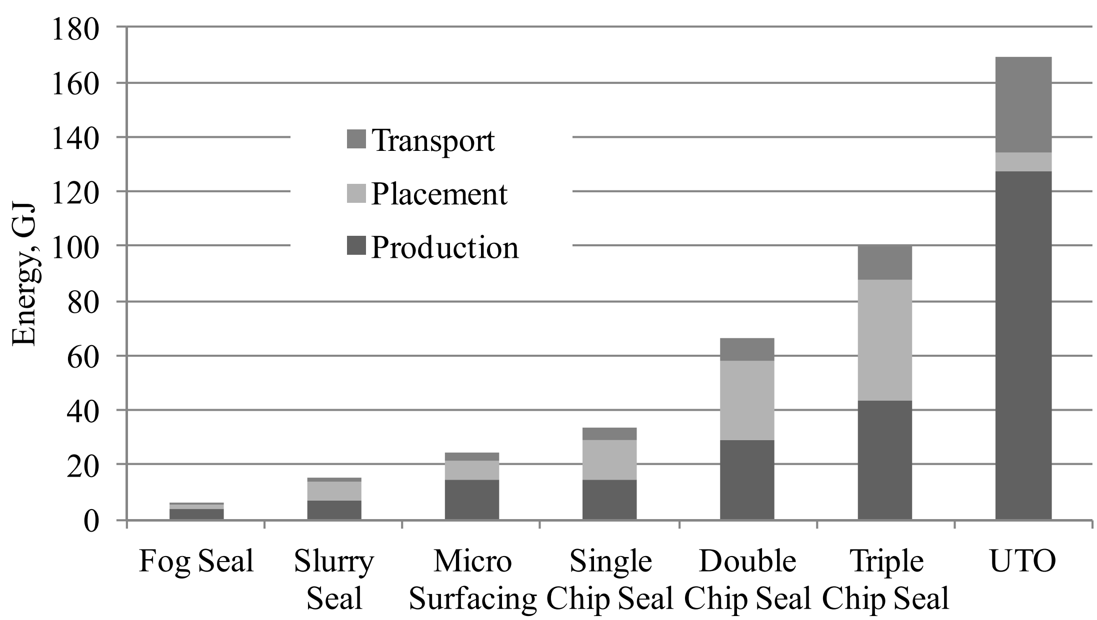

Figure 5.5 Energy Consumption by Sub-model for Maintenance Treatments

Table 5.6 GHG Emission Sub-model Percentages

	GHG Emissions (%)		
	Production	**Equipment**	**Transport**
Fog Seal	82	14	4
Slurry Seal	52	38	10
Micro Surfacing	73	18	9
Chip Seal	55	36	10
Ultra Thin Overlay	73	1	23
Mill and Fill	73	10	17
CIPR	81	4	14
FDR	86	6	7
R & R Virgin	53	22	25
R & R Recycled	57	24	20

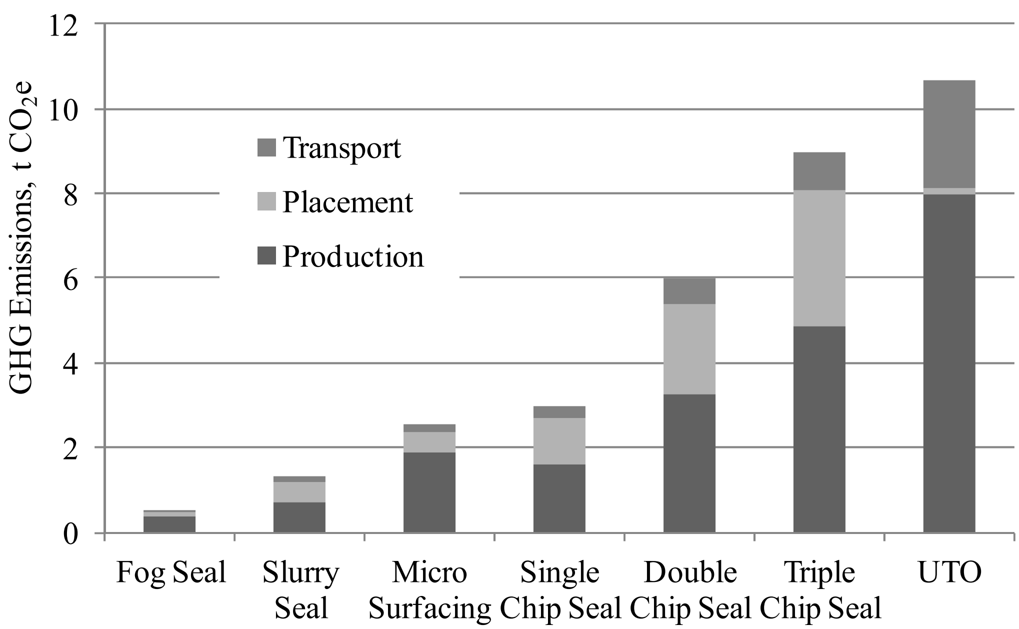

Figure 5.6 GHG Emissions by Sub-model for Maintenance Treatments

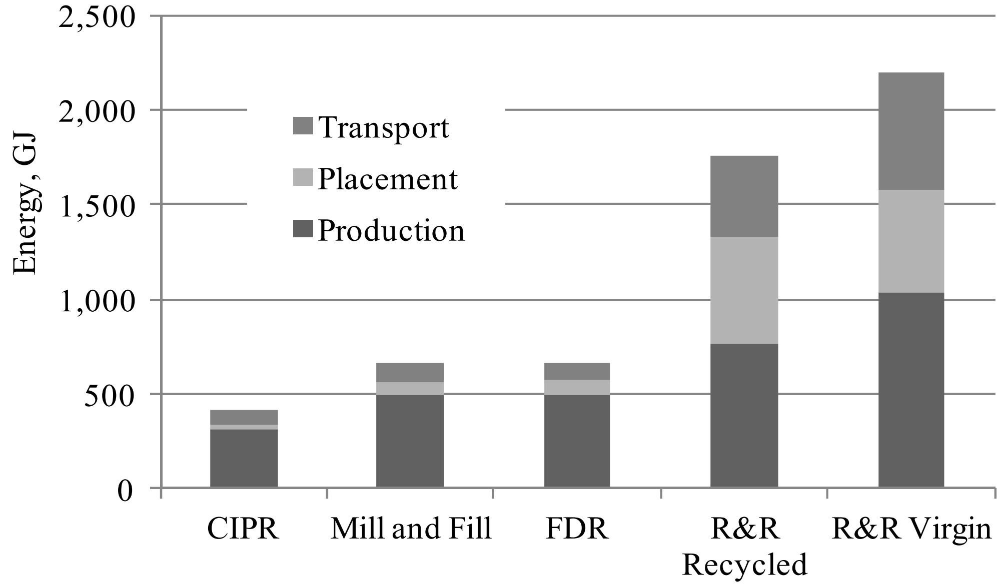

Figure 5.7 Energy Consumption by Sub-model for Rehabilitation and Reconstruction Treatments

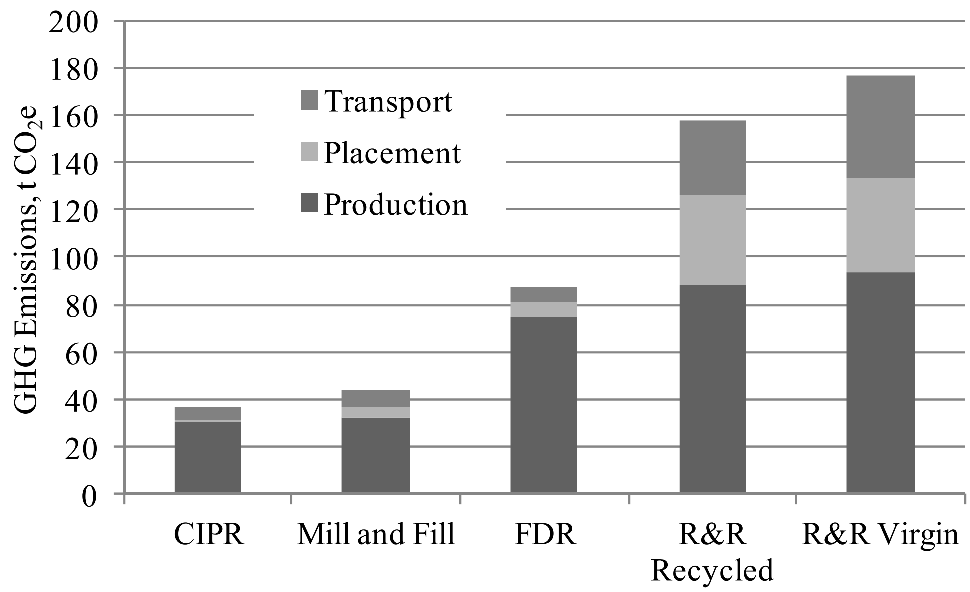

Figure 5.8 GHG Emissions by Sub-model for Rehabilitation and Reconstruction Treatments

Based on the sub-model percentages of the maintenance treatments for energy consumption, the production of materials consumed the greatest amount of energy except for slurry seal. The ultra thin overlay has a higher production value because of the production of the HMAC. As the amount of materials used in the treatments increases, the portion of energy consumed for material production also increases. For CO_2e emissions the production of the materials for all of the maintenance treatments is the greatest contributor to the overall CO_2e emissions that are generated except for fog seal.

For the rehabilitation and reconstruction treatments the majority of the energy consumed and CO_2e emissions that are generated are from the production of the materials.

5.3 Roadway Structure Material Production

For the treatments that have been reviewed, the highest percentage of energy consumed and CO_2e emissions from production, placement and transport is generally from the production of the materials that are used. To determine how the production of materials contributes to the total energy consumed and GHG emissions that are generated a review of the production of materials for the initial construction of a lane-km of roadway is completed. Table 5.7 and Figure 5.9 summarize the percentages that the material production for each layer contributes to the overall energy consumption values and Table 5.8 and Figure 5.10 summarize the CO_2e emissions for the production of the materials used in each layer.

Table 5.7 Energy Consumption by Flexible Pavement Layer

Layer	Energy (GJ)	% of Production	% of Total
ACO	374	36.1	20.0
ACB	359	34.6	19.2
GBC	87	8.4	4.6
Subbase	81	7.7	4.3
CSS	137	13.2	7.3
Total	1038	100.0	55.5

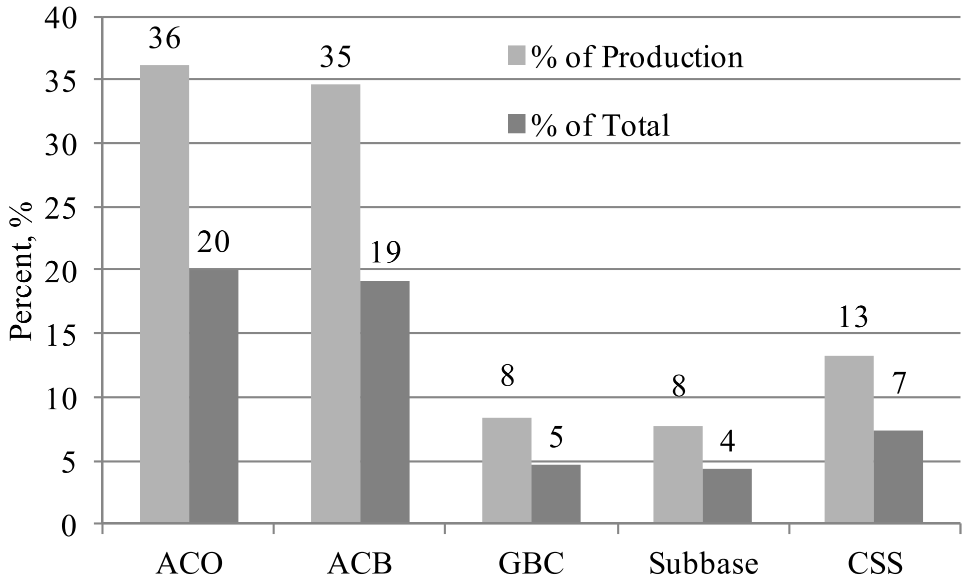

Figure 5.9 Energy Consumption by Flexible Pavement Layer

Table 5.8 GHG Emissions by Flexible Pavement Layer

Layer	GHG (t CO_2e)	% of Production	% of Total
ACO	24.9	26.6	16.3
ACB	23.6	25.3	15.5
GBC	14.2	15.2	9.3
Subbase	2.2	2.4	1.4
CSS	28.5	30.5	18.7
Total	93.4	100.0	61.3

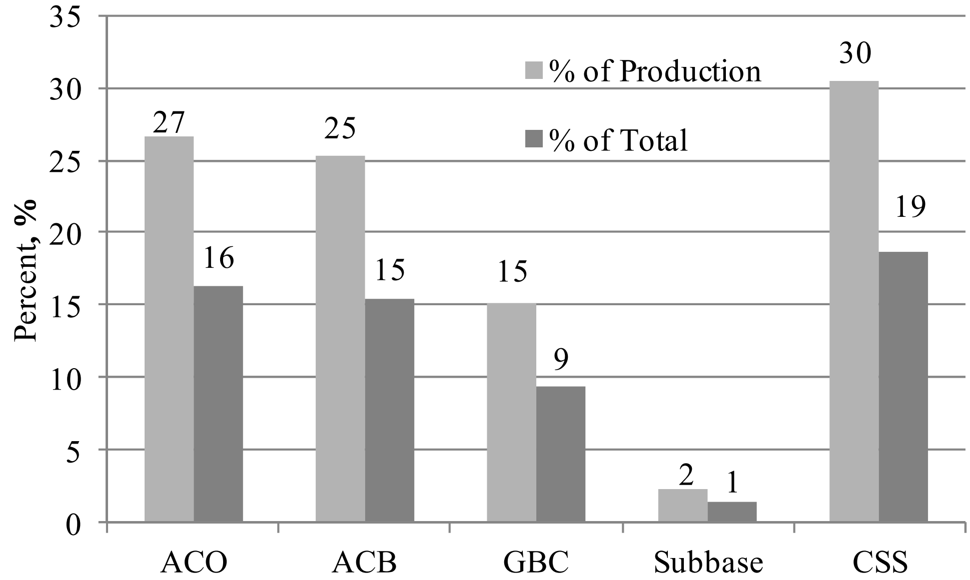

Figure 5.10 GHG Emissions by Flexible Pavement Layer

For the materials used in the initial construction base case, the production of the asphaltic layers combined account for 70.7 and 51.9 percent of the energy consumed and CO_2e emissions generated respectively, and 39.2 and 31.8 percent of the overall total energy consumed and CO_2e emissions. The second greatest contributor to the energy consumed and GHG emissions by layer for material production is the Portland cement that is used to stabilize the subgrade. The production of Portland cement contributes to 13.2 percent of energy consumed and 30.5 percent of CO_2e emissions for the materials that are produced. Table 5.9 and Figure 5.11 summarize the energy consumed and CO_2e emissions generated through the production of one tonne of HMAC. The production of asphalt has been divided into the production of the asphalt cement, the aggregate and the operations at the hot mix asphalt plant. The plant operations for the production of the HMAC is the greatest contributor to the energy consumed and CO_2e emissions generated.

Table 5.9 Energy Consumption and GHG Emissions for One Tonne of HMAC

Material	Energy Consumed		GHG Emissions	
	GJ	%	CO_2e	%
AC	0.083	15.5	9.495	26.6
Aggregate	0.046	8.6	7.642	21.4
Plant	0.406	75.9	18.578	52.0
Total	0.535	100.0	35.715	100.0

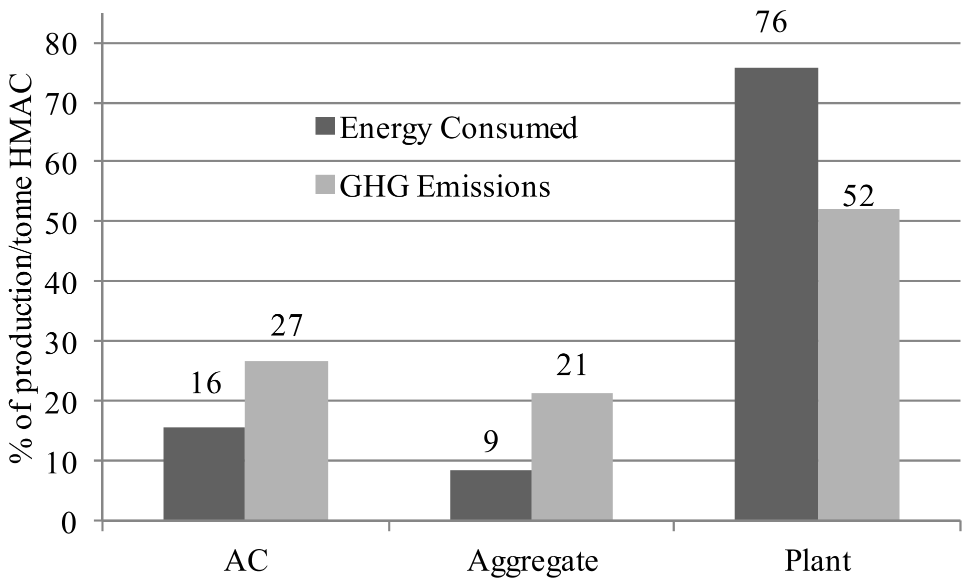

Figure 5.11 Energy Consumption and GHG Emissions for One Tonne of HMAC

5.4 Energy Costs

From the modeled energy consumption values the amount of fuel consumed can be determined. The number of litres of diesel consumed is calculated in the equipment and transport sub-models. For the production sub-model the number of litres of diesel is back calculated from the total energy consumed divided by the energy of one litre of diesel. The cost of the fuel for each treatment is calculated based on the average cost of diesel in Saskatoon from September 2011 to 2012 at $1.21/litre and is shown in Figure 5.12 and Figure 5.13 (NRC 2012).

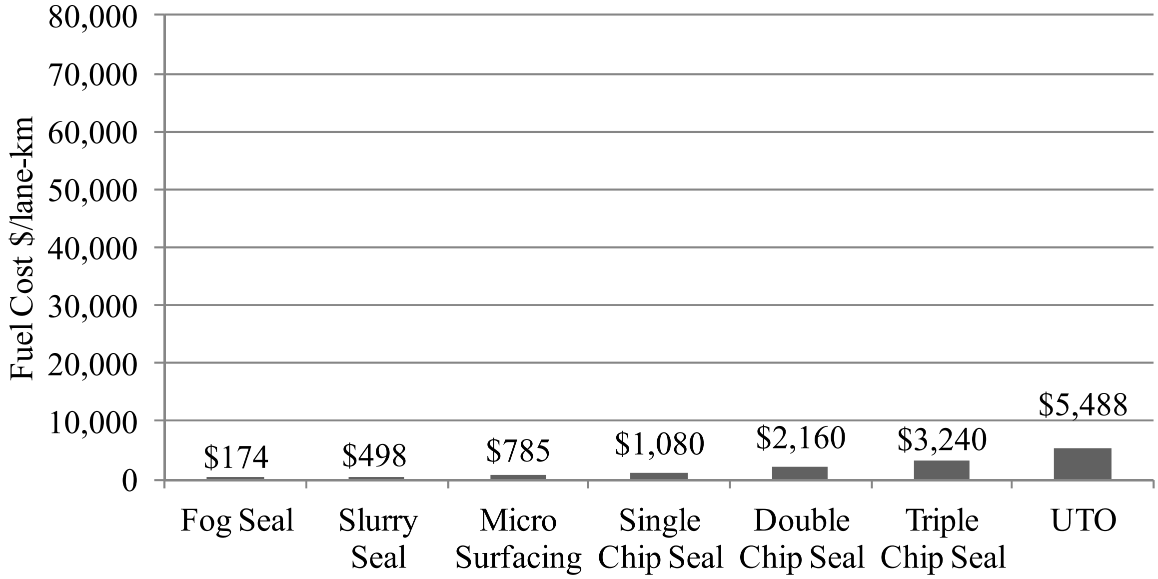

Figure 5.12 Cost of Fuel for Maintenance Treatments

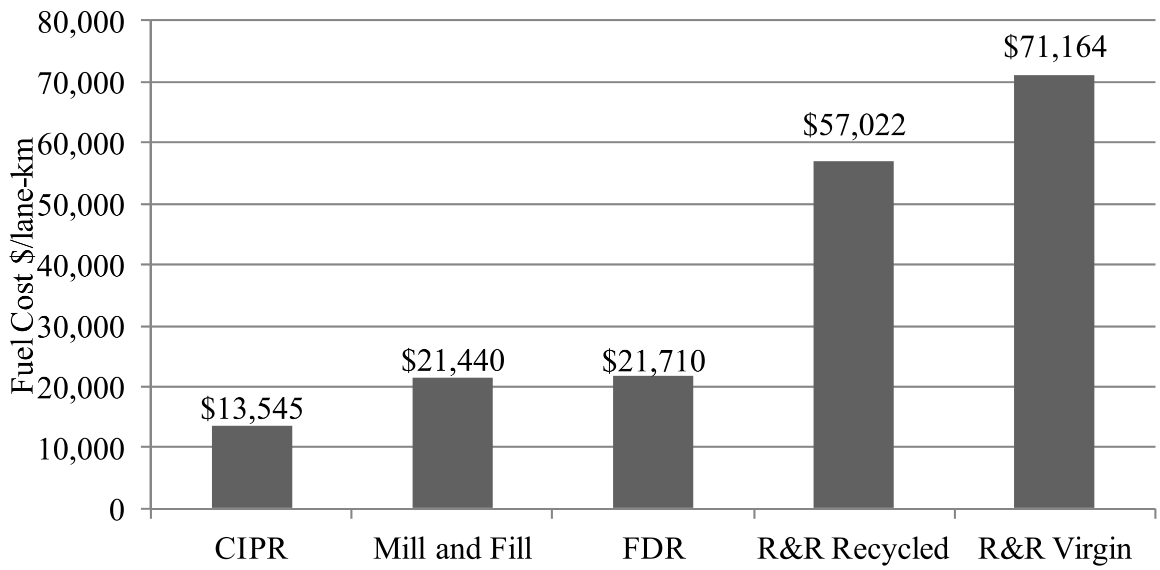

Figure 5.13 Cost of Fuel for Rehabilitation and Reconstruction Treatments

5.5 Emission Costs

The average cost of a voluntary market carbon credit in 2010 was $6 US per tonne (Peters-Stanley et al. 2011). Based on the amount of CO_2e generated for each treatment the cost of the carbon is summarized in Figure 5.14 and Figure 5.15.

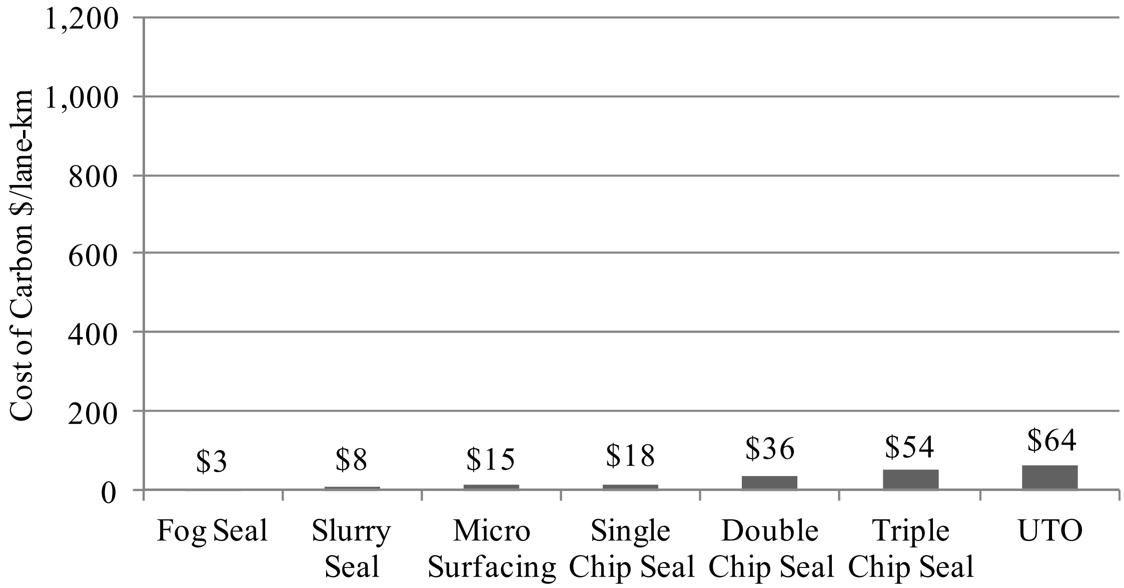

Figure 5.14 Cost of Carbon for Maintenance Treatments

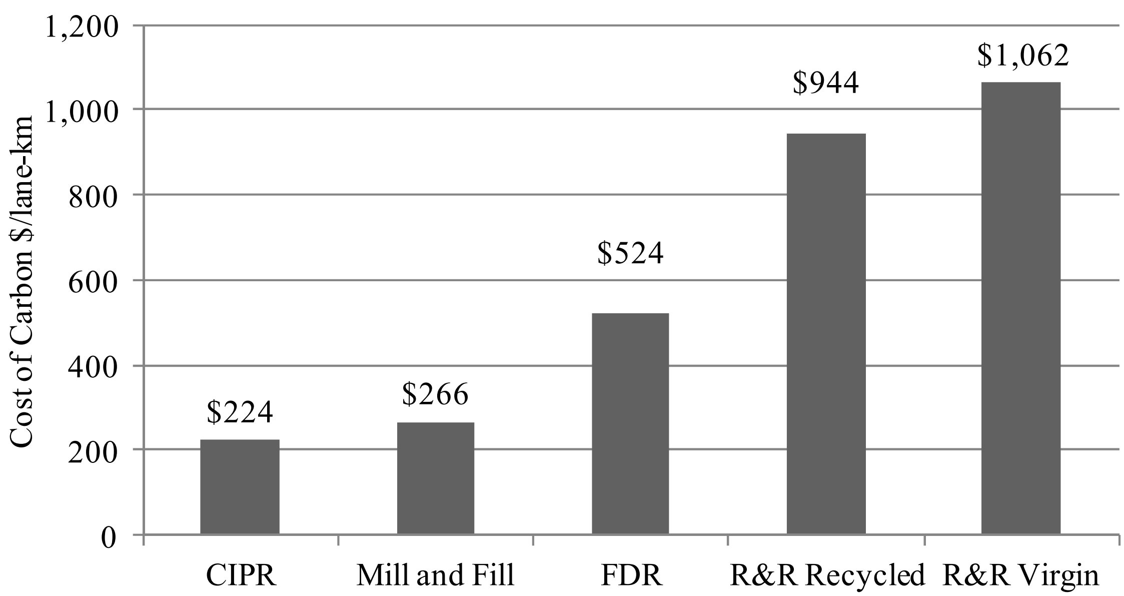

Figure 5.15 Cost of Carbon for Rehabilitation and Reconstruction Treatments

5.6 Summary

Further analysis of the model values generated in Chapter Four was completed including a review of the sensitive parameters, the activities that contributed the greatest to energy consumption and CO_2e emissions generated and the associated costs. Four sensitive parameters were found for maintenance treatments: the equipment efficiency, the rate at which the treatment was placed, the amount of asphalt cement material and the amount of aggregate in the treatment application design. For the rehabilitation and reconstruction techniques there were two sensitive parameters. The first was the production of HMAC and the second parameter was the amount of Portland cement that was added for the CIPR and FDR treatments.

In review of the sub-model percentages, it was generally observed that the production of materials contributed the greatest to the energy consumed and CO_2e emissions generated compared to the equipment used and the transport of the materials. Looking further into the production of materials, a review of the various layers in a flexible pavement structure found that the production of the HMAC contributed the greatest to the energy being consumed and CO_2e emissions being generated. It was also determined that from the production of HMAC the operation at the plant contributed the greatest to the energy being consumed and CO_2e emissions being generated.

Chapter 6

MODEL VALIDATION

The preceding chapters have discussed the model parameters, calculations and the formulation of the model through the presentation of case studies for construction, maintenance, rehabilitation and reconstruction treatments typically used on flexible pavement structure roadways. Further analysis was completed on the information that was collected from the model to determine the sensitive parameters and how energy consumption and GHGs are generated throughout the various treatments. This chapter will validate the model that was constructed based on published and modeled values that are available.

6.1 Comparison to Published and PaLATE Model Values

Published values for each type of construction, maintenance, rehabilitation and reconstruction treatments were reviewed. For the maintenance treatments unit rates were found. With construction, rehabilitation and reconstruction published values must be determined by the amount of material being placed in each layer. The published value determined for each treatment is discussed below and summarized in Table 6.5 and Table 6.6.

6.1.1 Initial Construction

Muench et al. (2010) conducted a review of 35 assessments for various flexible pavement structures. For energy consumption the results varied from less than one to less than seven terra joule (TJ) per lane-km with a high outlier at 17 TJ per lane-km. The median value was 3.17 TJ and a range of two to four terra joules per lane-km was found to be a fair representative range for the construction of a flexible pavement structure. Muench et al. (2010) also conducted a review of 31 assessments for the amount of GHGs generated through the construction of a typical lane-km flexible pavement structure and found a median value of 243 t per lane/km. Based on the information collected, a fair representative range of GHGs generated was determined to be 100 to 500 t CO_2e per lane-km.

6.1.2 Maintenance Treatments

Published values for the maintenance treatments were collected from Chehovits and Galehouse (2010) who reviewed the energy consumption and GHG generated from the extraction, production, transportation and placement of materials. Table 6.1 summarizes the values that were determined.

6.1.3 Rehabilitation Treatments

Published values for the rehabilitation treatments were collected from Chehovits and Galehouse (2010) and Dorchies (2008) who reviewed the energy consumption and GHGs generated from the extraction, production, transportation and placement of materials. Table 6.2 summarizes the values that were determined. These values were determined based on the weight of material being used for each treatment.

6.1.4 Reconstruction Treatments

As pavement structures can vary quite significantly from project to project it is difficult to find published values to be exact comparisons of the values determined from the model developed in this research. As such, these values generated for reconstruction treatments from the developed model are only compared to the values determined from PaLATE as discussed in the next section.

Table 6.1 Maintenance Published Energy Consumed and GHG Emission Values (Chehovits and Galehouse, 2010)

Treatment	Application Details	Energy Consumed MJ/m^2	Emissions $t\ CO_2/m^2$
Fog Seal			
	0.23 L/m^2	0.4	0.2
	0.46 L/m^2	0.8	0.4
	0.69 L/m^2	1.2	0.7
Slurry Seal/Micro Surfacing			
	Type III, 12% Emulsion, 13 kg/m^2	6.5	0.3
	Type II, 14% Emulsion, 8.7 kg/m^2	4.9	0.2
Chip Seal			
	Emulsion 2.0 L/m^2, Aggregate 21 kg/m^2	8.9	0.5
	Emulsion 1.6 L/m^2, Aggregate 15 kg/m^2	6.5	0.4
Hot Mix Asphalt Concrete			
	50mm	77.0	6.7

Table 6.2 Rehabilitation Published Energy Consumed and GHG Emission Values (Chehovits and Galehouse, 2010)

Treatment	Details	Energy Consumed MJ/t	GHG Emissions $kg\ CO_2/t$
Mill and Fill			
	Milling	35	2.3
	100mm HMAC	355	27.3
	Tack Coat	3490	221.0
CIPR			
	Emulsion In-situ Recycling	139	10.0
	CIP Recycling	15	1.13

6.1.5 PaLATE Model Values

The PaLATE Model was developed at the University of California, Berkeley and is used to determine the amount of energy consumed and GHG emissions generated through various roadway works. This model is available to the public on the worldwide web and may be used for the Lifecycle Inventory required credit for Greenroads. Muench et al (2010) identified a number of limitations to this model including transport and equipment efficiency calculations and material unit weight values. The information that is required to be entered into PaLATE includes the weight or volume of the basic materials used and the distance the materials are hauled. The values for the material production, equipment used for placement and the transport of materials from PaLATE are summarized for each model.

All of the treatments modeled within this work are entered into the PaLATE model and the values generated from the PaLATE model for the production, equipment, placement and total values for energy consumption and GHG emissions are provided in Table 6.3 and Table 6.4. As opposed to the PaLate model, the model developed in this work is fundamentals based, the calculations are detailed and it considers uncertainty allowing the key contributing factors to be identified.

Table 6.3 PaLATE Energy Consumption Values for Treatments

Treatment	Energy Consumed (GJ/lane-km)			
	Production	**Equipment**	**Transportation**	**Total**
Fog Seal	5.5	~0.0	1.0	6.5
Slurry Seal	11.1	0.1	7.1	18.3
Micro Surfacing	20.1	0.2	11.6	32.0
Chip Seal	25.5	0.1	16.7	42.2
UTO	75.1	1.2	56.6	132.9
Mill and Fill	287.2	9.8	255.8	552.7
CIP	109.8	5.6	18.4	133.8
FDR	519.3	2.6	95.7	617.6
R & R Virgin	1,337.3	916.3	41.9	2,295.5
R & R Recycled	610.8	9.8	555.4	1,176.0
Initial Construction	1,337.3	753.0	22.3	2112.6

Table 6.4 PaLATE GHG Emission Values for Treatments

Treatment	Energy Consumed (GJ/lane-km)			
	Production	**Equipment**	**Transportation**	**Total**
Fog Seal	0.4	~0.0	0.1	0.5
Slurry Seal	0.8	~0.0	0.5	1.3
Micro Surfacing	1.9	~0.0	0.8	2.7
Chip Seal	1.8	~0.0	1.2	3.0
UTO	5.3	0.1	3.9	9.3
Mill and Fill	20.4	17.6	0.7	38.7
CIP	11.4	1.3	0.4	13.0
FDR	64.3	0.2	6.6	71.1
R & R Virgin	110.6	2.9	63.2	176.7
R & R Recycled	60.5	0.7	38.3	99.5
Initial Construction	110.6	1.5	51.9	164.1

6.1.6 Comparison of Values

The values determined by the model are compared to the published and PaLATE modeled values discussed in the previous sections in Table 6.5 and Table 6.6. These values are also shown in Figure 6.1 to Figure 6.4. As a range of values was determined for the generated model values and the published/PaLATE values, the ranges of values were compared and when the two ranges overlapped the percent difference is zero. When the ranges did not overlap the appropriate low and high values of the modeled and published/PaLATE values were used to determine the percent difference. The percent difference of the modeled and published/PaLATE values were determined using Equation 6.1. Refer to Appendix B for a sample calculation. The treatments where the determined modeled value percent difference is greater than 10 percent are reviewed in further detail.

$$\%\,Difference = \frac{Model\,Value - Published\,Value}{Published\,Value} \times 100$$

Equation 6.1

For the comparison of the energy consumption values for maintenance treatments the developed model values for fog seal, micro surfacing and chip seal are found to be within the published/model values. For slurry seal and the ultra thin overlay, the percent difference was -2.6 and 10.9 percent, respectfully.

Through the review of the sensitive parameters in Chapter Five it was determined that the most sensitive parameter value was the energy for the production of the HMAC with a percent difference of the effective value of 11.5 percent. When examining the modeled values for the UTO, the sub-model material production for energy consumption was 127.0 GJ whereas for the PaLATE model it was 75.1 GJ. With the UTO, HMAC is the primary material used for the treatment. The variability in the production values for the HMAC may account for the percent difference between the model values in the developed model compared to the published and PaLATE model values used for comparison.

Table 6.5 Summary of Energy Consumed Comparison of Modeled and Published Values

Treatments	Energy GJ/lane-km						
	Model			Published		PaLATE	% Difference
	Low	Expected	High	Low	High		
Initial Construction	1803.3	1870.4	1964.0	2000.0	4000.0	2112.6	-1.8
Maintenance							
Fog Seal	4.2	5.4	6.5	1.5	4.4	6.5	0.0
Slurry Seal	13.8	15.3	17.7	18.1	24.1	18.3	-2.6
Micro Surfacing	15.3	24.2	33.0	18.1	24.1	32.0	0.0
Chip Seal	25.1	33.3	41.4	24.1	32.9	42.2	0.0
Ultra Thin Overlay	158.0	169.2	177.5	-	142.5	132.9	10.9
Rehabilitation							
Mill and Fill	616.1	660.9	694.0	259.7	-	552.7	11.5
Cold in-Place Recycling*	15.6	84.3	150.1	16.80	155.6	133.8	0.0
Reconstruction							
Full Depth Reclamation*	185.4	336.1	587.2	-	-	617.7	-15.3
Remove and Replace with Virgin Materials	2067.7	2193.7	2346.2	-	-	2295.5	0.0
Remove and Replace with Off-Site Recycled Materials	1631.7	1757.8	1878.5	-	-	1176.0	38.8

* Does not include 50 mm Overlay

Table 6.6 Summary of GHG Emissions Comparison of Modeled and Published Values

Treatments	GHG t CO_2e/lane-km						% Difference
	Model			Published		PaLATE	
	Low	Expected	High	Low	High		
Initial Construction	137.6	152.4	167.2	100.0	500.0	164.1	0.0
Maintenance							
Fog Seal	0.4	0.5	0.6	0.1	0.3	0.5	0.0
Slurry Seal	1.2	1.3	1.5	0.7	1.1	1.3	0.0
Micro Surfacing	1.5	2.6	3.6	0.7	1.1	2.7	0.0
Chip Seal	2.2	3.0	3.7	1.5	1.9	3.0	0.0
Ultra Thin Overlay	8.5	11.0	13.5	-	12.4	9.3	0.0
Rehabilitation							
Mill and Fill	34.3	44.1	54.0	-	-	38.7	0.0
Cold in-Place Recycling*	2.8	16.0	29.1	1.26	11.20	13.0	0.0
Reconstruction							
Full Depth Reclamation*	37.2	65.9	113.8	-	-	71.1	0.0
Remove and Replace with Virgin Materials	156.7	175.8	194.8	-	-	176.7	0.0
Remove and Replace with Off-Site Recycled Materials	137.3	156.4	175.5	-	-	99.5	38.1

* Does not include 50 mm Overlay

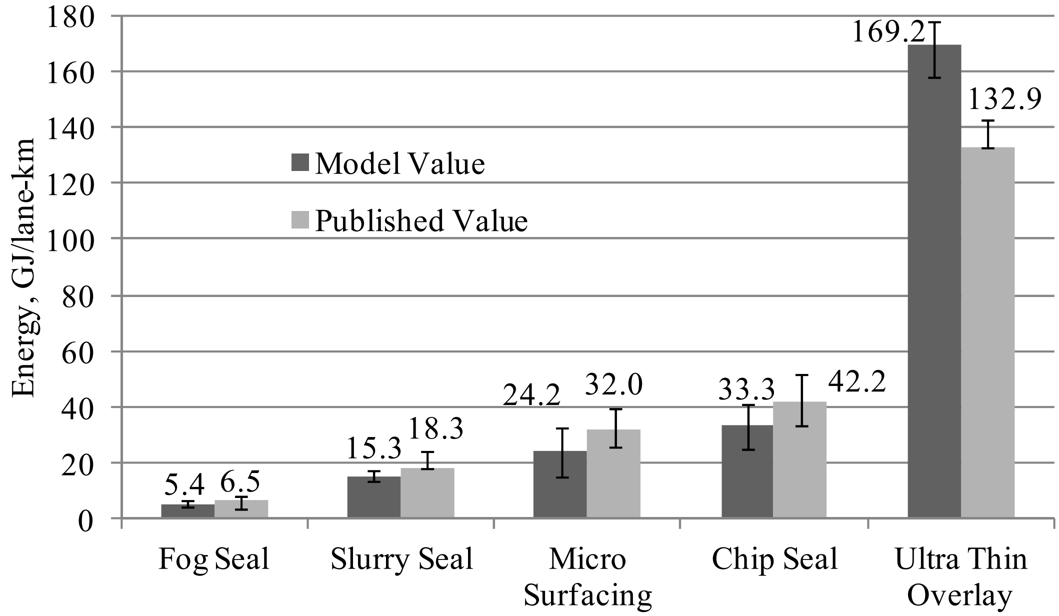

Figure 6.1 Energy Consumption Comparison of Modeled Values for Maintenance Treatments

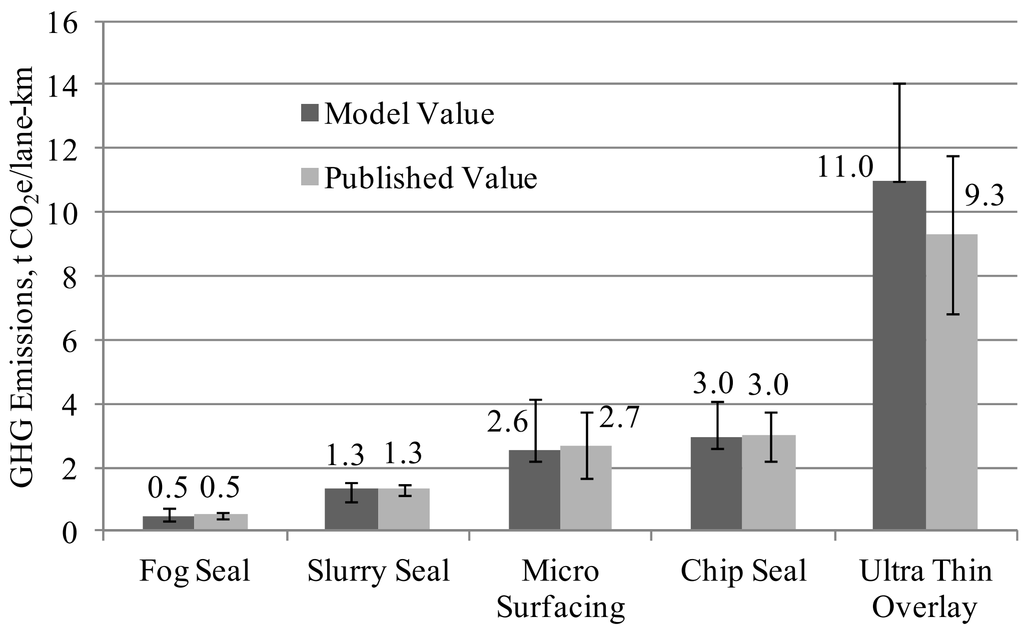

Figure 6.2 GHG Emissions Comparison of Modeled Values for Maintenance Treatments

For rehabilitation treatments the mill and fill model value was 11.5 percent greater than published values and the CIPR was within the published and model values. Similar to the UTO, HMAC is the main material that is used for a mill and fill treatment. When comparing the material production values from the models, the PaLATE model estimates the energy consumed at 287.2 GJ whereas the developed model value was 498.2 GJ. The machine used for milling can be a large machine which may consume larger amounts of energy. The energy consumed by equipment in the PaLATE model is 9.8 GJ and from the model developed in this research the energy consumed by the equipment is 62.8 GJ.

For reconstruction, the modeled FDR value was found to be 15.3 percent below the PaLATE model values. Through the sensitive parameter analysis in Chapter 5 the most sensitive parameter for FDR was determined to be the application rate of cement. A two percent cement application rate was placed into PaLATE model to achieve the result of 617.7 GJ/lane-km. By decreasing the amount of cement applied by 0.5 percent the result from the PaLATE model is 552.7 GJ/lane-km which falls within the range determined from the constructed model.

For the removal and replacement of the entire road structure, the replacement with virgin material was determined to be within the values determined from the PaLATE Model; however, the modeled values for replacement with recycled materials were found to be 38.8 percent greater than the PaLATE model values. The reason for this difference is found to be within the energy consumed from the equipment that is being used. The energy consumed by the equipment within the constructed model was 560.4 GJ whereas from the PaLATE model the energy consumed from the equipment model was 9.8 GJ. As the input values for the PaLATE are not known it is difficult to determine why this value for equipment is so low.

The values generated for each treatment in the GHG emissions model were all found to be within published values except for one – the removal and replacement with off-site recycled materials with a 38.1 percent difference. Similar to the case of energy consumption the difference is within the equipment usage emission values. The modeled value for the CO_2e generated from the equipment usage from the constructed model is 37.6 t CO_2e and from the PaLATE model it is 0.7 t CO_2e.

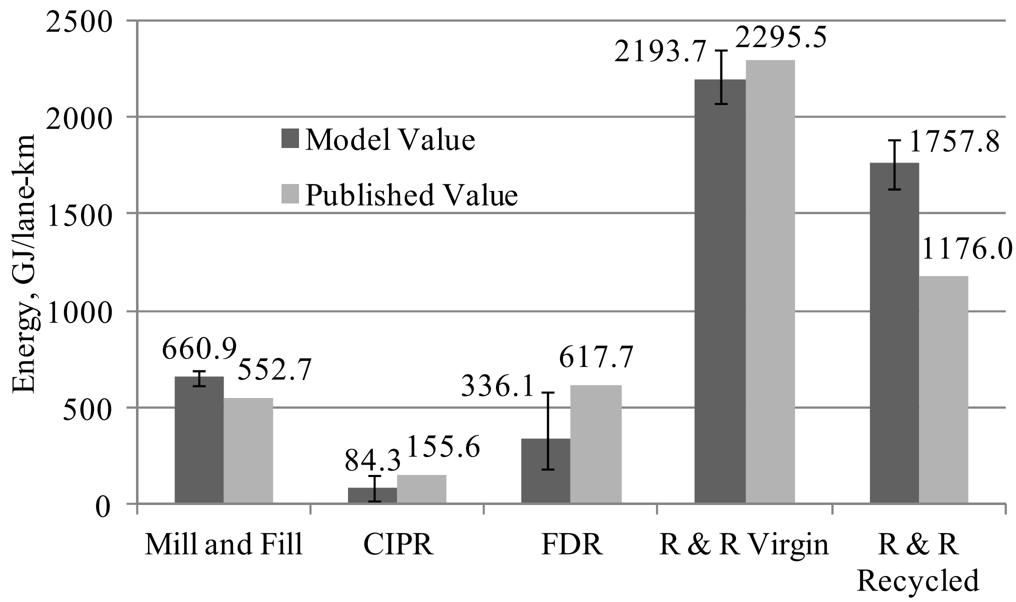

Figure 6.3 Energy Consumption Comparison of Modeled Values for Rehabilitation and Reconstruction Treatments

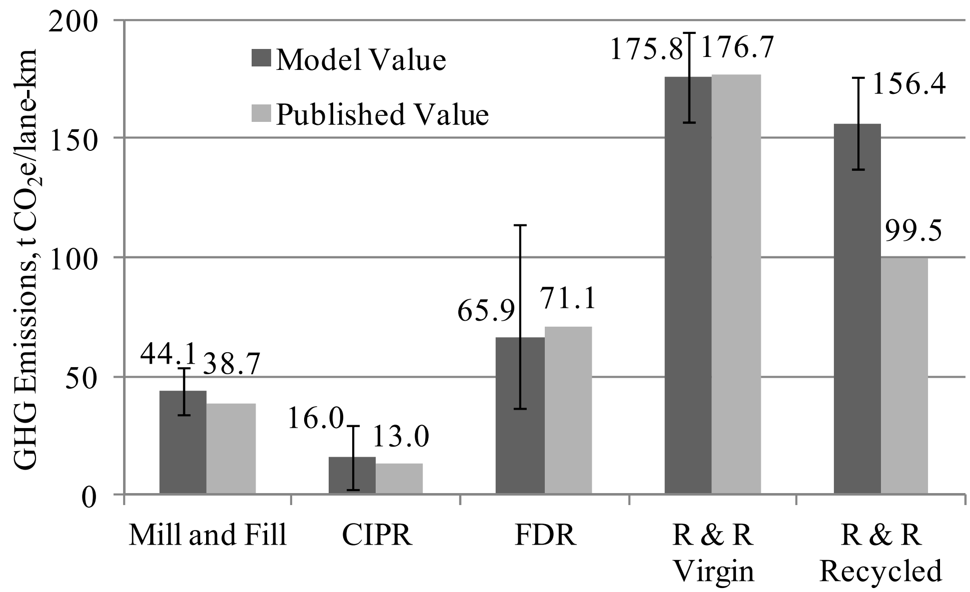

Figure 6.4 GHG Emissions Comparison of Modeled Values for Rehabilitation and Reconstruction Treatments

6.2 Summary

The model constructed was used to generate energy consumption and GHG emissions values for a lane-km of roadway for various maintenance, rehabilitation and reconstruction treatments. For energy consumption and CO_2e emission generation the majority of the values generated from the model were within or close to the published and modeled values that were found. Those that had greater than a ten percent difference included the UTO and the mill and fill. With both of these treatments the material that is used is HMAC which was also identified to be one of the most sensitive parameters. For the FDR the percent difference was -15.3 percent which may be attributed to the variability in the amount of Portland cement that is added. Finally the values determined for the remove and replace with off-site recycled materials from the constructed model were found to be approximately 38 percent different for the energy consumed and CO_2e emissions generated; however, when looking in more detail at the sub-model values it was found that the equipment values determined by PaLATE were significantly lower than those of the constructed model values.

Chapter 7

CASE STUDIES

This chapter will review four case studies for the application of the model developed. The case studies will include:

- The reconstruction of the rural roadway, Range Road (RR) 232 located in Strathcona County, Alberta;
- The reconstruction of an urban roadway, Kenderdine Road in Saskatoon, Saskatchewan;
- Further review of the reconstruction of Kenderdine Road with the use of alternative materials and;
- A review of the City of Saskatoon's 2012 proposed roadway restoration and reconstruction treatments.

Each case study will include the background of each project, the designed structure implemented and the generated values from the model for the amount of energy consumed and CO_2e emissions generated.

7.1 Range Road 232, Strathcona County

The section of roadway reconstructed of RR 232 used for this case study is located on the west side of Strathcona County on the City of Edmonton border, just north of Highway 16. This section of roadway is located in a growing industrial sector and with the new growth occurring in the area, upgrades were required for the existing 8.0 m wide rural roadway (ISL 2000).

The functional plan that was developed for RR 232 indicated that ultimately a four lane urban cross section with curb and gutter would be required to handle future traffic. In the interim, only the future southbound lanes would be constructed with a rural cross section and ditches for drainage. The construction to upgrade approximately one kilometer of RR 232 was completed in 2010 and is the basis of this case study. A typical cross section is shown in Figure 6.1 (ISL Engineering 2009).

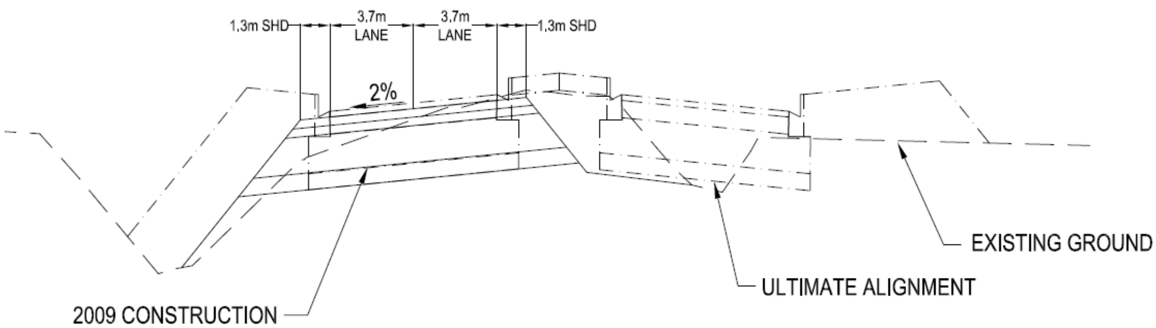

Figure 7.1 RR 232 Cross Section (ISL Engineering 2009)

7.1.1 Design Parameters

The design parameters that were used for the construction of RR 232 are summarized in Table 7.1. As this project has been constructed, the recorded values for progress are used as inputs for the model as included in Table 7.2. The hauling distances and the capacity of the trucks used are indicated in Table 7.3.

Table 7.1 RR 232 Design Parameters

Parameter	**Value**		**Unit**
Pavement Structure			
Layer 1	ACO	75	mm
Layer 2	ACB	75	mm
Layer 3	GBC	325	mm
Layer 4	CCS	150	mm
Material Composition			
AC Plant Type		Batch	
Cement		10	kg/m^2

Table 7.2 RR232 Construction Quantities

Item	Quantity	Unit
Pitrun Gravel	446	m^3
75mm ACO with Tack Coat	14,675	m^2
75mm ACB	15,090	m^2
ACO Milled Areas	18	t
325mm GBC	16,045	m^2
150mm Cement Stabilized Subgrade	15,245	m^2
Portland Cement	15,693	kg
Remove Asphalt Pavement Structure	5,455	m^2
Remove Existing GBC	1,773	m^3

Table 7.3 RR232 Hauling Information

Material	From	To	km*	Truck Capacity (t)
Removed Asphalt	Site	Stockpile	30	14
Removed Granular	Site	Waste Site	50	25
Aggregate	Source	Plant	270	40
Cement	Supplier	Site	50	26
GBC	Supplier	Site	100	25
ACO/ACB	Plant	Site	30	14

* Roundtrip

7.1.2 Energy Consumption and GHG Emissions

Based on the design parameters provided above, the expected energy consumed and CO_2e emissions generated for RR 232 by the production of material, the use of equipment and the transportation of the materials are indicated in Table 7.4 and are shown in Figure 7.2 and Figure 7.3.

Table 7.4 RR232 Energy Consumption and GHG Emission Values

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	**Avg/ML**	**High**	**Low**	**Avg/ML**	**High**
Production	3,389	3,659	3,859	251	311	370
On Site Equipment	1,794	2,058	2,321	130	150	169
Transport	1,798	1,885	1,972	129	136	167
Total	7,332	7,602	7,865	537	596	656

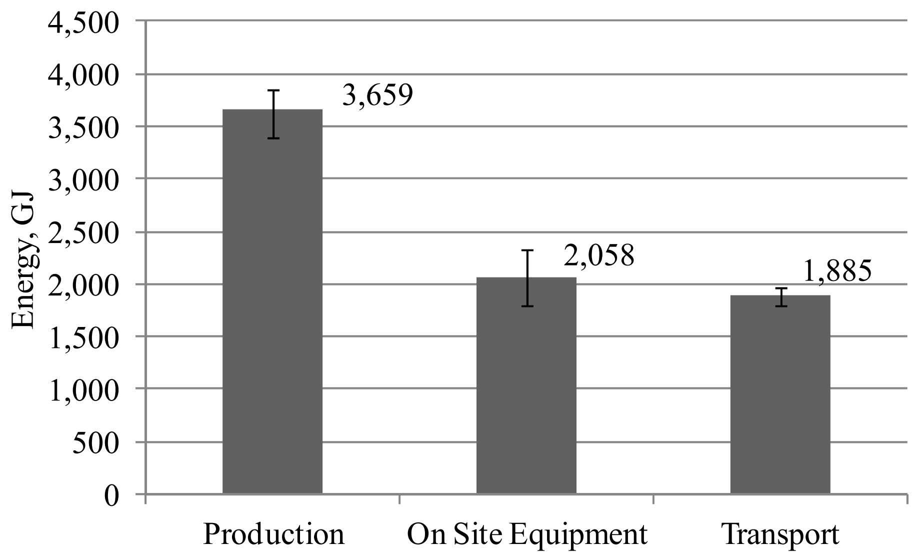

Figure 7.2 RR 232 Energy Consumed by Sub-model

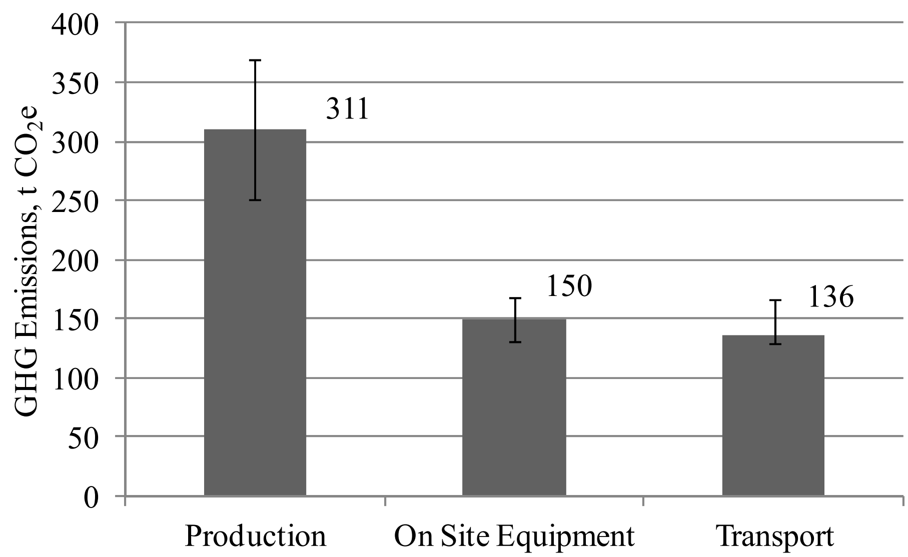

Figure 7.3 RR 232 GHG Emissions by Sub-model

Based on the expected values for RR 232 the calculated energy consumed for one lane-km is 1,917 GJ and the GHG emissions value is 150.3 t CO_2e. These lane-km values are considered to be conservative as the area used for the calculation was the area of the placed ACO rather than cross sectional top width of each layer.

7.2 Kenderdine Road, City of Saskatoon

The City of Saskatoon as part of its Green Street Infrastructure Program reconstructed a 250 m portion of Kenderdine Road from 115th Street to Attridge Drive in Saskatoon. Prior to reconstruction of the roadway, ground penetrating radar was used to assess the structural condition of the roadway and it was found to be in poor condition.

7.2.1 Design Parameters

The design parameters for the reconstruction of Kenderdine Road are summarized in Table 7.5. The material quantities used in reconstruction are summarized in Table 7.6 and the distances the materials were transported are summarized in Table 7.7. Within this pavement structure geosynthetics and drainage pipe were also placed and subgrade preparation was completed but these tasks are considered out of scope of the model.

Table 7.5 Kenderdine Road Design Parameters

Parameter		Thickness	Unit
Pavement Structure			
Layer 1	ACO	100	mm
Layer 2	RAP	200	mm
Layer 3	RPC	250	mm

Table 7.6 Kenderdine Road Construction Quantities

Material	**Quantity (t)**
Waste Excavation	2400
Material Rotomixed and Removed	1150
PCC Recycled Aggregate	1900
Rotomixed Material to Site	1150
Processed RAP to Site	380
Asphalt Concrete	920

Table 7.7 Kenderdine Road Hauling Information

Material	**From**	**To**	**Km**	**Truck – Axel**
Waste	Site	Stockpile	6	6
Rotomixed Material	Site	Stockpile	6	6
PCC Recycled Aggregate	Stockpile	Site	6	6
Rotomixed Material	Stockpile	Site	6	6
Processed RAP	Stockpile	Site	6	6
Asphalt Concrete	Plant	Site	9	3
Aggregate to Asphalt Concrete Plant	Source	Plant	100	8
Asphalt Cement to Concrete Plant	Refinery	Plant	250	8

7.2.2 Energy Consumption and GHG Emissions

Based on the parameters described above, the modeled energy consumed and GHG emissions generated for the reconstruction of Kenderdine Road are summarized in Table 7.8 and shown in Figure 7.4 and Figure 7.5. Based on the expected values for Kenderdine Road, the calculated energy consumed for one lane-km is 1,146 GJ and the GHG emissions value is 92.6 t CO_2e.

Table 7.8 Kenderdine Road Energy Consumed and GHG Emissions

	Energy Consumed (GJ)			GHG Emissions (t CO_2e)		
	Low	Avg/ML	High	Low	Avg/ML	High
Production	398	444	478	31.0	41.1	51.2
On Site Equipment	372	559	746	27.0	40.6	54.2
Transport	78	82	101	5.6	5.9	7.3
Total	898	1084	1271	74.0	87.6	101.2

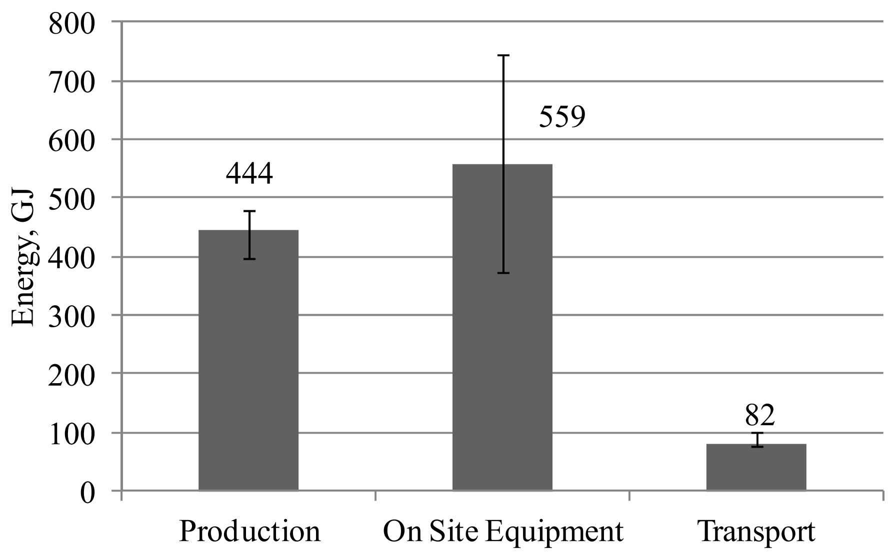

Figure 7.4 Kenderdine Road Energy Consumed by Sub-model

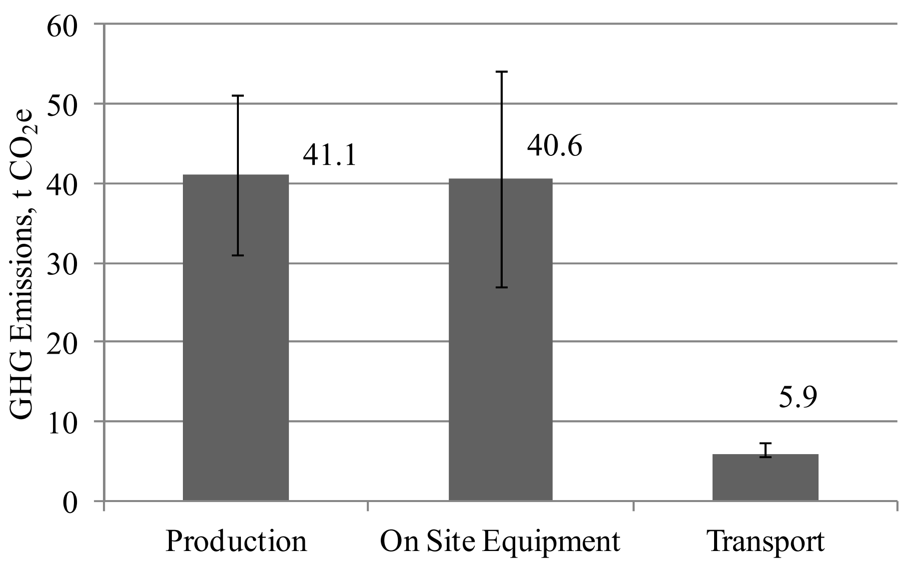

Figure 7.5 Kenderdine Road GHG Emissions by Sub-model

7.3 Kenderdine Road Alternative Structure Analysis

To show more applications of the model, further review with the use of other materials for Kenderdine Road as detailed in the previous section was conducted. This section reviews how the energy consumed and CO_2e emissions for the constructed roadway compare to a traditional virgin structure of the same area. Further use of green technologies such as WMAC and the use of RAP in the top layer of asphalt may impact the overall energy consumed and CO_2e emission values generated.

7.3.1 Design Parameters

The following scenarios are reviewed and compared for Kenderdine Road:

- A traditional structure that would typically be used in the City of Saskatoon for a roadway consisting of 100 mm of HMAC and 450 mm of GBC;
- The constructed structure as detailed in Section 7.2;
- The constructed structure with the use of WMAC; and
- The constructed structure with the use of WMAC and ten percent RAP.

7.3.2 Energy Consumption and GHG Emissions

The energy consumption and GHG emissions for the alternative pavement structures described in the previous section are shown in Figure 7.6 and Figure 7.7. The percent reductions of energy consumption and CO_2e emissions for each alternative structure compared to the construction of the traditional structure are summarized in Figure 7.8.

With the use of WMAC a 31.1 percent reduction of energy consumed from traditional construction methods and 26.3 percent reduction for CO_2e emissions are expected. With the additional use of ten percent RAP in the WMAC further reductions to 31.8 percent of the energy consumed and 34.8 percent of CO_2e emissions compared to the traditional structure are expected.

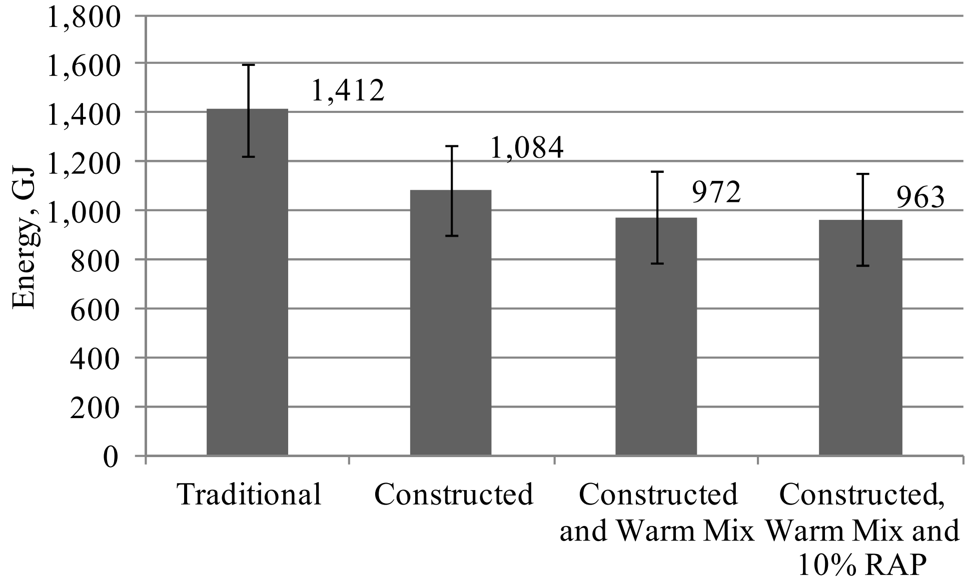

Figure 7.6 Kenderdine Road Energy Consumed Alternative Structures

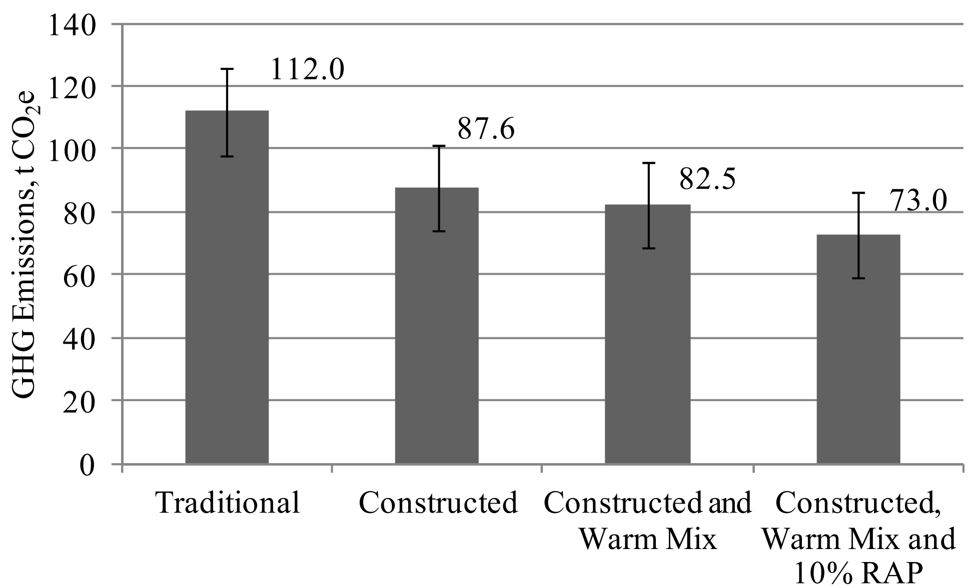

Figure 7.7 Kenderdine Road CO_2e Emissions Alternative Structures

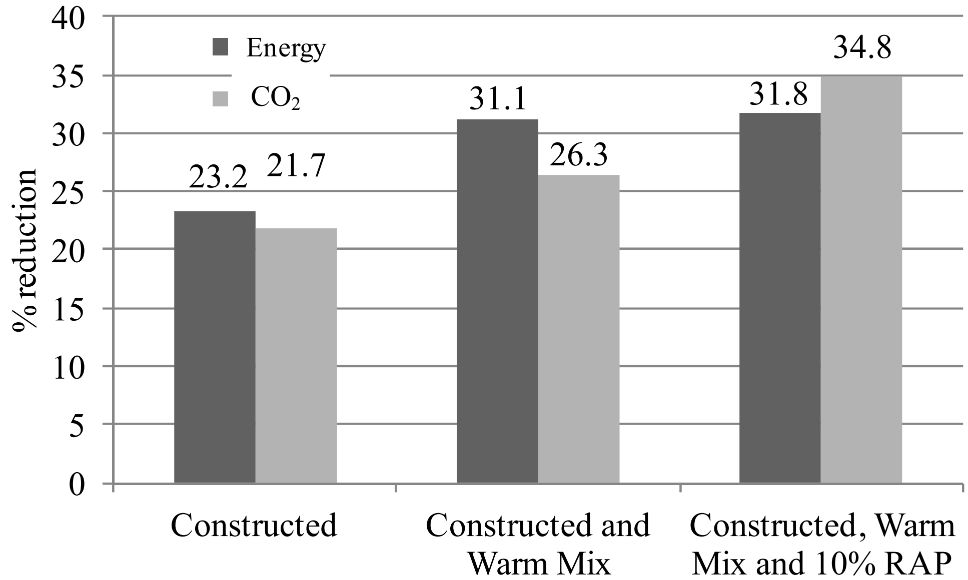

Figure 7.8 Kenderdine Road Energy Consumed and CO_2e Emission Percent Reductions from Traditional Structure

7.3.3 Carbon Credit Generation

For carbon credits to be generated under the Canadian Carbon Credit Offset System, the six eligibility criteria of scope, real, incremental, quantifiable, verifiable and unique must be achieved. For Kenderdine Road the scope of the project is within Canada and achieves real incremental reductions in GHG emissions. The quantities are also quantifiable and calculations of reductions can be verified by a third party. The final criterion is that the credits are unique and that they may only be accounted for once. As Kenderdine Road meets all of the criteria as detailed, it is assumed that carbon credits may be generated under the Canadian Carbon Credit Offset System.

One carbon credit is generated for every one tonne of CO_2e reduced. Based on the values generated from the model a reduction of 24.4 t CO_2e was achieved with the use of recycled materials compared to the traditional structure built with virgin materials. In 2010, the average value for a voluntary carbon credit was $6 US/t (Peters-Stanley et al. 2011). Expected revenues from the reduction of CO_2e for the constructed structure would be $146. With the use of warm mix and RAP a total of 39 t CO_2e reductions could be achieved for revenues of $234.

7.4 Saskatoon Network Treatment Analysis

Roadway agencies conduct regular maintenance on their roadway networks. The type of maintenance will be dependent on the distresses of each roadway that is being treated. In 2012 the treatments shown in Table 7.9 were proposed for the City of Saskatoon roadway network.

Table 7.9 City of Saskatoon 2012 Proposed Roadway Network Treatments

Treatment	Area (m^2)
Reconstruct	9,300
Resurfacing (Mill and Fill)	164,400
Leveling Course (Overlay)	7,200
Micro Surfacing	66,000
Ultra Thin Overlay	79,000
Chip Seal	18,750

As the specific design details of each treatment are not available, assumptions are required to determine the amount of energy that is consumed and the amount of GHG emissions that are emitted. The following is assumed:

- The reconstruct treatments are with virgin materials and a City of Saskatoon traditional structure of 450 mm GBC and 100 mm HMAC;
- The resurfacing will consist of 50 mm milling and placement of 100 mm HMAC;
- Leveling course will consist of a 50 mm overlay of HMAC;
- Micro surfacing will be the design as defined in the model;
- The ultra thin overlay will be 25 mm of HMAC; and
- Chip seal will be a single chip seal as defined in the model.

Based on these assumptions the values for the treatments for the amount of energy consumed and GHG emitted are summarized in Table 7.10.

Table 7.10 Energy Consumed and GHG Emissions for City of Saskatoon 2012 Roadway Treatments

Treatment	Energy Consumed (GJ)	GHG Emissions (CO_2e)
Reconstruct	3,751	298
Resurfacing (Mill and Fill)	29,365	1,959
Leveling Course (Overlay)	648	42
Micro Surfacing	432	46
Ultra Thin Overlay	3,613	235
Chip Seal	169	15
Total	37,978	2,595

Further review of this information determined that the cost of the energy consumed is approximately $1,232,000. At the end of 2012 the City of Saskatoon had an estimated population of 239,000 residents and 3,500 lane-km of roadways. Based on the overall roadway network numbers the amount of energy consumed for 2012 was 10.9 GJ/lane-km or 159 GJ/1,000 people and 0.74 t CO_2e/lane-km or 10.9 t CO_2e/1000 people.

7.5 Summary

The model that was developed in the research was applied to two roadways that have been constructed. These roadways included RR 232, a traditional remove and replace project, and Kenderdine Road, a project that utilized recycled materials. Based on the construction of one lane-km of roadway the energy consumed for these projects are 1,917 and 1,146 GJ and the GHG emissions generated are 150.3 t CO_2e and 92.6 t CO_2e respectively.

Further review of alternative structures including a traditional structure for construction alternative on Kenderdine Road was conducted in the third case study. It was found that with the use of recycled materials reductions of 23.2 percent for energy consumed and 21.7 percent for

CO_2e emissions were achieved. Further analysis to determine the impact of warm mix and the use of RAP in the asphalt concrete to the energy consumed and CO_2e emission values was conducted and it was found that an additional 8.6 and 13.1 percent reductions could be achieved for energy consumption and GHG emissions respectively. With the reduction of CO_2e emissions and the application of Canada's Carbon Credit Offset system it was determined that up to 39 carbon credits could have been earned on the Kenderdine Road Project.

The final case study reviewed the amount of energy that is consumed and the amount of GHGs that are emitted through the City of Saskatoon's 2012 roadway restoration and reconstruction program. The estimated amounts are 37,978 GJ for energy consumption and 2,595 t CO_2e for GHG emissions for treatment on 93 lane-km of roadway.

Chapter 8

SUMMARY AND CONCLUSIONS

Roadways are an essential part of a society as they are used to move people and goods. Jurisdictions have the task of maintaining this roadway infrastructure; however, this task is becoming more difficult as the roadway infrastructure is aging and deteriorating at a rate far greater than that of the funding that is available. As such innovative ways for maintenance and rehabilitation of roadways must be developed to allow more work to be completed with less funding.

In 1987, the Brundtland Commission brought the pressing need for sustainability to the world. Shortly after this in 1992, the United Nations Framework Convention on Climate Change was established to stop the increase in GHGs in the atmosphere. Through the Copenhagen Accord, Canada has committed to a 17 percent reduction in GHGs from 2005 levels by 2020.

The objective of this research was to develop and validate a probabilistic model that quantifies the amount of energy consumed and CO_2e generated for the construction, maintenance, rehabilitation and reconstruction of roadways was achieved. The model constructed was divided into three sub-models – 1) material production, 2) equipment used for placement and removals and 3) the transport of the materials.

The construction of the model began with the identification of the materials required for the various treatments reviewed. From there the fundamental parameters and equations that were required for each sub-model were determined forming the basis of each sub-model.

Once each sub-model was constructed based on the fundamental parameters and equations a base case study was developed using a lane-km (3,700 m^2) of roadway. The values for the energy consumed and CO_2e emissions generated for each maintenance, rehabilitation and reconstruction treatment were then determined. From the base case model further analysis was conducted to determine sensitive parameters and the percentage that each sub-model contributed to the overall values for the energy consumed and CO_2e emissions generated.

The order for increasing energy consumption and CO_2e emissions generated for maintenance treatments is fog seal, slurry seal, micro surfacing, single, double and triple chip seals and UTO. For rehabilitation and reconstruction treatments, the order of energy consumed is CIPR, mill and fill, FDR, remove and replace with recycled materials and finally remove and replace with virgin materials.

A review of the sensitive parameters was conducted for each treatment. For the maintenance treatments four sensitive parameters were identified including the efficiency of the equipment used, the rate at which an application is applied, the amount of asphalt cement product applied and the amount of aggregate applied. For the rehabilitation and reconstruction techniques the sensitive parameters were identified as the HMAC production value for the mill and fill and the full reconstructions with replacement of virgin and recycled materials. For the CIPR and FDR treatments the sensitive parameters were found to be the application rate of Portland cement.

When examining the percentage that each sub-model contributes to the overall energy consumed and CO_2e generated it can be found that the production of the materials is where the greatest amount of energy is consumed and CO_2e are generated. Looking further into the materials production it was observed that the production of the HMAC contributes the most to the energy consumed and CO_2e generated. For the initial construction, the asphaltic layers account for 39.2 and 31.8 percent of the overall energy consumed and CO_2e generated. From the production of materials the asphaltic layers account for 70.7 and 31.9 percent of the energy consumed and CO_2e generated respectively. Further analysis into the production of the HMAC showed that the energy consumed and the CO_2e emissions generated at the plant contribute the greatest to the values for the production of HMAC at 75.9 and 52.0 percent respectively.

The lane-km values generated from the developed model for each treatment were found to be within an acceptable range of current values that are published or generated in other models. For the energy consumption model the UTO, mill and fill, FDR and remove and replace with recycled materials treatments had percent differences greater than ten percent. The sensitive parameters that were identified can account for some of the differences within these values. The production of HMAC was identified as a sensitive parameter for the UTO and the mill and fill at 11.5 and 11.8 percent of the expected values respectively. The application rate of Portland cement was identified as a sensitive parameter for FDR at 119.6 percent of the expected value. When looking at the equipment sub-model values for the remove and replace with recycled materials the PaLATE value is less than the value generated from the model. The equipment values for the remove and replace with recycled materials from the developed model were 560.4 GJ and from PaLATE the equipment value is 9.8 GJ.

For the GHG emissions model only the remove and replace with recycled materials had a percent difference from the published or PaLATE modeled values and it was 38.1 percent. Similar to the energy consumption values the difference in these modeled values is within the equipment value generated. The equipment value generated from the developed model is 37.6 t CO_2e whereas from PaLATE it is 0.7 t CO_2e. As the calculations used within PaLATE are not available the reason for the difference is unable to be determined.

The cost of each treatment was reviewed based on the cost of diesel and the amount of energy consumed. The costs of energy for the maintenance treatments ranged from $174/lane-km for fog seal to $5,488/lane-km of the UTO. The rehabilitation and reconstruction treatments ranged in costs from $13,545/lane-km for the CIPR to $71,164/lane-km for remove and replace with virgin materials.

The costs of GHG emissions were also determined based on the amount of CO_2e generated and the value of one tonne of carbon on the voluntary carbon credit market. The costs of carbon for the maintenance treatments ranged from $3/lane-km for fog seal to $64/lane-km for the UTO. For the rehabilitation and reconstruction treatments the cost of carbon ranged from $224/lane-km for CIPR to $1,062/lane-km for remove and replace with virgin materials.

Further work that may be considered in the future is field level application of the model through the tracking of the amount of fuel that is used in each stage of material processing, equipment usage and transport. Based on the information that is provided through the generated sub-models, the processes that consume the greatest amount of energy and GHGs emitted can be identified. These processes such as the production of HMAC and Portland cement can then be the focus of future research to encourage the development of new technologies or methods to reduce the amount of energy that is consumed and GHGs that are emitted.

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Appendix A

MODEL CONSIDERATIONS AND INPUTS

Table A.1 Material Production Consideration by Layer

Layer	Alternative Types	Production Considerations
Asphalt Concrete Overlay (ACO) / Asphalt Concrete Base (ACB)	Traditional	Virgin Aggregate Asphalt Cement Asphalt Plant
	Recycled	Virgin Aggregate Recycled Aggregate Asphalt Cement Asphalt Plant
Base Course / Subbase	Traditional	Virgin Aggregate
	Recycled	Recycled Aggregate
Subgrade Preparation	Traditional	Not Applicable
	Cement Stabilized	Portland Cement
Maintenance	Fog Seal	Emulsion
	Slurry Seal	Asphalt Cement Virgin Aggregate
	Micro Surfacing	Asphalt Cement Virgin Aggregate Portland Cement
	Chip Seal	Asphalt Cement Virgin Aggregate
	Ultra Thin Overlay	Emulsion Refer to ACO Layer
Rehabilitation/ Reconstruction	In-situ Cold in-Place	Emulsion Portland Cement
	Full Depth Reclamation	Emulsion Portland Cement Lime
	Mill and Fill	Refer to ACO Layer

Table A.2 Equipment Consider in Model (USACE 2009)

Equipment	**Gross Horse Power**			**Horse Power**
	Low	**Most Likely**	**High**	**Factor**
Aggregate Spreader	137	152	167	0.70
Asphalt Paver	107	154	200	0.70
Chemical Spreader	137	152	167	0.70
Distributor	200	250	300	0.65
Dozer	60	95	130	0.70
FDR Reclaimer	360	480	600	0.70
Front End Loader	75	283	490	0.70
Micro Surfacing Machine	70	90	110	0.60
Miller	230	590	950	0.95
Motor Grader	125	185	245	0.60
Pavement Breaker	60	95	130	0.65
Pneumatic Roller	70	90	110	0.80
Road Mixer	60	95	130	0.65
Slurry Seal Paver	99	110	121	0.60
Stabilizer	320	360	400	0.70
Steel Wheel Roller	75	88	101	0.80
Tandem Roller	75	88	101	0.80
Vibratory Double Roller	107	126	145	0.90
Water Truck	175	253	330	0.65

Table A.3 Material Placement Rates (RS Means 2005)

Layer	Placement Rate			
	Low	**Average**	**High**	**Unit**
ACB	522	647	771	t/day
ACO	522	647	771	t/day
Asphalt Concrete Removal	250	351	577	m^2/day
Chip Seal	4181	6,271	8,361	m^2/day
Cold in-Place Recycling	2,341	2,926	3,512	m^2/day
CSS	803	862	920	m^2/day
Emulsion Application	878	2,508	4,181	m^2/day
Full Depth Reclamation	1,672	1,839	2,007	m^2/day
GBC	653	769	885	t/day
GBC Removal	250	275	300	m^3/day
Micro Surfacing	5,017	6,689	8,361	m^2/day
Milling	3,340	4,206	5,071	m^2/day
Slurry Seal	5,017	6,689	8,361	m^2/day
Subbase	490	1,130	1,769	t/day
Tack Coat Application	20,441	22,712	24,984	l/day

Table A.4 EFE Model Input Values

Layer	Equipment	Quantity	HP*HPF		
			Low	Average	High
ACO	Asphalt Paver	1	74.9	107.8	140.0
	Tandem Roller	1	60.0	70.4	80.8
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	190.9	250.2	308.8
ACB	Asphalt Paver	1	74.9	107.8	140.0
	Steel Wheel Roller	2	120.0	140.8	161.6
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	250.9	320.6	389.6
GBC	Motor Grader	1	75.0	111.0	147.0
	Front End Loader	1	52.5	198.1	343.0
	Dozer	1	42.0	66.5	91.0
	Vibratory Double Roller	1	96.3	113.4	130.5
	Water Truck	0.5	56.9	82.2	107.3
		Sum	322.7	571.2	818.8
Subbase	Motor Grader	1	75.0	111.0	147.0
	Dozer	1	42.0	66.5	91.0
	Vibratory Double Roller	1	96.3	113.4	130.5
	Water Truck	0.5	56.9	82.2	107.3
		Sum	270.2	373.1	475.8
CSS	Motor Grader	1	75.0	111.0	147.0
	Stabilizer	2	448.0	504.0	560.0
	Chemical Spreader	1	95.9	106.4	116.9
	Vibratory Double Roller	1	96.3	113.4	130.5
	Water Truck	0.5	56.9	82.2	107.3
		Sum	772.1	917.0	1,061.7

Table A.4 EFE Model Input Values (Continued)

Layer	Equipment	Quantity	HP*HPF		
			Low	Average	High
Emulsion Application	Distributor	1	130.0	162.5	195.0
		Sum	130.0	162.5	195.0
Slurry Seal	Slurry Seal Paver	1	59.4	66.0	72.6
	Steel Wheel Roller	1	60.0	70.4	80.8
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	175.4	208.4	241.4
Micro Surfacing	Micro Surfacing Machine	1	42.0	54.0	66.0
	Steel Wheel Roller	1	60.0	70.4	80.8
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	150.0	196.4	234.8
Chip Seal	Distributor	1	130.0	162.5	195.0
	Aggregate Spreader	1	95.9	106.4	116.9
	Steel Wheel Roller	1	60.0	70.4	80.8
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	341.9	411.3	480.7
Milling	Miller	1	218.5	560.5	902.5
	Front End Loader	1	52.5	198.1	343.0
		Sum	271.0	758.6	1,245.5
Asphalt Concrete Removal	Front End Loader	1	52.5	198.1	343.0
	Pavement Breaker	1	39.0	61.8	84.5
		Sum	91.5	259.9	427.5
GBC Removal	Front End Loader	1	52.5	198.1	343.0
		Sum	52.5	198.1	343.0

Table A.4 EFE Model Input Values (Continued)

Layer	**Equipment**	**Quantity**	**HP*HPF**		
			Low	**Average**	**High**
Cold in-Place Recycling	Road Mixer	1	39.0	61.8	84.5
	Steel Wheel Roller	1	60.0	70.4	80.8
	Pneumatic Roller	1	56.0	72.0	88.0
		Sum	155.0	204.2	253.3
Full Depth Reclamation	FDR Reclaimer	1	252.0	336.0	420.0
	Tandem Roller	1	60.0	70.4	80.8
	Motor Grader	1	75.0	111.0	147.0
	Front End Loader	0.5	26.3	99.0	171.5
	Water Truck	0.5	56.9	82.2	107.3
		Sum	470.2	698.6	926.6
Rotomixing and Loading	Road Mixer	1	39.0	61.8	84.5
	Front End Loader	0.5	26.3	99.1	171.5
		Sum	65.3	160.9	256.0

Appendix B

CALCULATIONS

Calculation for CO_2e – Aggregate Extraction and Processing

Global warming potentials are from Figure 2.4 and GHG emission rates for aggregate extraction and processing are from Table 3.3.

$$Aggregate\ Extraction\ and\ Processing\ CO_2e = Amount\ CO_2 \times 1\frac{CO_2e}{CO_2} + Amount\ CH_4 \times 21\frac{CO_2e}{CH_4} + Amount\ N_2O \times 310\frac{CO_2e}{N_2O}$$

$$Aggregate\ Extraction\ and\ Processing\ CO_2e = 7.965\ \frac{kg}{t}CO_2 \times 1\frac{CO_2e}{CO_2} + 0.007\frac{kg}{t}\ CH_4 \times 21\frac{CO_2e}{CH_4} + 0\ \frac{kg}{t}\ N_2O \times 310\frac{CO_2e}{N_2O} = 8.130\frac{kg}{t}CO_2e$$

Note: Calculating SF_6, HFCs and PFC emissions were outside of the scope of this work and are not included in this calculation.

Calculation of the Transport of Asphalt Cement to Refinery by Pipeline for Energy Consumed and GHG Emissions (Table 3.4 and 3.5)
References: (Davis 2011, Environment Canada 2008, Eurobitume 2011)

Variables

Assumed Distance, d	=	100km
Electricity Used, E	=	0.75 kWh/t/100km
Diesel Generator Efficiency, DGE	=	0.2 l/kWh
Energy Content of Diesel, EC	=	37.3 MJ/l
CO_2 of Diesel, CO_2 D	=	2.663 kg CO_2/l

$$Diesel\ = d \times E \times DGE = 200km \times \frac{\frac{0.75kWh}{t}}{100km} \times 0.2\frac{l}{kWh} = 0.3l$$

$$Transport\ Energy\ = Diesel \times EC = 0.3l \times 37.3\frac{MJ}{l} = 11.2\frac{MJ}{l}$$

$$Transport\ GHG\ = Diesel \times CO_2\ D = 0.3l \times 2.663\frac{kg\ CO_2}{l} = 0.799\frac{kg\ CO_2}{l}$$

Calculation of Energy Consumed for SBS Production and Transport (Table 3.6)

Table B.1 Variables for SBS Production and Transport Energy Calculation (Eurobitume 2011, Rodrigue et al 2009)

Fuel (/t PMB)	**SBS (Production & Transport)**	**Energy Content (MJ/kg)**
Natural Gas (kg)	29.8	47.2
Crude Oil (kg)	20.1	41.9
Coal (kg)	5.4	23.9

$$\frac{Energy\ SBS}{tPMB} = \sum\nolimits_{Material} Weight\ \times Energy\ Content$$

$$\frac{Energy\ SBS}{tPMB} = 29.8kg \times 47.2\frac{MJ}{kg} + 20.1kg \times 41.9\frac{MJ}{kg} + 5.4kg \times 23.9\frac{MJ}{kg} = \frac{2{,}377.8MJ}{t\ PMB}$$

Calculation for Energy Consumed for the Production of Emulsifier and HCl (Table 3.8)

Table B.2 Variables for Emulsifier and HCl Energy Consumption Calculation (Eurobitume 2011, Rodrigue et al 2009)

Fuel (/t residual asphalt)	**Emulsifier**	**HCl**	**Energy Content (MJ/kg)**
Natural Gas (kg)	0.22	0.34	47.2
Crude Oil (kg)	1.40	0.40	41.9
Coal (kg)	0.30	0.67	23.9

$$\frac{Energy\ Production\ Emulsifier\ or\ HCl}{t\ Residual\ Asphalt} = \sum\nolimits_{Material} Weight\ \times Energy\ Content$$

$$\frac{Energy\ Production\ Emulsifier}{t\ Residual\ asphalt} = 0.22kg \times 47.2\frac{MJ}{kg} + 1.4kg \times 41.9\frac{MJ}{kg} + 0.3kg \times 23.9\frac{MJ}{kg} = 76.214MJ$$

$$\frac{Energy\ Production\ HCl}{t\ Residual\ Aspahlt} = 0.34kg \times 47.2\frac{MJ}{kg} + 0.4kg \times 41.9\frac{MJ}{kg} + 0.67kg \times 23.9\frac{MJ}{kg} = 48.821MJ$$

Sample Calculation for Validation Base Case Using Average / Most Likely Values

Material Production

Calculations for Weight of Materials

$ACO\ W = ACO\ Volume * ACO\ Compacted\ Density$

$ACO\ W = 277.5m^3 * 2.42\ {}^{t}/_{m^3} = 671.55t$

Similarly for ACB, GBC and Subbase

$ACB\ W = 277.5m^3 * 2.42\ {}^{t}/_{m^3} = 671.55t$

$GBC\ W = 740m^3 * 2.36\ {}^{t}/_{m^3} = 1{,}746.4t$

$Subbase\ W = 1{,}110m^3 * 2.24\ {}^{t}/_{m^3} = 2{,}486.4t$

$Cement\ W = Cement\ Area * Application\ Rate$

$Cement\ W = 3{,}700m^2 * 10\ {}^{kg}/_{m^2} * {}^{t}/_{1{,}000kg} = 37t$

$Tack\ Coat\ Volume = 3{,}700m^2 * 0.45\ {}^{l}/_{m^2} = 1665l$

$Tack\ Coat\ W = 1665l * 1\ {}^{kg}/_{l} * {}^{t}/_{1000kg} = 1.665t$

Calculation for Weight of Total Coarse Aggregate

$Coarse\ Aggregate\ from\ ACO = ACO\ W * (1 - ACO\ Percent\ AC) * ACO\ Percent\ Cor$

$Coarse\ Aggregate\ from\ ACO = 671.55t * (1 - 0.06) * 0.40 = 252.5t$

Similarly for Coarse Aggregate from ACB and GBC,

$Coarse\ Aggregate\ from\ ACB = 671.55t * (1 - 0.05) * 0.50 = 319.0t$

$Coarse\ Aggregate\ from\ GBC = 1{,}746.4t * 0.45 = 785.9t$

$Total\ Coarse\ Aggregate = \sum Coarse\ Aggregate\ from\ ACO, ACB\ and\ GBC$

$Total\ Coarse\ Aggregate = 252.5t + 319.0t + 785.9t = 1{,}357.4t$

Calculation for Weight of Total Fine Aggregate

$Fine\ Aggregate\ from\ ACO = ACO\ W * (1 - ACO\ Percent\ AC) * (1 - ACO\ Percent\ Cor)$

$Fine\ Aggregate\ from\ ACO = 671.55t * (1 - 0.06) * (1 - 0.40) = 378.8t$

Similarly for Fine Aggregate from ACB and GBC

$Fine\ Aggregate\ from\ ACB = 671.55t * (1 - 0.05) * (1 - 0.50) = 319.0t$

$Fine\ Aggregate\ from\ GBC = 1{,}746.4t * (1 - 0.45) = 960.5t$

$Total\ Fine\ Aggregate = \sum Fine\ Aggregate\ from\ ACO, ACB, GBC\ and\ Subbase$

$Total\ Fine\ Aggregate = 378.8t + 319.0t + 960.5t = 1{,}658.3t$

Calculation for Energy Consumed for the Production of Aggregate

$$\begin{aligned} Agg\ Pro\ Energy &= (Coarse\ Agg\ W + Fine\ Agg\ W + Subbase\ W) * Extraction\ Energy \\ &+ Coarse\ Agg\ W * Coarse\ Aggregate\ Production + Fine\ Agg\ W \\ &* Fine\ Aggregate\ Production + Subbase\ W * Subbase\ Production \end{aligned}$$

$$\begin{aligned} Agg\ Pro\ Energy &= (1{,}357.3828t + 1{,}658.27t + 2{,}486.4t) * 0.027\, {}^{GJ}/_{t} + 1{,}357.4t \\ &* 0.0108\, {}^{GJ}/_{t} + 1{,}658.27t * 0.0324\, {}^{GJ}/_{t} + 2{,}486.4t * 0.0054\, {}^{GJ}/_{t} \\ &= 148.6GJ + 14.7GJ + 53.7GJ + 13.4GJ = 230.4GJ \end{aligned}$$

Calculation for Energy Consumed for the Production of Asphalt Cement

$AC\ W = ACO\ W * ACO\ Percent\ AC + ACB\ W * ACB\ Percent\ AC$

$AC\ W = 671.55t * 0.06 + 671.55t * 0.05 = 73.9t$

$AC\ Production\ Energy = AC\ W * Unit\ AC\ Production\ Energy$

$AC\ Production\ Energy = 73.9t * 1.7\, {}^{GJ}/_{t} = 122.0GJ$

Calculation for Energy Consumed for the Production of Asphalt Concrete

$ACon\ Productio\ Energy = (ACO\ W + ACB\ W) * \ Plant\ Energy$

$ACon\ Production\ Energy = (671.55t + 671.55t) * \ 0.41\, {}^{GJ}/_{t} = 545.3GJ$

Calculation for Energy Consumed for the Production of Portland Cement

$Cement\ Production\ Energy = Cement\ W * Cement\ Energy$

$$Cement\ Production\ Energy = 37t * 3.704\ {}^{GJ}/_{t} = 137.0\ GJ$$

Calculation for Energy Consumed for the Production of Tack Coat

$$Tack\ Coat\ Production\ Energy = Tack\ Coat\ W * Asphalt\ Emulstion\ Energy$$

$$Tack\ Coat\ Production\ Energy = 1.665t * 1.961\ {}^{GJ}/_{t} = 3.3\ GJ$$

Calculation for Total Energy from Material Production

$$Total\ Production\ Energy = \sum Energy\ from\ Production\ of\ Aggregate, AC, ACon\ and\ Cement$$

$$Total\ Production\ Energy = 230.4GJ + 122.0GJ + 545.3GJ + 137.0GJ + 3.3GJ = 1{,}037.9GJ$$

Calculation for CO_2e Consumed for the Production of Aggregate

$$Agg\ Pro\ CO_2e = (Coarse\ Agg\ W + Fine\ Agg\ W) * Unit\ Agg\ Pro\ CO_2e + Subbase\ W * Unit\ Subbase\ Pro\ CO_2e$$

$$Agg\ Pro\ CO_2e = (1{,}357.9t + 1{,}658.3t) * 8.130\ {}^{kg}/_{t}\ CO_2e + 2{,}486.4t * 0.903\ {}^{kg}/_{t}\ CO_2e$$

$$Agg\ Pro\ CO_2e = 26.8\ t\ CO_2e$$

Calculation for CO_2e Consumed for the Production of Asphalt Cement

$$AC\ Production\ CO_2e = AC\ W * Unit\ AC\ Production\ CO_2e$$

$$AC\ Production\ CO_2e = 73.9t * 158.258\ {}^{kg}/_{t}\ CO_2e = 11.7\ t\ CO_2e$$

Calculation for Energy Consumed for the Production of Asphalt Concrete

$$ACon\ Production\ CO_2e = (ACO\ W + ACB\ W) * Plant\ CO_2e$$

$$ACon\ Production\ CO_2e = (671.55t + 671.55t) * 18.578\ {}^{kg}/_{t}\ CO_2e = 25.0\ t\ CO_2e$$

Calculation for Energy Consumed for the Production of Portland Cement

$$Cement\ Production\ CO_2e = Cement\ W * Cement\ CO_2e$$

$$Cement\ Production\ CO_2e = 37t * 769.000\ {}^{kg}/_{t}\ CO_2e = 28.5\ t\ CO_2e$$

Calculation for CO_2e Consumed for the Production of Tack Coat

$$Asphalt\ Emulsion\ Production\ CO_2e$$
$$= Tack\ Coat\ W * Unit\ Asphalt\ Emulsion\ Production\ CO_2e$$

$$Asphalt\ Emulsion\ Production\ CO_2e = 1.665t * 188.200\ {}^{kg}/_{t}\ CO_2e = 0.31\ t\ CO_2e$$

Calculation Total CO_2e from Material Production

$$Total\ Production\ CO_2e$$
$$= \sum CO_2e\ from\ Production\ of\ Aggregate, AC, ACon\ and\ Cement$$

$$Total\ Production\ Energy$$
$$= 26.8\ t\ CO_2e + 11.7\ t\ CO_2e + 25.0\ t\ CO_2e + 28.5\ t\ CO_2e + 0.31\ t\ CO_2e$$
$$= 92.2\ t\ CO_2e$$

Equipment

Calculation for Fuel Consumption of Equipment

$$Fuel\ Consumption = \frac{Material\ Quantity}{Placement\ Rate} \times \sum_{Equipment} EFE$$

$$Fuel\ Consumption = \frac{Material\ Quantity}{Placement\ Rate} \times \frac{FC}{FW} \sum_{Equipment} HP \times HPF$$

$$Fuel\ Consumption\ ACO\ Placement = \frac{671.55t}{647\,{}^{t}/_{day}} \times \frac{0.17\,{}^{kg}/_{bhp-hr}}{0.84\,{}^{kg}/_{l}} \times 250.2hp \times \frac{8hr}{day}$$

$$= 420.5l$$

Similarly for ACB, GBC, Subbase and CSS.

$$Fuel\ Consumption\ ACB\ Placement = \frac{671.55t}{647\,{}^{t}/_{day}} \times \frac{0.17\,{}^{kg}/_{bhp-hr}}{0.84\,{}^{kg}/_{l}} 320.6hp \times \frac{8hr}{day}$$

$$= 538.8l$$

$$Fuel\ Consumption\ GBC\ Placement = \frac{1746.4t}{769\,{}^{t}/_{day}} \times \frac{0.17\,{}^{kg}/_{bhp-hr}}{0.84\,{}^{kg}/_{l}} \times 571.2hp \times \frac{8hr}{day}$$

$$= 2{,}100.2l$$

$$Fuel\ Consumption\ Subbase\ Placement$$

$$= \frac{2{,}486.4t}{1130\,{}^{t}/_{day}} \times \frac{0.17\,{}^{kg}/_{bhp-hr}}{0.84\,{}^{kg}/_{l}} \times 373.1hp \times \frac{8hr}{day} = 1{,}329.2l$$

$$Fuel\ Consumption\ CSS\ Placement = \frac{3{,}700m^2}{862\,{}^{m^2}/_{day}} \times \frac{0.17\,{}^{kg}/_{bhp-hr}}{0.84\,{}^{kg}/_{l}} \times 917.0hp \times \frac{8hr}{day}$$

$$= 6{,}372.9l$$

$Fuel\ Consumption\ Tack\ Coat\ Placement$

$$= \frac{1{,}665l}{22{,}712\ ^{l}/_{day}} \times \frac{0.17\ ^{kg}/_{bhp-hr}}{0.84\ ^{kg}/_{l}} \times 162.5hp \times \frac{8hr}{day} = 19.3l$$

Calculation Total Energy from Material Placement

$Total\ Placement\ Energy$

$= \ Energy\ of\ Fuel$

$\times \sum Fuel\ Consumption\ from\ Placement\ of ACO, ACB, GBC, Subbase, CSS\ and\ Tack\ Coat$

$Total\ Placement\ Energy$

$$= \ 0.0373\ ^{GJ}/_{l} \times (420.5l + 538.8l + 2{,}100.3l + 1{,}329.2l + 6{,}372.9l + 19.3l)$$

$$= 402.1GJ$$

Calculation Total CO_2e from Material Placement

$Total\ Placement\ CO_2e$

$= \ CO_2e\ of\ Fuel\ for\ Equipment$

$\times \sum Fuel\ Consumption\ from\ Placement\ of ACO, ACB, GBC, Subbase, CSS\ and\ Tack\ Coat$

$= 2.711\ ^{kg\ CO_2e}/_{l} * (420.5l + 538.8l + 2{,}100.3l + 1{,}329.2l + 6{,}372.9l + 19.3l)$

$= 29.2\ t\ CO_2e$

<u>Transport</u>

Haul AC Cement from Refinery to Plant

$$Total\ Fuel\ AC = \frac{AC\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Total\ Fuel\ AC = \frac{73.87t}{40t} \times 250km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ AC = 182.4l$$

Haul Aggregate to Asphalt Plant

$$Total\ Fuel\ Agg\ to\ Plant = \frac{Agg\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Agg\ W = ACO\ W + ACB\ W - AC\ W$$

$$Total\ Fuel\ Agg\ to\ Plant = \frac{671.55t + 671.55t - 73.87t}{25t} \times 100km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Agg\ to\ Plant = 2{,}005.4l$$

Haul Aggregate to Stockpile

$$Total\ Fuel\ Agg\ to\ Stockpile = \frac{Agg\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Agg\ W = GBC\ W + Subbase\ W$$

$$Total\ Fuel\ Agg\ to\ Stockpile = \frac{1786.4t + 2486.4t}{40t} \times 100km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Agg\ to\ Stockpile = 4{,}219.4l$$

Haul Aggregate to Site

$$Total\ Fuel\ Agg\ to\ Site = \frac{Agg\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Agg\ W = GBC\ W + Subbase\ W$$

$$Total\ Fuel\ Agg\ to\ Site = \frac{1786.4t + 2486.4t}{25t} \times 50km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Agg\ to\ Site = 3{,}375.5l$$

Haul Asphalt to Site

$$Total\ Fuel\ Asphalt\ to\ Site = \frac{ACO\ W + ACB\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Total\ Fuel\ Asphalt\ to\ Site = \frac{671.55t + 671.55t}{10t} \times 50km \times 21.6\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Asphalt\ to\ Site = 1{,}450.5l$$

Haul Cement to Supplier

$$Total\ Fuel\ Cement\ to\ Supplier$$
$$= \frac{Cement\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Total\ Fuel\ Cement\ to\ Supplier = \frac{37t}{25t} \times 500km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Asphalt\ to\ Site = 292.3l$$

Haul Cement to Site

$$Total\ Fuel\ Cement\ to\ Site = \frac{Cement\ W}{Truck\ Capacity} \times km\ travelled \times Truck\ Fuel\ Efficiency$$

$$Total\ Fuel\ Cement\ to\ Supplier = \frac{37t}{25t} \times 50km \times 39.5\ {}^{l}/_{100km}$$

$$Total\ Fuel\ Asphalt\ to\ Site = 29.2l$$

Calculation Total Energy from Material Transport

$$Total\ Placement\ Energy$$
$$= Energy\ of\ Fuel$$
$$\times \sum Fuel\ Consumption\ from\ Transport\ of\ ACO, ACB, GBC, Subbase\ and\ Cement$$

$$Total\ Transport\ Energy$$
$$= 0.0373\ {}^{GJ}/_{l}$$
$$\times (182.4l + 2{,}005.4l + 4{,}219.4l + 3{,}375.5l + 1{,}450.5l + 292.3l + 29.2l)$$
$$= 431.0GJ$$

Calculation Total CO_2e from Material Transport

$$Total\ Transport\ CO_2e$$
$$=\ CO_2e\ of\ Fuel\ for\ Equipment$$
$$\times \sum Fuel\ Consumption\ from\ Transport\ of\ ACO, ACB, GBC, Subbase\ and\ Cement$$
$$= 2.711\ {}^{kg\ CO_2e}/_{l}$$
$$\times (182.4l + 2{,}005.4l + 4{,}219.4l + 3{,}375.5l + 1{,}450.5l + 292.3l + 29.2l) = 31.3\ t\ CO_2e$$

Total Energy Consumed

$$Total\ Energy\ Consumed = \sum Production, Equipment\ and\ Transportation\ Energy$$
$$Total\ Energy\ Consumed = 1{,}037.9\ GJ + 402.1\ GJ + 431.0GJ$$
$$Energy\ Consumed = 1{,}871.0GJ$$

Total CO_2e Generated

$$Total\ CO_2e\ Generated = \sum Production, Equipment\ and\ Transportation\ Energy$$
$$Total\ CO_2e\ Generated = 92.2t\ CO_2e\ + 29.2t\ CO_2e\ + 31.3t\ CO_2e$$
$$Energy\ Consumed = 152.7t\ CO_2e$$

Sample Calculation for Sensitive Parameters – Fog Seal, Seal Placement EFE

Variables
Low Value = 5.197 GJ
High Value = 13.338 GJ
Expected Value = 9.278 GJ

$$\%\ of\ Expected\ Value = \frac{High\ Value - Low\ Value}{Expected\ Value} \times 100$$
$$\%\ of\ Expected\ Value = \frac{13.338\ GJ - 5.197\ GJ}{9.278\ GJ} \times 100$$
$$\%\ of\ Expected\ Value = 87.7\%$$

Sample Calculation for Percent Difference – Initial Construction Energy Consumption

Variables
Model Value (High) = 1964.0 GJ
Published Value (Low) = 2000.0 GJ

$$\%\ Difference = \frac{1964.0\ GJ - 2000.0\ GJ}{2000.0\ GJ} \times 100$$

$$\%\ Difference = -1.8\ \%$$

Appendix C

MODEL DIAGRAMS

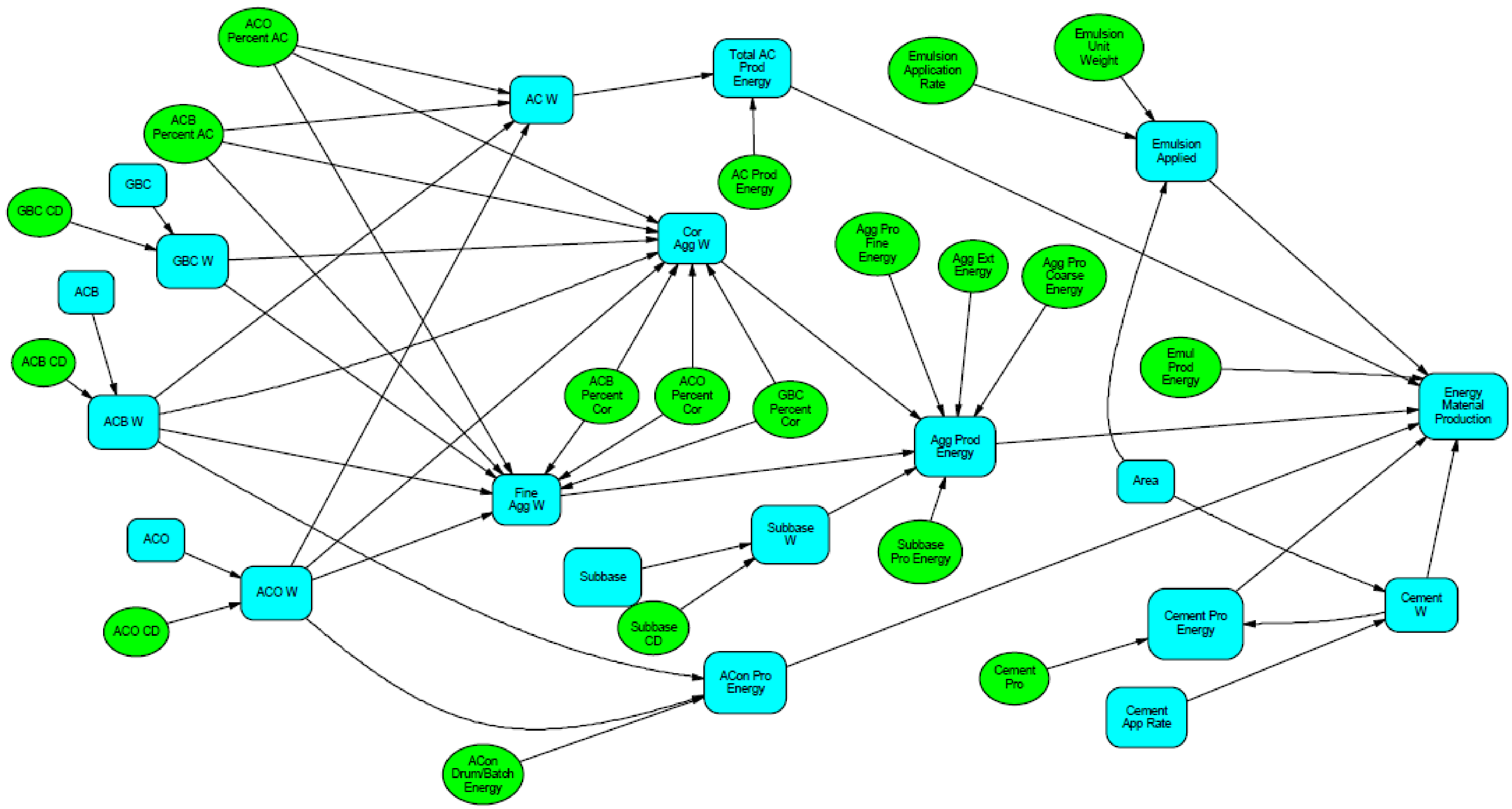

Figure C.1 Material Production Sub-model

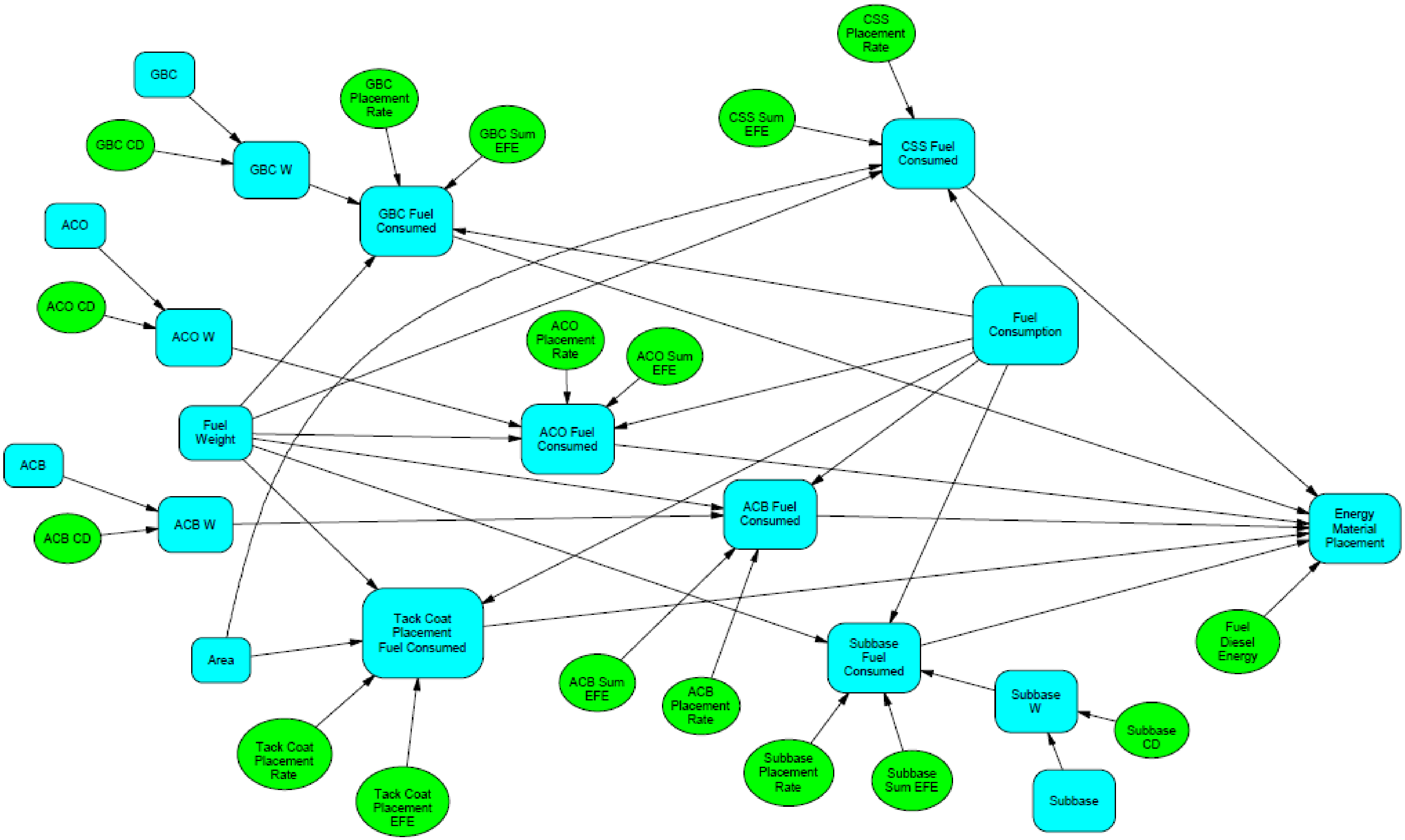

Figure C.2 Material Placement Sub-model

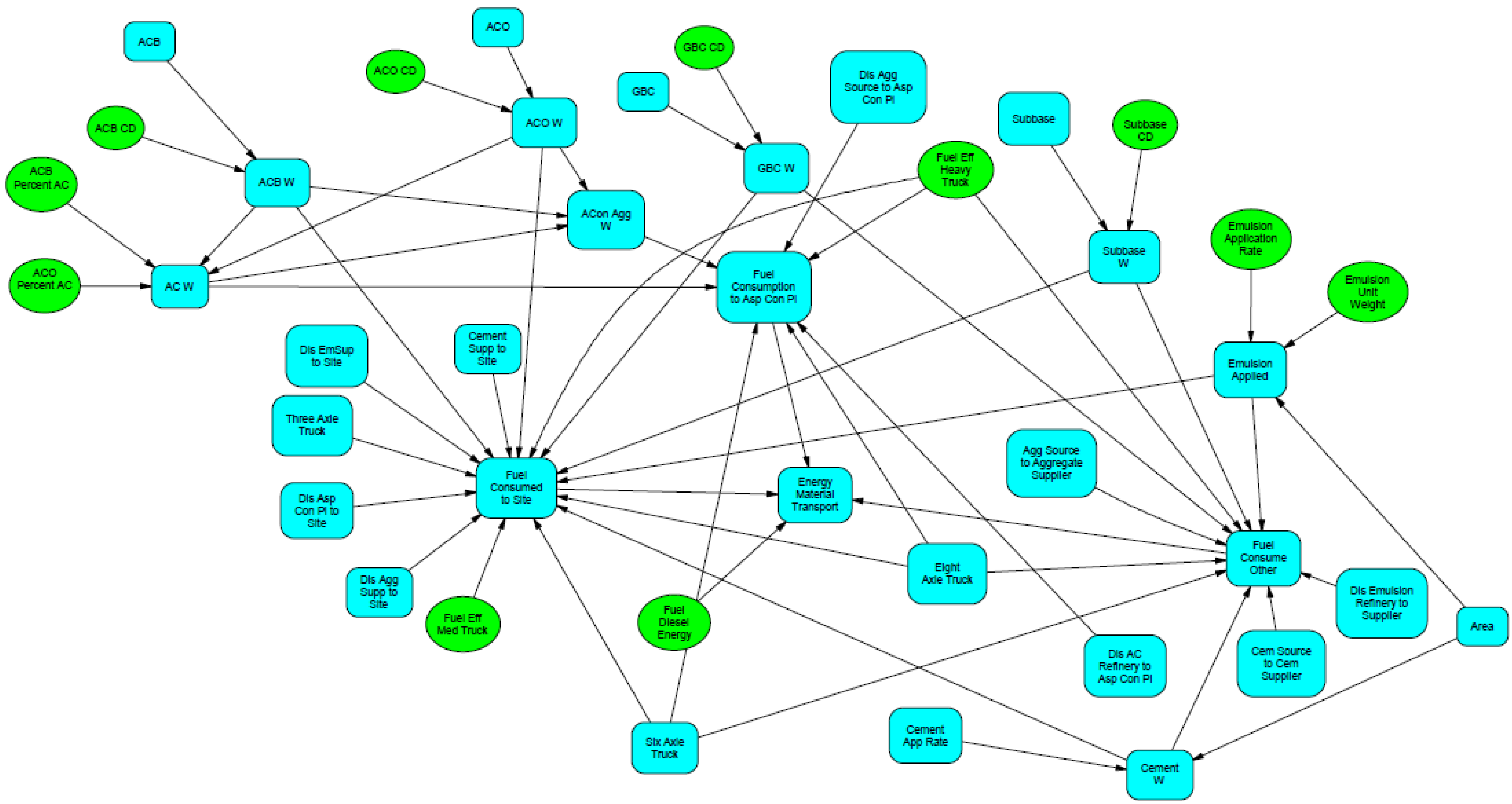

Figure C.3 Material Transport Sub-model