Quantifying Pavement Sustainability For Ontario Highways

by

Peter Cheuk Pan Chan

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2010

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

With the emerging trend of sustainability, sustainable infrastructure is highly regarded by the general public. Sustainable pavement is also a concept that has driven many research motivations today. These motivations are in the form of sustainable paving material utilization, innovative design and construction methods. One of the goals behind these research motivations is maximizing pavement performance using the given funding and resources available.

Despite the significant research attention for innovation and actual sustainable pavement practices already commencing, there is no readily available system or score card to quantify sustainable pavement engineering practice. In 2008, the Ministry of Transportation Ontario (MTO) initiated a research project with the University of Waterloo Centre for Pavement and Transportation Technology (UW CPATT) regarding quantifying pavement sustainability. The ultimate goal of the research is to develop a framework for formally incorporating sustainability into pavement engineering for MTO.

In order to achieve this goal, the research reviewed the state-of-practice sustainable pavement material and technologies. A sustainable pavement workshop is hosted by CPATT and MTO that invited key stakeholders in Ontario pavement industry for a discussion of sustainable pavement. The environment and economic benefits of different technologies are explored to understand their sustainable elements. Indicators to measure pavement sustainability are proposed based on the recent MTO GreenPave evaluation program and life cycle cost of pavements. Lastly, network level pavement management and ideas to improve sustainability at network level is examined.

Acknowledgements

I would like to acknowledge the follow individuals for their assistance in completing this research study.

- Ms. Susanne Chan, P.Eng, Pavement Design Engineer, MTO
- Ms. Becca Lane, P.Eng, Head of Pavements and Foundations Section, MTO
- Mr. Steve Senior, P.Eng, Head of Soil and Aggregates Section, MTO
- Dr. Chris Raymond, P.Eng, Head of Bituminous Section, MTO
- Ms. Mireya Hidelgo, Engineer-In-Training, MTO
- Ms. Tara Thornton, Engineer-In-Training, MTO
- Ms. Fiona Leung, Engineer-In-Training, MTO
- Mr. Sam Cui, Pavement Management Analyst, MTO
- Mr. Keith Davidson, Technical Advisor, McAsphalt Industries Limited
- Mr. Rico Fung, P.Eng, LEED® AP, Director, Markets & Technical Affairs - Ontario Region, Cement Association of Canada
- Ms. Ashley Monteiro, Undergraduate Student, University of Waterloo
- Ms. Laura Bland, Administrative Officer, University of Toronto
- Dr. Jeff West, P.Eng, Assistant Professor, University of Waterloo
- Dr. Jun Yang, Professor, Southeast University, China

I would like thank my supervisor, Dr. Susan Tighe, from the Department of Civil and Environmental Engineering at University of Waterloo for her guidance, encouragement, and support, over the course of my research and completion of my thesis.

I would like to thank my family and Cathy Cheng for supporting me throughout the years of university career with their genuine love and care. A big thank to Tony Horton for introducing me to the importance of taking care of good health and fitness, which provide me strength, energy, and the ability tackle challenges with a positive attitude. Lastly, I would also like to thank my friend, Mimi Ng, for cooking delicious meals and ensuring I received proper nutrition to refuel my body during my research career living away from home.

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

Roadway infrastructure is critical to quality of life and prosperity of society. The pavement structure of the road ages and deteriorates over time. Proper construction and maintenance techniques are essential to ensure roads are providing the required performance for road users. In a society today where resources and funding are limited, transportation agencies have begun seeking ways to utilize the resources to maximize benefits as part of daily operations. In general, sustainability is about maintaining the current infrastructure without compromising the resources of the future generation. The basis of sustainability commonly consists of three elements: economy, society, and environment. Figure 1 shows the components of sustainable transportation, which considers a board spectrum of engineering activities.

Figure 1: Components of Sustainable Transportation

Sustainable pavement is a subset of sustainable transportation with the main emphasis in pavement design and management, material use and recycling. In order to achieve sustainable pavement, it is necessary to integrate economic, social, and environmental considerations into practice. The challenge of this project lies in how to move sustainable practices forward in a progressive and balanced manner.

With the objective of sustainability promoting to the general public, the need to quantify sustainable practices is highly desirable. The initiatives by LEED®, Greenroads, and GreenLITES certification programs are leading examples of interest in sustainable practices. The Ministry of Transportation (MTO) owns over 10,000 kilometres of highways in the province of Ontario and is currently working on a research project called "Quantifying Pavement Sustainability" under its Highway Infrastructure Innovation Funding Program (HIIFP). This project is a joint effort by the University of Waterloo, Centre of Pavement and Transportation Technology (UW CPATT) and MTO. The project began in September 2008 and concluded in April 2010. The ten chapters of this thesis cover the research findings from this project. Through the different research activities in this project, the ultimate goal is to develop a sustainable pavement framework for pavement engineering practice in Ontario. Chapter 2 introduces the project tasks, and brief overview of research content and layout of the thesis.

Chapter 2
Research Plan

The project, Quantifying Pavement Sustainability, consists of seven primary Tasks proposed in 2008 as shown in Figure 2. Although the content of this thesis are outcomes of the individual project tasks from Figure 2, the layout and order of the thesis does not follow Figure 2 completely. Throughout this thesis, references are made to individual project tasks because each project task consists of research activities completed. This chapter provides an overview of these project tasks and their corresponding chapter in this thesis.

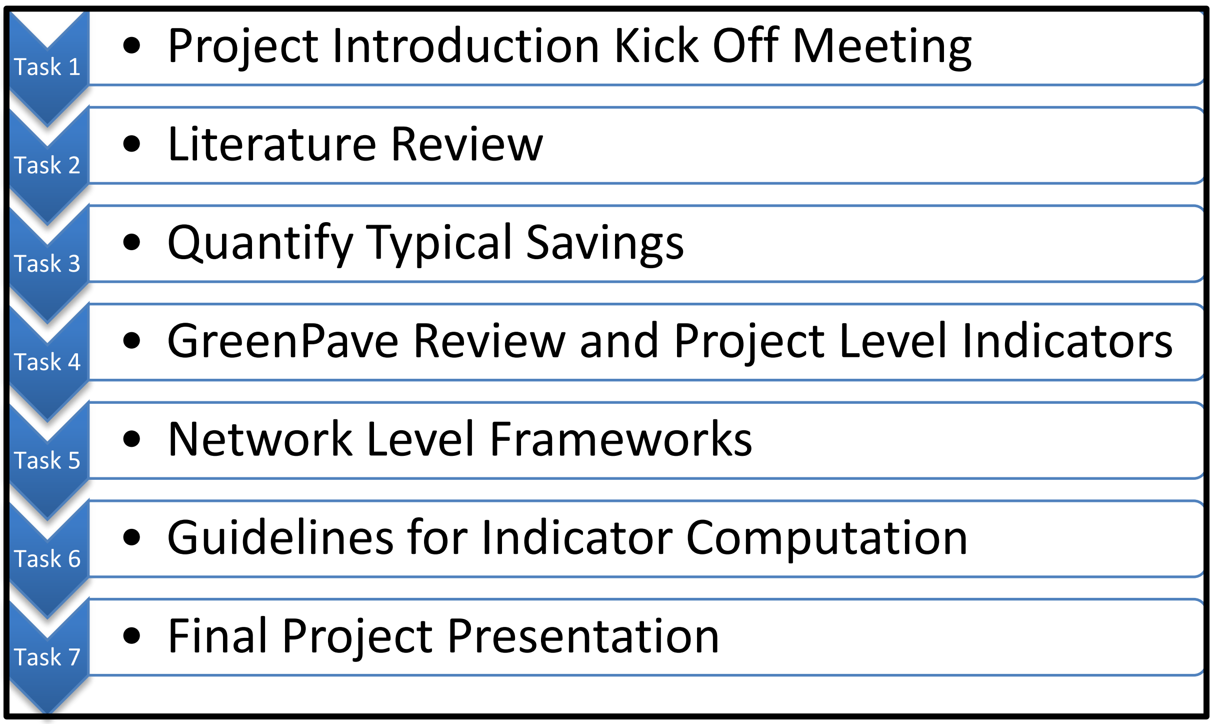


Figure 2: Summary of Project Tasks

Figure 2 shows the order of primary research activities chronologically from 2008 to 2010. Task 1 is the kick-off meeting between CPATT and MTO for this project, which was held on September 5, 2008. Items discussed at this meeting included topics for the literature review, sustainable materials and technologies, a sustainable pavement workshop, and quantifying pavement sustainability. The meeting introduced the project team from CPATT and MTO.

Figure 3 shows the organization team of this project and key members' role over the entire duration of the project.

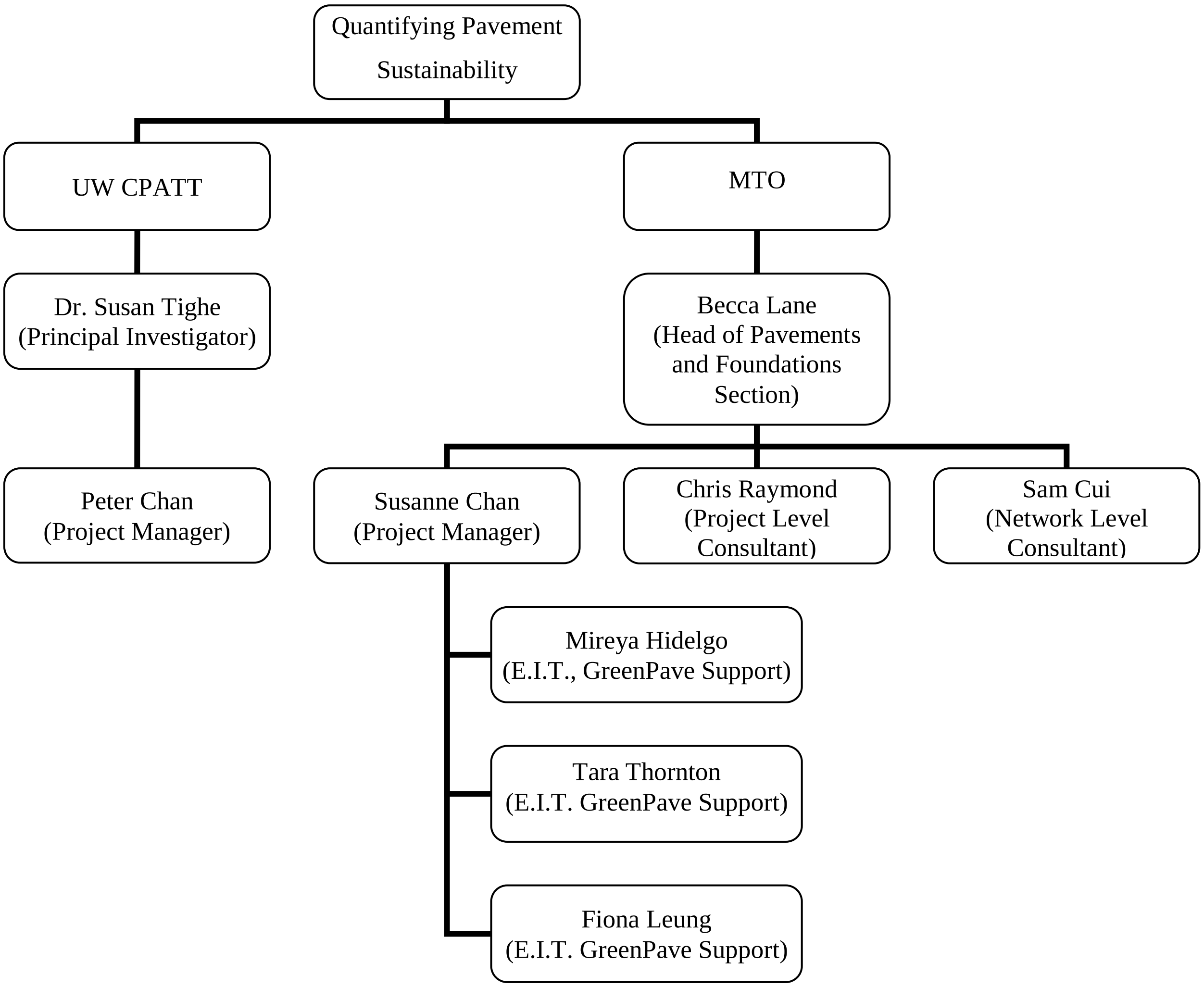


Figure 3: Project Organization Chart

A project schedule is developed in the form of a Gantt chart shown in Appendix B Figure 25. The Gantt chart demonstrates the key research activities that have been completed over the duration of the project.

The first research activity is the literature review, as represented by project Task 2, Chapter 3 of this thesis. The literature review is categorized into three main themes: pavement materials, design or construction methods, and sustainability initiatives. The goal of the literature review is to understand different pavement technologies and their sustainable elements. The CPATT/MTO sustainable pavement workshop is a sub task for project task 2. The workshop is a gathering of pavement professionals in Ontario for the discussion on sustainable pavement. The outcome and details of the workshop are covered in Chapter 4 of the thesis.

The literature review provides a qualitative means to understand different pavement technologies that act as the basis for Task 3. Task 3 of the project involves the numeric quantification of economic and environmental savings between different construction and rehabilitation technologies. All of the quantification activities are discussed in Chapter 5 of the thesis. The environmental savings of technologies are quantified using the PaLATE software. The economic savings of the technologies are quantified through life cycle cost analysis and material savings. These environmental and economic savings are examined at individual project basis and life cycle perspective.

The next phase of the research involves developing a green pavement rating system, unofficially named GreenPave, and performing trial evaluations for Task 4 of the project. Based on the results from Task 2 and 3, a green pavement rating system was developed by MTO to evaluate environmental sustainability of different pavement projects. The overview of GreenPave is discussed in Chapter 5. Based on the trial GreenPave evaluation, indicators are also developed to express pavement sustainability through simple calculations. Two indicators are developed in this project for project level applications. Chapter 6 discusses all the details for the basis and derivation of the indicators.

Task 1 to Task 4 of this project focuses on project level pavement engineering. In general, project level pavement engineering considers the design, construction, maintenance, and rehabilitation aspects of pavement. The other aspect of pavement engineering focuses on network level application. Task 5 of the project considers the network level pavement engineering in MTO. Network level pavement engineering focuses on strategically planning of rehabilitation schedules, budget allocation, and pavement performance data analysis. For this research, the network level engineering component revolves MTO pavement management system, PMS2. Chapter 7 discusses the state-of-practice of network level pavement engineering at MTO. Ideas and indicators are proposed to enhance the sustainability of the practice.

The other research activity in Task 5 is development of sustainable pavement framework for practice. Chapter 8 of the thesis presents the two frameworks developed in this project: for project level application, and for network level application. The framework demonstrates how to integrate sustainability in pavement engineering practice. Chapter 8 also explains the importance of network and project level cooperation to achieve sustainable pavement.

Task 6 of the project involves demonstrating numerical examples of the indicators developed in the project. The numerical examples to calculate the indicators are explained in Chapter 6 and Chapter 7 of the thesis. Task 7 of the project is the final MTO project presentation to MTO. Task 7 is not covered explicitly as a dedicated chapter in this thesis.

Chapter 3
Literature Review

As the concept of sustainability gains more recognition and momentum, the transportation industry has responded accordingly. Currently, there are a vast number of innovative materials, designs, construction techniques, maintenance practices, and green initiatives, which advocate environmentally friendly pavement. Presently in Canada, transportation agencies believe there is a strong need to classify these innovative contributions. In the development of such a classification system, a literature review was conducted to evaluate the state of the art practices related to environmentally friendly pavement.

Task 2 can be separated into three main areas: review for pavement engineering, review for sustainability initiatives, and a workshop hosted by CPATT and MTO that included pavement industry stakeholders regarding sustainable pavement. For pavement engineering, the main emphasis will be targeted toward the sustainability in materials, design, construction, and maintenance techniques applicable to Ontario highways maintained by MTO. For green initiatives, the main emphasis will be targeted to rating systems that are currently available for different infrastructure projects. The CPATT/MTO sustainable pavement workshop involved a gathering of several pavement professionals in Ontario for the discussion of sustainable pavement. The main references for this literature review included study results from CPATT, MTO, online research articles, Ontario Provincial Standard Specifications (OPSS), Pavement Design Guide by Transportation Association of Canada (TAC), etc. Table 1 shows the items reviewed by CPATT in this chapter.

Table 1: Literature Review Items

Materials	Construction Techniques	Preservation Techniques	Green Initiatives
Reclaimed Asphalt Pavement (RAP)	Perpetual Pavement	Cold In-place Recycling (CIR)	Greenroads 1.0
Recycled Concrete Aggregates (RCA)	Porous Asphalt	Cold In-place Recycling with Expanded Asphalt Mix (CIREAM)	LEED®
Glass	Pervious Concrete	Full Depth Reclamation (FDR)	GreenLITES
Ceramic Whiteware	Permeable Interlocking Concrete	Microsurfacing	Green Guide for Road Task Force
Shingles	Warm Asphalt Mix	Diamond Grinding	
Crumb Rubber	Quiet Pavements – Asphalt	Precast Concrete Panels	
Interlocking Concrete	Two Lifts Concrete Construction	Rubblization	
Supplementary Cement Materials (SCM)	Quiet Pavements - Concrete	Concrete Overlays	

3.1 Materials

Recycling, reusing, and reclaiming of existing materials are crucial to advance sustainable development. Construction materials can be expensive and some resources have limited supply, so it is important to make good utilization of available materials. The incorporation of innovative materials can also potentially enhance pavement performance, and reduce the demand for virgin materials. Therefore, a first step to quantify pavement sustainability involves evaluating how materials are currently used and how their benefit can be maximized.

3.1.1 Reclaimed Asphalt Pavement

Asphalt pavement is a highly recycled material in road construction applications. Reclaimed Asphalt Pavement (RAP) is an efficient way to reduce the demand for virgin materials required to produce asphalt. RAP can be used for granular or hot mix pavement depending on the agency's specification and contract requirements. RAP aggregates are often coated, which acts as a binding agent, therefore, decreasing the amount of binder required [Soderlund, 2007]. Proper processing of RAP can result in equivalent performance to virgin aggregate [Infraguide, 2005]. Careful blending and crushing of RAP is required to achieve consistent gradation of the material [Infraguide, 2005]. Another reason that RAP is commonly recycled is that it can be stockpiled in a central plant for future need. Ultimately, the reclamation of old asphalt is an effective way to reduce construction waste transported to landfills.

The use of RAP in Ontario highways is governed by the OPSS 1150. It suggests the maximum amount of RAP in pavement is 40% in the binder course [OPSS 1150, 2008]. In Ontario, contractors are usually reluctant to employ more than 20% RAP, because a different asphalt cement gradation is required to utilize more than 20% RAP in pavement. Hence, the change in asphalt cement's gradation may not be economically justified from the contractors' perspective.

3.1.2 Recycled Concrete Aggregate

Recycled concrete in pavement applications is most commonly in the form of Recycled Concrete Aggregate (RCA). The application consists of reusing concrete fragments from demolished sidewalks, curbs and gutters in place of virgin aggregate in paving applications. Concrete from other structural applications such as bridges, buildings or pavement are often not acceptable for pavement applications because of the high variability in concrete material; whereas the aforementioned are built to specific OPSS that dictate strength, aggregate gradation, air void properties, etc. Many successful case studies report RCA is an excellent material for road fill and as granular materials applications [Mehta, 2001], [OPSS 1010, 2004]. The most current research suggested that RCA is a good substitute for coarse aggregate, with little detail regarding use of fine aggregates in recycled concrete.

Most research studies with RCA focus on preparation and usage of various concrete mix design with different RCA content in the concrete mixes. Research studies have shown strength and workability of concrete reduces noticeably with increase RCA content [Bairagi, 1993], [Smith, 2008]. Users of RCA shall note that RCA is a highly absorptive and porous material. For concrete applications, it is suggested that pre-wetting of RCA prior to mixing with portland cement to enhance the workability of the concrete [Infraguide, 2005], [Bairagi, 1993]. A study conducted by University of Waterloo has placed four concrete sections at the UW CPATT test track with 0%, 15%, 30%, and 50% RCA aggregates. The UW CPATT test track is a landfill area in Waterloo, Ontario, that CPATT builds pavement test sections and conduct field tests. The test track contains heavy truck traffic leading to the landfill, thus provide the heavy loading to the pavement built. The experiment also demonstrated that after two years there are no differences in pavement condition index (PCI) performance of the sections with RCA and without RCA [Smith, 2008].

3.1.3 Glass

Currently, recycled glass is a new form of aggregate being researched. A study by Huang et al., found that it can be recycled continuously, without losing its original properties; it is an ideal aggregate for pavement [Huang et al., 2007]. Once crushed, glass has similar strength to rock [Arnold et al., 2008]. Glass can be effective in base course as an aggregate substitute. Various transportation agencies have attempted to incorporate glass in pavement. A study by New Zealand Transport Agency was completed using repeated load triaxial test to determine the effect of rut depth by adding crushed glasses into aggregate in New Zealand [Arnold et al., 2008]. The study shows that crushed glass up to 30% by mass in base course aggregate has no impact on rut depth of the pavement [Arnold et al., 2008]. However, mix results of success and failure in using glass in asphalt seem to be reported.

However, recycled glass has not been a common recycled material to date. The most prominent reason is due to the availability of crushed glass for a project. Glass has weak adhesion with asphalt cement [Senior et al., 1994]. The weak adhesion causes weak structural pavement performance and ravelling on the pavement surface. Another reason is that the crushed glass often contains sugar. The sugar will react with the portland cement in concrete [Senior et al., 1994]. The addition of glass as aggregate in concrete also poses alkali silica reaction (ASR) of the concrete [Liang et al., 2007]. Chemical addictives must be added to mitigate the ASR [Liang et al., 2007]. According to OPSS 1010, glass may be use as granular A, M, or S at 15% maximum of total aggregate [OPSS 1010, 2004].

3.1.4 Ceramic Whiteware

Ceramic whiteware typically includes crushed toilets from the local area. Based on lab testing by MTO, these ceramic whiteware products are high strength aggregate for granular [Senior et al., 1994]. However, once the toilet is crushed, the fragments tend to have a flat elongated shape. The flat and elongated aggregate shape is not desirable for compaction. In addition, ceramic whiteware is not commonly available and the effort of cleaning the ceramic whiteware may not be economically feasible.

3.1.5 Crumb Rubber

Due to the large availability of scrap tires, there has been research into the usage of old rubber tire fragments as replacement aggregates in pavement. The benefit of using rubber tire in pavement is that it has good tensile strength and saves on waste disposal cost.

A study by Mahboub found that scrap tire chips could be used as a successful interlayer membrane within asphalt pavements. The study estimated that approximately 1760 tires could be used per lane mile of pavement [Mahboub, 1996]. Mahboub's study shows that rubber is a viable material above subgrade. Crumb rubber can be incorporated into asphalt pavement primarily by one of the two processes: wet, or dry. The wet method consists of rubber reacting with hot asphalt cement while the dry process occurs when rubber is added to asphalt hot mix as an aggregate before binder is added [Maupin, 1996]. The dry method involves adding crumb rubber as aggregate as part of the asphalt mixing, and the process does not involve heating up the rubber to high temperatures as compared to the wet method [Maupin, 1996]. Maupin's study concludes crumb rubber is an acceptable material to use for asphalt pavement given the material is economically feasible for the project [Maupin, 1996]. A consensus among researchers is that the addition of recycled tires into asphalt mixes decreases both temperature susceptibility as well as rutting and fatigue probability [Zanzotto, 1996].

However, the lack of popularity with rubber tire in pavement is the fact that rubber bonds poorly with the asphalt cement [Senior et al., 1994]. The poor bonding of rubber causes severe pop out and ravelling on the pavement [Senior et al., 1994]. Further research is required to better utilize this material. MTO has no plan to incorporate rubber in asphalt or granular [Senior et al., 1994]. The availability and cost of processing crumb rubber are two major obstacles that limit its utilization in pavement applications.

3.1.6 Recycled Asphalt Shingles

Many research efforts have been devoted into incorporating shingles into asphalt pavement. Shingles are commonly used for roofing or insulation applications. Shingles typically consist of asphalt cement, fibres, hard rock granules, and fillers [Tighe, 2008a]. Shingles for pavement application can be divided into two primary types: Recycled Asphalt Shingles (RAS) or manufactured asphalt shingles tabs. RAS are shingles removed from old roofing applications. RAS has higher asphalt content because hard granules are worn out due to weather conditions and have been aged generally twelve to twenty years. Manufactured asphalt shingle tabs are shingles derived from shingle manufacturing process and provide better material consistency because the source of the shingle is uniform.

CPATT, the Material Manufacturing Ontario, and Miller Paving Limited performed a research study about the performance of RAS [Tighe, 2008a]. The mix designs in the study use different combinations of virgin aggregates, RAP and RAS. These mixes were tested in the lab for structural characteristics such as dynamic modulus, rutting, resilient modulus and tensile strength.

In addition to the fact that RAS saves waste disposal costs, researchers believe that the incorporation of RAS in pavement mixes can reduce the amount of asphalt cement required in the mix. The result of the study shows incorporating RAS at 3% increases the pavement resistance to rutting and low temperature cracking [Tighe, 2008a].

The current OPSS does not allow RAS as part of the surface course for pavement. Only manufactured shingles tabs from manufactured scrap of 0.1% are allowed to replace 1% RAP in hot mix [OPSS 1151, 2007].

3.1.7 Interlocking Concrete Pavement

Common reported applications of interlocking concrete pavements include parking lots, walkways, city streets, intersections and crosswalks [Hein, 2007]. The Interlocking Concrete Pavement Institute (ICPI) conducted a study in Downtown North Bay, Ontario. The study results show that the interlocking concrete roads require no maintenance after 12 years of initial construction [ICPI, 1997]. This study in North Bay was a successful result of interlocking concrete performance under cold climate. Another study by ICPI was conducted at Hong Kong International Airport to use interlocking concrete pavers on the parking area for airplanes [ICPI, 2004]. For the study at the Hong Kong Airport, the interlocking concrete pavers are placed on an asphalt base to create a fuel-resistant surface [ICPI, 2004]. Concrete pavers are an appropriate alternative to use at Hong Kong Airport because it can sustain the differential subgrade settlement that the airport is built on without severely damage the pavement [ICPI, 2004]. It is evident that interlocking concrete pavers have the properties of sustaining large load, and climate ranges. Unfortunately, interlocking concrete pavers is an under-utilized alternative for Ontario highways because the heavy traffic load on the highway would destroy the pavers over time. However, they could be used on carpool parking lots at MTO highway interchanges.

3.1.8 Supplementary Cement Material

Supplementary cement materials (SCM) are materials added to portland cement mix to enhance the properties of concrete. There are three common SCM available in Ontario: blast furnace slag, fly ash, and silica fume. SCM are sustainable because they are by-products of manufacturing processes.

Blast furnace slag is a by-product of processing iron ore in an iron blast furnace [Macleod, 2005]. Blast furnace slag is generated by rapid cooling of slag, which results in the formation of glassy sandy material [MacLeod, 2005]. When used with cement, blast furnace slag can undergo hydration reaction with the presence of water, which makes it an adequate substitute for portland cement. The current MTO OPSS allows a maximum of 25% of blast furnace slag by mass of cementing material [OPSS 1350, 2007].

Fly ash is a by-product generated from coal power plants [MacLeod, 2005]. Fly ash is a powder formed by impurities in coal combustion [MacLeod, 2005]. Fly ash contains calcium oxides, which allow it to undergo hydration reaction similar to cement. The current MTO OPSS allows a maximum of 10% fly ash [OPSS 1350, 2007].

Silica fume is a by-product from silicon metal manufacturing from electric arc furnaces [MacLeod, 2005]. The silica fume is condensed and cooled in the electric arc furnaces that operate 2000°C [MacLeod, 2005]. Silica fume is captured by bags in powdered form. Silica fume particles are about 100 times finer than conventional cement particles, which allow its application as SCM in high strength concrete [MacLeod, 2005]. According to current MTO OPSS 1350, high performance concrete must incorporate silica fume with a maximum content of 25% [OPSS 1350, 2007].

Although the degree of utilization of SCM varies by material availability and specification, SCM reduces the amount of cement needed in the concrete. Cement manufacturing emits significant carbon dioxide, hence the ability to utilize SCM contribute to environmental sustainability. A case study by MacLeod was completed on testing of concrete pavement with SCM. Freeze thaw resistance and scaling of different concrete pavement sections in North America were examined in the study [MacLeod, 2005]. The study concluded that the incorporation of SCM in concrete demonstrated good performance in freeze thaw and de-icing environment [MacLeod, 2005].

3.2 Design and Construction Techniques

Although proper pavement material selection is an important element of road construction, pavement performance also depends on the design, construction and maintenance over the pavement service life. This section discusses some techniques that have characteristics to improve sustainable development of roadways.

3.2.1 Perpetual Pavement

Perpetual pavement is not a new design concept. The asphalt pavement industry in partnership with MTO has recently decided to examine the costs and benefits into perpetual pavement designs. Perpetual pavement is a pavement designed for a durable surface to achieve a life span of 50 years or longer [El-Hakim et al., 2008]. Perpetual pavement is designed to eliminate repair on bottom layers during the life of the pavement [El-Hakim et al., 2008]. The goal in using perpetual pavement is to minimize cost and frequency for maintenance and rehabilitation, as well as user costs over the life cycle of the pavement.

A research study is currently underway at CPATT in partnership with MTO and others on the performance evaluation of perpetual pavement in Ontario highways. In order to achieve minimal repair for the base and subbase, each layer in the perpetual pavement structure is designed to address one or more specific distresses namely rutting, low temperature cracking, and fatigue cracking [El-Hakim et al., 2008]. In this study, the perpetual pavement incorporates a rich bottom mix at the bottom of the base layer to reduce the tensile strain at the bottom of the pavement [El-Hakim et al., 2009]. A life cycle cost analysis shows that the price differential for perpetual pavement and conventional pavement are insignificant [El-Hakim et al., 2008].

3.2.2 Porous Asphalt Pavement

Porous asphalt pavement is designed to manage stormwater within the pavement structure. Porous asphalt is composed of standard bituminous asphalt with a reduced amount of fine aggregates. Thus, it produces a high void ratio for water to drain through the pavement structure. Beneath the porous asphalt surface, a 45 to 90 centimetres (18 to 36 inches) thick open-graded stone bed is built for water infiltration into the underlying soil [Cahill, 2004]. It is suggested that the best use for porous asphalt pavement is on low volume parking lots and access roads [EPA, 1999], [Cahill, 2004]. Porous asphalt pavement has the potential for improved skid resistance, reduced spray to drivers and pedestrians as well as noise reduction [Moore, 2007]. Several studies have concluded a reduction in spraying and splashing from traffic during rain by up to 95% with porous asphalt pavement [Elvik, 2005]. Studies by Fwa and the U.S. Environmental Protection Agency (EPA) indicate the implementation of porous asphalt also contributes to higher skid resistance, which is extremely important in wet road conditions in cold climates [Fwa, 1999], [EPA, 1999]. However, porous asphalt requires resurfacing twice as often because it stays frozen and exposes to ice longer compared to traditional asphalt pavements [Elvik, 2005]. Cahill recommends the addition of polymer and/or fibre to improve strength and durability of the porous asphalt [Cahill, 2004].

3.2.3 Pervious Concrete Pavement

Pervious concrete is similar to traditional concrete mixes as it contains portland cement, aggregate and water, but differs in that it contains little to no fine aggregate and it is open graded [Henderson, 2008]. This creates a void space most often between 15-25%, allowing storm water to infiltrate through its structure. Common applications include parking lots, tennis courts, greenhouse floors, sidewalks and pathways, low-volume roads, driveways and patios [Henderson, 2008]. The pavement structure contains pervious concrete surface placed on clear stone base [Henderson, 2008]. Pervious concrete pavement performs its excellent drainage characteristic with a permeable subgrade. This type of pavement is gaining momentum as it not only eliminates runoff from over passing traffic, but also reduces the need for storm water management systems. This can translate into financial gain for developers, such as more available land to develop and less money spent on incorporating storm water management systems. In fact, MTO has been involved in a trial of pervious concrete and is leading efforts to place more sections in the future. There are three major concerns regarding this type of pavement: clogging, ravelling and structural capacity. Clogging reduces drainage characteristic of pervious concrete. Ravelling affects the durability, skid resistance and life span of the pavement. The lack of structural capacity in pervious concrete prohibits its uses on high traffic roads with heavy vehicle loads. Several studies have determined pressure flushing and vacuuming as a maintenance routine for clogging to restore pavement permeability and friction properties [Henderson, 2008]. A general consensus is that primary causes of ravelling include saw cut joints, poor curing processes, dry mixes and under compaction [Delatte, 2007]. The current research in CPATT also employs RCA in the mix to determine an optimal RCA content in pervious concrete pavement application [Henderson, 2008], [Rizvi, 2010].

3.2.4 Permeable Interlocking Concrete Pavement

Permeable Interlocking Concrete Pavement (PICP) creates permeable surface with permeable interlocking concrete pavers. There are four types of PICP suggested by ICPI: concrete grid pavers, porous concrete unit, widened permeable joints, and interlocking shapes with openings [ICPI, 2008]. Concrete grid pavers facilitate infiltration by allowing grass growth in its large void [ICPI, 2008]. Porous concrete unit is manufactured with no fine aggregates [ICPI, 2008]. Widened permeable joints use spacers to create gaps between individual pavers for infiltration [ICPI, 2008]. Interlocking shapes with openings provides infiltration using its shape geometry arrangements [ICPI, 2008]. The primary goal of PICP is the same as pervious concrete or porous asphalt pavement: to facilitate drainage, reduce stormwater runoff, reduce detention, etc.

There are several benefits with PICPs. PICP are manufactured under strict quality control in the central plant, so it provides little variation between individual pavers. PICP construction is not dependent on temperature; hence, no curing is required at the end of construction [ICPI, 2008]. PICP can be individually repaired when damaged and can be custom manufactured with different colours to reduce the urban heat island effect [ICPI, 2008].

However, PICP faces the same drawback as typical interlocking concrete pavers, which prohibits PICP to be a popular alternative used in MTO highways.

3.2.5 Warm Mix Asphalt

Significant research effort has been put into warm mix asphalt (WMA) pavement. The idea of warm mix asphalt is to allow the placement of asphalt pavement at lower temperatures. A variety of additives is available in the market for creating warm mix asphalt. Most of these additives are proprietary material with different chemical compositions. Warm asphalt additives are added during the manufacturing of asphalt in the plant. The concept of warm asphalt is very sustainable to road construction because it potentially uses less fuel to heat up the asphalt at construction site. Because asphalt is difficult to heat up under cold temperature in general, the utilization of warm asphalt can also potentially increase the paving season by heating the asphalt to a temperature lower than conventional practices.

Research by CPATT and McAsphalt Industries Limited was conducted to evaluate the structural and environmental aspect of warm asphalt mix design. In this research, the Evotherm technology was introduced to the warm asphalt mixing process and placed in the field. Evotherm technology is a chemical process that adds addictives to improve coating, workability, adhesion promoters and emulsification agents [Tighe, 2008]. Laboratory result from the samples taken from the field shows Evotherm warm mix can be produced at a temperature of 60°C [Tighe, 2008]. The research also shows Evotherm warm asphalt mix can reduce fuel consumption during construction by 55% compared to conventional hot mix construction [Tighe, 2008].

3.2.6 Quiet Pavement - Asphalt

The purpose of quiet pavement is to reduce the noise generated from vehicle traffic contacting with the pavement surface. In 2007, CPATT completed a research on the sound attenuation properties on four different asphalt mixes [Leung, 2007]: rubberized Open Friction Course (rOFC), rubberized Open Graded Course (rOGC), Stone Mastic Asphalt (SMA), and Hot Laid 3 (HL3) asphalt. The test results show that rOFC and rOGC have the best sound attenuation properties of all four mixes [Leung, 2007]. The research also included a life cycle cost analysis on the four mixes. This life cycle cost analysis results show rOFC and rOGC are most expensive options [Leung, 2007]. Possible reasons for the higher maintenance cost for rOFC and rOGC pavement are due to their lower service life than traditional HL3 mix and their maintenance requires two lifts of asphalt [Leung, 2007]. Because rOFC and rOGC are economically infeasible, highway agencies such as MTO cannot afford to maintain rOFC and rOGC on their pavement even though being able to reduce noise is a sustainable advantage.

In early 1990, the open graded friction course (OGFC) was introduced for Ontario highways. The OGFC was paved on Highway 401 in the Toronto corridor. OGFC has an open graded texture that allows water to drain through to the base layer similar to that of pervious pavement. The OGFC also has good skid resistance for drivers. The open graded texture also allows heat to transfer through the pavement, hence reducing the surface temperature.

Despite the environmental benefits in the OGFC, short observed life span and higher winter maintenance cost are also driving factors that limit its usage. Although OGFC allows a lower temperature on pavement surface, it also freezes quicker and plagues the OGFC with black ice [Yildirim, 2007].

A new trend on developing a new generation open graded friction course (NGOGFC) has been adopted by various transportation agencies in the U.S. It is believed that NGOGFC will inherit the benefit of OGFC such as lower noise, reduce splash and spray, higher visibility, reduce hydroplaning, and reduce night time surface glare in wet weather conditions [Yildirim, 2007]. Current research demonstrates that NGOGFC are more open graded, have increase air void to 18%, have more asphalt cement by 20%, enhanced by rubber polymer asphalt, and use fibre addictives to achieve high permeability in the mix [Yildirim, 2007].

3.2.7 Quiet Pavement – Concrete

The surface texture of concrete pavement relates to its noise characteristic. Whisper grinded and longitudinal tining are two surface texturing methods capable to reduce pavement-tire noise. Whisper grinded involves narrow grooves placed closely in the direction parallel to the wheel path [Ahammad, 2008]. The close proximity test result from whisper grinded pavement in Arizona showed 3 decibel lower than longitudinal tined pavement [Ahammad, 2008]. Longitudinal tining is similar to whisper grounded instead the grooves are more widely spaced out. MTO currently has longitudinal and transverse tining sections on

Highway 3 near Windsor to demonstrate the performance of quiet concrete pavement in Ontario cold climate.

3.2.8 Two Lifts Concrete Construction

Two lifts concrete construction is a construction method that builds two layers of concrete on the pavement base. This technique constructs the concrete pavement into two layers. The bottom layer of the concrete is constructed on the base using less premium or recycled aggregates because it is not exposed to surface friction. The top layer of the concrete will use high quality premium aggregate to achieve strength, friction, and noise characteristic of conventional concrete pavement. The goal of two lifts concrete construction is to reduce the demand of virgin material because the bottom layer concrete does not utilize high quality material and allow potential economic savings. A study by the Iowa State University was completed on two lifts concrete construction in United States and European countries. In general, two lifts concrete construction is capable to achieve high strength, friction, and noise mitigation [Cable, 2004]. The study also shows successful example of incorporating recycled asphalt and concrete material in the bottom layer concrete construction [Cable, 2004]. However, the drawbacks of two lifts concrete construction include use of two pavers and material availability, which is not always economically feasible.

3.3 Pavement Maintenance and Rehabilitation Techniques

In order to preserve pavement performance, proper maintenance and rehabilitation must be applied to the pavement. There is a wide range of maintenance and rehabilitation techniques currently available and significant research has been devoted to innovative methods for maintenance and rehabilitation. This section discusses a few of the popular maintenance and rehabilitation techniques that are deemed to have sustainable elements.

3.3.1 Cold In-Place Recycling

Cold In-place Recycling (CIR) is a pavement rehabilitation technique that involves cold milling of pavement surface, adding emulsified asphalt and other modifiers to improve the properties of original asphalt concrete mix followed by screeding and compaction of the reprocessed material in one continuous operation [Haas, 1997]. CIR is a commonly used pavement rehabilitation treatment in North America primarily because it is a well-established technique with many successful uses to date supporting the benefits of this method. The rehabilitation allows high percentage of existing material to be reused because it is processed in place. In Ontario, CIR is better than hot in-place recycling (HIR) for two reasons: It mitigates reflective cracking arises from the base layer; and heating up asphalt to complete HIR operation requires energy [Uzarowski, 2007]. CIR is an effective pavement rehabilitation technique for highways and municipal roads.

The drawback of CIR is its curing time is dependent on temperature [Infraguide, 2005], [OPSS 333, 2007], which makes this alternative not feasible for highly trafficked highways and winter roadway maintenance. Typical CIR curing time is approximately 14 days prior to opening for traffic [Chan et al., 2010].

The MTO specification for CIR is listed in OPSS 333, which demonstrates the submission, construction, and quality control requirements of CIR rehabilitation.

3.3.2 Cold In-Place Recycling with Expanded Asphalt Mix

Cold In-place Recycling with Expanded Asphalt Mix (CIREAM) is similar to CIR, but it uses expanded asphalt to mix with RAP [OPSS 335, 2005]. Expanded asphalt is simply heated asphalt cement injected with small amount of water, hence causing the mixture to be foamed asphalt [OPSS 335, 2005], [Uzarowski, 2007]. Expanded asphalt has a lower viscosity than conventional hot mix asphalt cement due to the addition of water. The lower viscosity eases foamed asphalt to blend in with the in-situ RAP [Chan, 2009].

CIREAM has many benefits as with CIR. CIREAM only requires four days of curing [Uzarowski, 2007], and in turn user costs are saved. CIREAM is targeted to restore pavement due to block cracking, poor patching, ravelling thermal cracking, fatigue cracking, and reflective cracking [OPSS 335, 2005], [Chan, 2009]. CIREAM does not pulverize the existing pavement during the rehabilitation.

As of 2010, MTO has completed 13 CIREAM contracts in Ontario [Lane, 2010]. MTO also conducted post-construction lab testing and statistical modeling for CIREAM versus CIR mix to further understand the behaviour of CIREAM and CIR [Lane, 2010]. The test results show CIREAM and CIR both provide similar performance characteristics statistically [Lane, 2010]. The OPSS 335 governs the design, construction and quality requirement of CIREAM use in MTO project.

3.3.3 Full Depth Reclamation

Full Depth Reclamation (FDR) is a rehabilitation technique that pulverizes the distressed pavement surface layer and a portion of granular base simultaneously [Haas, 1997]. The pulverized pavement materials are stabilized with additives to restore strength and uniformity. These additives include foam asphalt, portland cement, and lime [Infraguide, 2005]. Foam asphalt as FDR stabilizing material is gaining popularity recently because of its short curing duration similar to CIREAM [Infraguide, 2005]. The pulverized material from the FDR process is compacted and reused as granular on the existing ground.

FDR utilizes high reused content because existing pavement does not recollect as RAP. Another benefit of FDR is that it mitigates reflective cracking caused by base layer failure, provide good resistance to rutting and fatigue cracking by using foam asphalt [Infraguide, 2005].

For roads plagued with fatigue, longitudinal, and transverse cracking, full depth reclamation with cement becomes a viable alternative to rehabilitate the pavement. At Point Michaud Beach Road, Nova Scotia, the first FDR section was rehabilitated in 2007 with cement stabilization [CAC, 2008]. FDR was chosen as the rehabilitation treatment primary for reflective cracking mitigation in the underlying pavement layers [CAC, 2008]. In order to utilize FDR rehabilitation successfully, the FDR material must undergo a micro-cracking process, which spread a network of fine cracks immediately after construction by vibratory steel drum roller [CAC, 2008]. Micro-cracking reduces the effect of shrinkage effect by the cement and also reduce reflective cracking potential [CAC, 2008]. Another advantage to use portland cement to stabilize the FDR material is that it is less sensitive to temperature compared to asphalt emulsion used in FDR rehabilitation [CAC, 2008].

A study in New Hampshire uses portland cement as a FDR stabilization material [Miller, 2010]. The study compares conventional pavement reconstruction versus cement stabilized FDR rehabilitation through in-situ instrumentation and laboratory testing. The study results show minimal thermal cracking appears on the FDR section with nearly no rutting after four years of surface [Miller, 2010].

3.3.4 Microsurfacing

Microsurfacing is a common pavement maintenance treatment for flexible pavement. It is often applied on asphalt pavement surface that has signs of deterioration but is still structurally adequate. Microsurfacing mixture generally consists of polymer modified asphalt emulsion, medium to fine graded high quality aggregates, fillers, additives and water [Haas, 1997]. It is aimed to address rutting and improve surface friction on the pavement [Haas, 1997]. Microsurfacing has an expected surface life of 7 to 9 years [Haas, 1997]. There are currently three types of microsurfacing treatments available according to OPSS 336: Type II, Type III, and Type III modified [OPSS 336, 2005]. These different types of microsurfacing emphasize different aggregates and material gradation [OPSS 336, 2005]. Generally, Type II microsurfacing is used on arterial, collector and local roads; type III microsurfacing is used on freeway with high design speed and traffic volume [OPSS 336, 2005]. Type III modified microsurfacing is essentially Type II microsurfacing with noise reduction [OPSS 336, 2005]. Another benefit of micosurfacing is that it has a short curing time, which ultimately saves user cost due to delay and road closure [Uzarowski, 2007].

A study by CPATT evaluated how microsurfacing affects road safety. The study involved a statistical comparison of microsurfacing and conventional resurfacing in York Region. The results showed that microsurfacing provides reduction to crashes better than resurfacing in the study [Erwin, 2008]. Because microsurfacing uses finer aggregates than chip seal, the potential of damage caused by flying aggregates is lower than chip seal applications [Haas, 1997].

The drawback of microsurfacing is that its application is weather and time dependent. According to OPSS 336, microsurfacing operation can only be done under warm, dry weather conditions, and between May 15 to September 30 of a given year [OPSS 336, 2005].

3.3.5 Diamond Grinding

Diamond grinding is a rehabilitation treatment used for rigid pavement to restore ride quality and frictional properties given the pavement is still structurally adequate [Haas, 1997]. It is an effective treatment to lower the noise generated by pavement [Hein, 2006]. Diamond grinding is an excellent alternative to remove roughness due to joint faulting and restore skid resistance [MTAG, 2006]. Diamond grinding removes the surface for 4 to 8 millimetres with a diamond saw blade, to enhance service life by 10 years [Hein, 2006]. Typical rigid pavement can undergo three to four diamond grinding treatments as long as the pavement is structurally sound and there are no visible signs of joint problems [Hein, 2006].

The major benefit of diamond grinding is that it can be completed quickly when the road is not experiencing peak hour traffic [MTAG, 2006]. Diamond grinding is a cost effective rehabilitation treatment. There is no construction specification in the OPSS for diamond grinding. However, OPSS 350 describe the machinery requirement for diamond grinding operations.

3.3.6 Precast Concrete Panels

Another new method for concrete pavement repair is using precast concrete panels for full depth repair. Precast concrete is a mature technology, but the experience of using precast concrete for pavement restoration is limited [Hein, 2006]. The benefit of precast concrete is the concrete is properly cured under strict quality control to reduce the variation in the material [Hein, 2006]. Therefore, the performance of concrete will not be affected by temperature, moisture, and curing during installation. Precast concrete does not require on site curing, which means the damaged area can be opened to traffic quickly.

With the ability to perform rapid repair for pavement, the utilization of precast concrete panels in rigid pavement is gaining popularity on roadway exposed to busy truck traffic.

There are three methods to install precast concrete panels: Michigan Method, Fort Miller Intermittent Method, and Fort Miller Continuous Superslab Method [Kenter, 2010]. The Michigan Method involves placing precast slab on the pavement base filled with flowable cement material [Kenter, 2010]. In the Michigan Method, the precast slab has dowel bars pre-installed in the slab at the precast plant prior to the installation [Kenter, 2010]. The Fort Miller Continuous Superslab Method involves placing the precast slab on compacted road base. The precast slabs in the Fort Miller Continuous Superslab Method contain pre-cut slots at the bottom of the slab for on-site dowel bar insertion and grout filling [Kenter, 2010]. The Fort Miller Continuous Superslab Method uses the same installation compared the Fort Miller Intermittent Method. However, the precast slabs used in the Fort Miller Continuous Superslab Method contain dowel bar at one end and insert slot on the other [Kenter, 2010]. The Fort Miller Continuous Superslab Method allows adjacent precast slab to interlock together. Proper installation of dowel bar is critical in precast concrete panels because slab damage can occur due to dowel bar misalignment. MTO has successfully implemented two contracts on Highway 427 using precast concrete slabs in 2008 and 2009, which demonstrated precast concrete panels is an effective fast track rehabilitation alternative [Kenter, 2010].

3.3.7 Concrete Rubblization

Concrete rubblization is a process of breaking existing concrete pavement to produce an in-place granular material. According to OPSS 361, the concrete is broken into fragments that are less than 150mm and compaction shall satisfy the specification for Granular A [OPSS 361, 2005]. Clearly, the process of rubblization saves a significant amount of granular required for a project by reusing existing pavement. Rubblized concrete is combined with asphalt overlay or concrete overlay for finished pavement surface. Rubblization is best used when the concrete pavement exhibits structural distresses or material related distresses such as freeze thaw damage in concrete and alkali-silica reactivity [ACPA, 1998]. Although concrete rubblization and overlay mitigate reflective cracking, the drawback of concrete rubblization is the subgrade condition of the pavement after rubblization is unknown at the design stage of the project [ACPA, 1998].

3.3.8 Concrete Overlays

Concrete overlay is a rehabilitation that uses concrete to restore riding surface of the pavement. A concrete overlay constructed on an existing asphalt surface is called whitetopping. However, it should be noted a concrete overlay can be applied to an existing concrete pavement. A concrete overlay provides a strong and durable riding surface. Since concrete pavement are not susceptible to rutting, concrete overlay is a desirable rehabilitation treatment for pavement exposed to heavy truck traffic load. There are two types of concrete overlays available: bonded concrete overlay and unbonded concrete overlay. Bonded concrete overlay are commonly used for minor rehabilitation or resurfacing purposes, it does not improve structural support of the pavement. [Fung, 2010] An unbonded concrete overlay rehabilitates the road that shows signs of structural distresses in addition to restore the riding surface friction [Fung, 2010]. An unbonded concrete overlay is capable of achieving the desirable performance characteristics without the bond to other pavement layers [Fung, 2010]. Concrete overlays can also utilize SCM and recycled materials in the concrete mix to improve sustainability of the rehabilitation. The Cement Association of Canada has performed studies on concrete overlay projects across Canada, and their results show that concrete overlays require little maintenance post construction [Fung, 2010].

3.4 Green Initiatives

As the concept of sustainable infrastructure becomes more prevalent, different agencies will develop rating systems to quantify the sustainability or environmental benefit associated with their infrastructure. These sustainability initiatives act as scorecards to quantify the sustainable element associated with the infrastructure evaluated. For this project, it is important to evaluate the differences between the current sustainability initiatives available since Task 4 of this project involves using MTO’s green pavement rating system. This project reviews four sustainability initiatives: LEED®, Greenroads, GreenLITES, and Green Guide for Roads Task Force.

3.4.1 LEED®

In Canada, Leadership in Energy and Environmental Design (LEED®) Green Building Rating System is a green system established by the Canada Green Building Council (CaGBC). LEED® encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria [CaGBC, 2008]. LEED® is a third party certification program that acts as a benchmark for design, construction, and operation of green buildings [CaGBC, 2008]. Therefore, a fee is required to register and process LEED® certification. The LEED® rating systems for different building applications are available for download online at www.cagbc.org free of charge.

The CaGBC has LEED® rating systems for six different building applications [CaGBC, 2008]:

1. New Construction
2. Existing Building
3. Commercial Interior
4. Cores and Shells
5. Homes
6. Neighbourhood Development

For each type of building application submitted for LEED® certification, six common key areas of sustainability are assessed for credit [LEED®, 2008]:

1. Sustainable Site
2. Water Efficiency
3. Energy and Atmosphere
4. Materials and Resources
5. Indoor Environmental Quality
6. Innovation and Design

For any LEED® certification building application, each criterion above requires specific prerequisites and submission documents to determine whether credit can be rewarded. As LEED® certification mainly focuses in building evaluation; it has little technical references applicable for sustainable pavement practices. However, LEED® is a mature sustainable rating system that has a proven record of accomplishment and awareness among practitioners and general public. It acts as the benchmark for many sustainable infrastructure assessment programs that are currently available and under development.

3.4.2 Greenroads

Greenroads is an assessment program for new or rehabilitated roadways initiated in 2007 by Martina Soderlund and Professor Stephen Muench at the University of Washington. The work for Greenroads is now being carried on as a joint effort by CH2M Hill and University of Washington. Greenroads is a project based assessment program for design and construction of roads [Muench, 2010]. The Greenroads manual is available for download at www.greenroads.us and contains all the details about the current Greenroads. In order for a project to get Greenroads certified, the project must be registered with Greenroads at their website. Project documents are then submitted to Greenroads team for review. Greenroads is currently a third party rating system, and applicable fees are required for getting the Greenroads certification. Greenroads version 1.0 contains two main categories of credits: project requirements, and voluntary credits [Muench, 2010]. Project requirements credits consist of total 11 credits that must be demonstrated by the project in order to be considered for Greenroads certification [Muench, 2010]. There are a total of 118 voluntary credits available in Greenroads [Muench, 2010].

Greenroads' voluntary credits are summarized by six main categories [Muench, 2010]:

- Environment and Water 21 Credits
- Access and Equity 30 Credits
- Construction Activities 14 Credits
- Materials and Resources 23 Credits
- Pavement Technologies 20 Credits
- Custom Credits 10 Credits

For the particular interest of pavement sustainability, the two main categories of concern are Material and Resources, and Pavement Technologies. Figure 4 shows a screen capture from Greenroads about the credits available [Muench, 2010].

	Materials & Resources (MR)			
☐	MR-1	Lifecycle Assessment (LCA)	2	Conduct a detailed LCA of the entire project
☐	MR-2	Pavement Reuse	5	Reuse existing pavement sections
☐	MR-3	Earthwork Balance	1	Balance cut/fill quantities
☐	MR-4	Recycled Materials	5	Use recycled materials for new pavement
☐	MR-5	Regional Materials	5	Use regional materials to reduce emissions
☐	MR-6	Energy Efficiency	5	Improve energy efficiency of operational systems
		MR Subtotal:	**23**	
	Pavement Technologies (PT)			
☐	PT-1	Long-Life Pavement	5	Design pavements for long-life
☐	PT-2	Permeable Pavement	3	Use permeable pavement as a LID technique
☐	PT-3	Warm Mix Asphalt	3	Use WMA in place of HMA
☐	PT-4	Cool Pavement	5	Use a surface that retains less heat
☐	PT-5	Quiet Pavement	3	Use a quiet pavement to reduce noise
☐	PT-6	Pavement Performance Tracking	1	Collect performance data as related to construction
		PT Subtotal:	**20**	

Figure 4: Pavement Related Credits in Greenroads Version 1.0

The credits shown in Figure 4 are specific sustainable pavement engineering practices considered in Greenroads. Greenroads has a custom credits categories for unlisted sustainable practices that should be considered for credits [Muench, 2010]. In general, Greenroads does not consider land planning, material manufacturing processes, structural integrity, maintenance and preservation activities that are associated with the life cycle of transportation infrastructure [Muench, 2010].

Greenroads also features different certification levels; given the entire project requirement credits are satisfied. Table 2 shows the different certification as per Greenroads requirement [Muench, 2010].

Table 2: Greenroads 1.0 Certification Levels

Certification Level	Voluntary Credits Required
Not Certified	0-31
Certified	32-42
Silver	43-53
Gold	54-63
Evergreen	64+

The Greenroads team is currently accepting co-pilot projects for evaluation and certification. Greenroads should not be interpreted as standards, nor it is legislated that transportation projects must achieve Greenroads certification.

3.4.3 GreenLITES

In September 2008, the New York State Department of Transportation (NYSDOT) released the GreenLITES. GreenLITES is a certification program for NYSDOT transportation designs meeting criteria for sustainable transportation infrastructure as a whole [NYSDOT, 2009].

GreenLITES is a "self certification program" that evaluates sustainable design in a transportation project [NYSDOT, 2009]. GreenLITES is used internally by NYSDOT to measure performance, good practices, and identify improvements where needed [NYSDOT, 2009]. In other words, users of GreenLITES are agency staffs that evaluate transportation design. GreenLITES main emphasis is on the design aspect of transportation projects. Therefore, GreenLITES considers different aspects of the transportation project as a whole such as pavement, alignment, traffic, lighting, land use, materials, water quality, etc. In addition, NYSDOT releases the GreenLITES scorecard, which is an excel spreadsheet that contains a comprehensive description of the different categories regarding how credit(s) should be awarded. Two screen captures of the GreenLITES scorecard in Figure 5 demonstrate the broad nature of credits available in GreenLITES [GreenLITES, 2009].

GreenLITES Project Environmental Sustainability Rating System Scorecard v 2.0.1

Please fill in all yellow highlighted cells and follow all instructions in red text.

Project: PIN: Type: Contact Name:

CATEGORY	ID	DESCRIPTION	POINTS Available	POINTS Scored	INSTRUCTIONS
M-2 *Recycled Content*	M-2a	Use tire shreds in embankments.	2		*<= Please enter 0 or 2*
	M-2b	Use recycled plastic extruded lumber or recycled tire rubber (e.g. for noise barriers).	2		*<= Please enter 0 or 2*
	M-2c	Specify hot-in-place or cold-in-place recycling of hot mix asphalt pavements.	2		*<= Please enter 0 or 2*
	M-2d	Specify the use of recycled glass in pavements and embankments, as drainage material or filter media where adequate local sources can be obtained.	2		*<= Please enter 0 or 2*

GreenLITES Project Environmental Sustainability Rating System Scorecard v 2.0.1

Please fill in all yellow highlighted cells and follow all instructions in red text.

Project: PIN: Type: Contact Name:

CATEGORY	ID	DESCRIPTION	POINTS Available	POINTS Scored	INSTRUCTIONS
E-1 *Improved Traffic Flow*	E-1a	Special use lane (HOV/Reversible/Bus Express).	3		*<= Please enter 0 or 3*
	E-1b	Innovative interchange design and/or elimination of freeway bottlenecks (diverging diamond, single point urban).	3		*<= Please enter 0 or 3*
	E-1c	Specify new roundabout(s).	3		*<= Please enter 0 or 3*
	E-1d	Implementation of a robust Traffic Management Center / Traveler Information System operation (e.g., TMC, CCTV, VMS freeway detection, ramp metering, road weather info system and/or weigh in motion devices, travel time signs).	3		*<= Please enter 0 or 3*
	E-1e	Installation of a closed-loop coordinated signal system.	2		*<= Please enter 0 or 2*
	E-1f	Installation of a transit express system (queue jumper, pre-emptive signals, etc)	2		*<= Please enter 0 or 2*

Figure 5: GreenLITES Excel Scorecard

As seen in Figure 5, a GreenLITES credit is awarded based on whether the project satisfies the credit description at a yes or no condition. GreenLITES evaluates the plans, specification, and estimate submitted to the NYSDOT [NYSDOT, 2009]. In general, GreenLITES evaluates a project based on five main categories below [NYSDOT, 2009].

1. Sustainable Sites
2. Water Quality
3. Material and Resources
4. Energy and Atmosphere
5. Innovation/Unlisted

GreenLITES also provides certification level as certified, silver, gold, and evergreen based on the points obtained on a project [NYSDOT, 2009]. Table 3 shows the GreenLITES certification levels [NYSDOT, 2009].

Table 3: GreenLITES Certification Level 2009

Certification Level	Points Range
Non-certified	0-14
Certified	15-29
Silver	30-44
Gold	45-59
Evergreen	60 or more

Table 3 shows the point ranges required to get GreenLITES certified. Although, there are a maximum of 279 points available, one can view that GreenLITES is a scoring platform for all different types of transportation project. In other words, many points in GreenLITES are not applicable for pavement projects.

The 2009 revision of GreenLITES contains many updates regarding individual points. It also addresses the role of construction quality monitoring to ensure the final product is built as per the design requirements [NYSDOT, 2009].

3.4.4 Green Guide for Roads Task Force

The Transportation Association of Canada (TAC) is currently undertaking a project to develop the "Green Guide for Roads Task Force". According to the task force road map, it is meant to [GGRTF, 2010]:

> "Provide guidance on roadway planning, design, construction, commissioning, maintenance and operation, and life cycle assessment activities and will address the full functional hierarchy of roads in urban and rural settings."

The Green Guide considers thirteen application areas in relation for sustainable transportation practices as shown in the number list below [GGRTF, 2010]:

1. Community Interface
2. Environmental Footprint
3. Mobility Choices
4. Intersections and Driveways
5. Hard Surfaces
6. Landscaping
7. Street Furnishings
8. Drainage

9. Safety
10. Energy Consumption
11. Construction
12. Operation and Maintenance
13. Services and Utilities

The Green Guide has a unique aspect of considering the operation and maintenance in transportation. Most other green initiatives that are currently available do not consider the operational aspects. The Green Guide is anticipated to consider the entire transportation infrastructure such as the main road structure, roadside feature, and adjacent land use within the road corridor. As the name suggests, the Green Guide is expected to provide guideline for the Canadian transportation industry rather than a certification program.

Chapter 4
CPATT/MTO Sustainable Pavement Workshop

The CPATT/MTO Sustainable Pavement Workshop was held on December 12, 2008 at MTO Downsview Office. 44 participants were present at the workshop which consisted of members from industries, consultants, contractors, material suppliers, MTO and University of Waterloo as shown in Table 4.

Table 4: Workshop Participants and Group

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Rico Fung	Sandy Brown	Dave Anderson	Bart Kanters	Steve Goodman	Ryan Essex
John Pontarollo	Vince Aurilio	Heather Crewe	Rob Bradford	Salmon Bhutta	Frank Hull
John Hull	Keith Davidson	Anne Holt	Wayne Lazzarato	Murray Ritchie	Tom Dzieziedjko
Maria Bianchin	Mike McKay	Harry Sturm	Mike Greco	Malcolm Matheson	Dave Snow
Louie LaRocca	Pamela Marks	Gord Lavis	Maryam Latifpoor-Keparoutis	Chris McColl	Steve Senior
Susanne Chan	Mireya Hidelgo	Tim Smith	Chris Thompson	Tom Kazmierowski	Finlay Buchanan
Susan Tighe	Trevor Moore	Chris Raymond	Becca Lane	Jodi Norris	Peter Chan
		Alex Campbell	Jennifer Yang		

The goal of the workshop is to understand the current state of sustainable pavement practices available in Ontario and the industry perspective toward sustainable pavement in the future.

The workshop began with an introductory presentation of all participants by Dr. Susan Tighe and Ms. Becca Lane. Mr. Finlay Buchanan, coordinator technology innovation at MTO, provided a presentation about the MTO Highway Innovation Infrastructure Funding Program (HIIFP). Dr. Chris Raymond provided a presentation on MTO Pavement Sustainability Initiatives. Lastly, Dr. Susan Tighe presented LEED®, Green Guide by

Alberta Chapter of Canadian Green Building Council, and Greenroads by University of Washington.

The participants at the workshop were pre-assigned into six groups based on their expertise as shown in the group breakdown below:

1. Concrete Materials
2. Asphalt Materials
3. Design Processes
4. New Construction / Reconstruction
5. Preservation Strategies
6. Rehabilitation

Each of the six groups above is responsible to discuss the ten questions in the breakout session. The next section summarizes the results of the workshop in point forms.

1. Possible ideas for sustainable pavement?
2. Identify sustainable technologies (concrete materials, asphalt materials, pavement design tools and asset management, new construction and reconstruction processes, preservation strategies, and rehabilitation.)
3. Why are these technologies sustainable?
4. What are the benefits of using the technologies? How well are these technologies currently utilized? Can we better utilize the technologies?
5. Are there barriers to implementation?
6. How can we address pavement sustainability in 5, 10, and 50 years?
7. What are the costs to develop sustainable technologies?
8. What are the benefits of implementing pavement sustainability?
9. How should we achieve a balanced quantification of a sustainable pavement technology?
10. Are there other technologies that should be explored?

The workshop was an overall great success and it was a thoughtful exercise for all participants. The above results will act as the basis for project Task 3 in relation to identify social aspect of sustainable pavement.

4.1 Breakout Session Question Result

Possible Ideas for Sustainable Pavements?

- Use of pervious concrete
- Two layer concrete systems
- Use of cement open graded drainage layer

- Warm asphalt technologies
- Increasing percentages of RAP in pavement
- In-place recycling (use of RAP)
- Use of recycled asphalt shingles
- Porous asphalt
- Use of by-products in pavement design and construction
- Incorporating sustainability into designs and asset management practices
- Role of environmental benefits in Life Cycle Costing
- Dowel bar retrofit, cross stitching, and diamond grinding for concrete pavement
- Crack mitigation through chip seal, microsurfacing, crack sealing
- Fast track repairs
- Innovative precast repair products
- Role of emissions in production
- Long life pavement
- Quiet pavements and noise reduction
- User delay costs
- Impacts of climate change

What Sustainable Technologies are Available?

- Cement: reducing CO_2 footprint and energy consumption, through use of alternate fuel, supplementary cement materials, and reduce the clinker to cement ratio by using up to 15% limestone interground with clinker, energy cogeneration mechanisms
- With aggregate recycled concrete/RAP/possible glass and plastic to preserve virgin aggregate sources, Using mineral fillers for fine aggregate
- Use of warm mix asphalt technologies
- Water conservation by capture processed water & recycled into mixing water, and use of water reducing admixtures
- Transportation: local against foreign in term of truck transportation fuel consumption and greenhouse gas emission. Optimum balance of emission between stationary and portable plant at construction site
- Design tools such as: DARWIN, AI SW1, MEPDG, PerRoads, StreetPave, Pavement and rehab design manual provide grounds for sustainable design
- Longer design service life such as 50 years
- Heavy lift technology, improved project staging, design for future traffic conditions are also key consideration to sustainable pavement
- Excess material management, surplus material plans (design stage), material storage depots are key components to conserve material at design
- Proactive planning of preservation treatments instead of reactive
- Preservation techniques such as chip seal, microsurfacing, slurry seals, thin hot mix overlay, epoxy based seals, reinforced chip seals, surface correction, micro-milling and diamond grinding are examples of sustainable pavement preservations

- Rehabilitation Technologies
  – In place recycling (CIR, HIR, FDR, rubblization)
  – Use of recycled and excess materials for granular bases, fill, shoulders
  – Deep milling and paving
  – Precast concrete for pavement and roadside structures

Benefits of Sustainable Pavements

- Reducing CO_2 emission and use of natural resources such as limestone
- Alternate fuel will reduce emission and truck fuel savings
- Use less potable water
- Reducing urban heat island effect with high solar reflectance
- Long life and lower embodied primary energy
- Saving money for all road classifications
- Noise reduction
- Adequate structural design
- Reduced user costs due to delays
- Longer service life and lower life cycle costs by deferring rehabilitation and reconstruction
- Reduced energy inputs
- Material conservation
- Improved level of service and reduced complaints, enhanced safety for workers and travelling public
- Porous pavement for stormwater infiltration

What are Degree of Utilization and Drawback?

- Low utilization due to government or environmental regulation for fuel usage
- SCM: medium usage, can be improved by utilizing high % due to agency concrete specifications
- Recycled Materials: low to none due to specifications, and lack of performance data
- Testing Protocols: the procedures have to keep pace with the advancing concrete technology and innovation
- Degree of use is better by larger agencies. For smaller the municipality, the less likely it is to use 'greener' technologies and to use design tools
- Insufficient knowledge of new technologies and the solution is through education
- The simpler to use tools and better availability are highly regarded
- Gradual implementation of new technologies
- Inconsistent implementation of sustainable practice province wide

How Can We Improve the Utilization to Its Best Value?

- Utilization improves through research, development, and partnership with stakeholders to raise the awareness for using innovative methods, and recycled materials through education.
- Continuous update of the test protocols for materials and quality control/assurance
- A measuring system must first be created to quantify cost and benefit of each option in long term
- Lobby for dedicated funding for preservation activities is needed
- Multi-year rehabilitation planning and budgeting with proactive implementation
- Long term warranty contracts and other innovative contracting methods
- Allow innovative design
- Application, setting and enforcing of policies that increase use of sustainable rehabilitation strategies

Barriers to Implement Pavement Sustainability

- Restrictions from specifications
- Risk management
- Lack of education and understanding of performance specifications
- Habit causing resistance to change
- Perceived larger costs to implement sustainability
- Training for all team members
- Inadequate information exchange, tough sell to citizens and politicians
- Motivations of various members
- Existing environmental regulations in place
- Either lack of funding, no dedicated funding for preservation
- Lack of long term rehabilitation planning, budget and asset management
- Lack of champions and leadership
- Lack of performance modeling data for preservation
- No incentives for sustainable design and construction
- Comfort level of designer to use innovative and sustainable techniques are missing

How to Address Pavement Sustainability in Future?

- Develop green procurement policies, green pavement specifications with quantified measurement performance involving life cycle cost analysis
- Increase the use of performance specifications
- Investing in green research, development, and innovations
- Mandating use of a alternative technologies
- Proactive design inputs – minimum requirements for 50 year road designs and 100 year bridge designs
- Increase design requirements for construction such as avoiding 5 to 7 year repair projects
- Modify asset management systems to allow for proactive repairs

- Educate municipalities and younger generation through road shows and webinars training
- Accommodate future recycling into today's design
- Reward for sustainable design and innovation
- Owner to clearly set level of expectation for performance, % of recyclables, emissions and energy reductions

Costs Required to Achieve Sustainability?

- There are none to slight additional costs initially but taper off once the market place has adopted the principals because most suppliers have the technology in practices but not at the optimum level
- Investing in training to acquire expertise in developing green procurements and specifications
- Detailed investigation of new products and structural value
- Cost of research, development, and validation
- Cooperation of team member in utilizing sustainability
- Increased research and quantification of benefits
- Increased cost to contractors for source separation

How Should Sustainability be Quantified Reasonably?

- Greenhouse gas reduction
- Fuel and energy savings
- Long term performance, service life must be measured
- Materials conservation through reclaim, reuse, and recycle material
- Minimizing the environmental, economical and social impact during construction and operations
- A fair and simple sustainability rating mechanism
- Life cycle costing
- Better understand repair costs
- Societal benefits such as time and user delays
- Cost savings with incremental service life extension
- Recycling (% used on job/across network)
- Asset value of materials leaving site
- Testing and monitoring of final product

What Other Technologies Should be Explored?

- Portland-limestone cement to reduce demand of cement
- Using RAP/Glass/Plastic/Mineral as coarse aggregate
- Need to explore broader range of potential materials such as new generation asphalt, precast panels and acoustic panels
- Exploring technologies through research and academic partnerships

- Improving contractor process control systems
- Cradle to grave recycling by multi-pass removal/screening and reuse
- Both in-place recycling and plant recycling work together
- Reducing open cut trenching and access to utilities
- Use of recycled materials for preservation treatments
- Specifications to encourage innovation and material preservation

Chapter 5
Quantification of Sustainability

This chapter focuses on quantifying typical savings associated with different pavement engineering practices. In general, the quantification is broken down into three parts in this project: 1) Environmental and Economic Savings, 2) Social Cost, and 3) Green Pavement Rating System. Previously in Chapter 3, various pavement technologies were explored qualitatively. This chapter explores the different technologies in a quantitative manner. The goal of the quantification is to distinguish the performance differences between various pavement engineering practices.

For the quantification of environmental and economic savings in the project, typical design sections are set up for different pavement alternatives. Environmental and economic savings are quantified in two perspectives: individual project level and life cycle level. Project level quantification examines the savings as an individual treatment. Life cycle level quantification estimates environmental and economic savings as a series of pavement treatment totalled over the life cycle of the pavement. The environmental savings of different pavement alternatives in this project is analyzed using the PaLATE software. This analysis estimates emissions and energy of different pavement alternatives at project basis and life cycle perspectives. The economic savings of the pavement alternatives are analyzed through pavement materials savings and life cycle cost analysis. The social cost of the quantification is identified from the result of CPATT/MTO sustainable pavement workshop. The green pavement rating system in this project is intended as a simple assessment tool to evaluate the extent of environmental sustainability for MTO projects.

5.1 Environmental Savings Quantification With PaLATE

PaLATE stands for "Life-cycle Assessment Tool for Environmental and Economic Effects" [Horvath, 2009]. According the author of PaLATE, Dr. Arpad Horvath from University of California Berkeley, PaLATE is [Horvath, 2009]:

> an Excel-based tool for life-cycle assessment (LCA) of environmental and economic effects of pavements and roads. The tool takes user input for the design, initial construction, maintenance, equipment use, and costs for a roadway, and provides outputs for the life-cycle environmental effects and costs.

For this project, PaLATE serves as the life cycle analysis (LCA) tool to quantify environmental impacts of road construction or rehabilitation projects. The environmental impact quantities estimated by PaLATE are CO_2, NO_X, SO_2, CO, leachate, $PM_{10,}$ Pb, Hg, HTP, etc. [PaLATE, 2009]. For the purpose of the environmental quantification, a series of PaLATE workbooks are compiled to estimate these environmental impact quantities in January 2009. The pavement technologies evaluated by PaLATE in this project are summarized Table 5.

Table 5: Pavement Technologies Being Quantified by PaLATE

New Construction	**Rehabilitation**	
Asphalt Arterial	Cold In-place Recycling (CIR)	Mill & Overlay
Asphalt Expressway	Cold In-place Recycling with Expanded Asphalt Mix (CIREAM)	Rubblization with Asphalt Overlay
Concrete Arterial	Hot In-Place Recycling (HIR)	Mill & Overlay with 20% RAP
Concrete Pavement with 30% RCA	Full Depth Reclamation (FDR)	Mill & Overlay with Warm Mix Asphalt
Concrete Expressway	Expanded Asphalt Stabilization (EAS)	Concrete Overlay
Pervious Concrete Pavement		
Porous Asphalt Pavement		

For each of the pavement technologies identified in Table 5, PaLATE requires three major components in order to estimate the environmental impact: Pavement Thickness Design, Material Ingredients, and Material Transportation Distance. Pavement thickness design governs the pavement dimension in terms of length, width, and depth. For this project, all PaLATE workbooks assumed a typical length of pavement to be 1 km and the width of 7m (2-lane highway with lane width 3.5m). The depth of the pavement is dependent on the pavement design, material, structure and the specific pavement layer.

For the second component, material ingredients, PaLATE requires the volumetric proportion of the materials in each pavement layer. Some assumptions used for simplifying the estimation include:

- Hot Mix Asphalt (HMA) contains 95% aggregates and 5% bitumen by volume.
- Warm Mix Asphalt (WMA) emission savings are discounted from the emission of HMA production, refer to Appendix D for more details regarding WMA discounting with PaLATE.
- Open Graded Drainage Layer (OGDL) is assumed to contain 98% aggregates and 2% bitumen by volume.
- Concrete material proportions are calculated using example from *Design and Control of Concrete Mixture 7th Edition* by Cement Association of Canada, OPSS 1002 Material Specification for Aggregates – Concrete, and OPSS 1301 Material Specification for Cementing Materials [Kosmatka et al., 2002], [OPSS 1002, 2004], [OPSS 1301, 2007]. Detail calculation example is shown in Appendix C.

For the third component, material transport distance, PaLATE requires the material transportation distances from the contractor's plant to the construction site. MTO suggested the assumed transportation distances as summarized in Table 6.

Table 6: Assumed Material Transport Distance

Item	Assumed Transportation Distance
Virgin Aggregate, Hot Mix Asphalt, Concrete	10 km (6.21 miles)
Bitumen	300 km (186.3 miles)
Reclaimed Asphalt Pavement (RAP)	10 km (6.21 miles)
Recycled Concrete Aggregates (RCA)	50 km (31 miles)
Portland Cement	50km (31 miles)

Table 6 provides a summary of the basic assumptions that aggregates are readily available in the province, so a 10km transport distance is assumed. For bitumen, which is not an abundant resource in Ontario, is conservatively assumed a provincial wide transport distance of 300km. For RCA, a transport distance of maximum 50km is assumed because for transport distance greater than 50km may result a reductions in economic and environmental cost savings. Portland cement is assumed to have a transport distance of 50km because cement is manufactured locally around Ontario.

Appendix D provides a detailed PaLATE documentation for compiling the PaLATE workbooks using the pavement technologies suggested in Table 5. The documentation discusses the required input formulation and how the environmental impact quantifications are derived for each PaLATE workbook. It will also cover the general layout for new users to get familiar with PaLATE to perform environmental quantification on pavement design alternatives.

5.1.1 PaLATE Result for Rehabilitation and Construction

The numerical results from PaLATE are attached in Appendix E Table 41. For pavement rehabilitation, Mill and Overlay (M&O) is assumed as the control option. All of the other rehabilitations are compared to the control option, M&O. The environmental impacts further analyzed are energy, carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrous oxide (NO_x). Appendix F shows these environmental impacts in the form of bar charts for different rehabilitations. The PaLATE analysis results for pavement rehabilitation are shown Figure 30 to Figure 34 in Appendix F. For the rehabilitations shown in Figure 30 to Figure 34, the output is divided into two parts: Process, and Overlay. The 'overlay' output in PaLATE considers the addition of asphalt or concrete material on top of existing pavement surface. The 'process' output in PaLATE considers all the equipment activities and additional of material (such as bitumen or asphalt emulsion) that are used to prepare the existing pavement prior to the addition of overlay. From the PaLATE analysis, it is observed the process output in the rehabilitation contributes minimal energy or emission.

Based on the results in Appendix E and Appendix F, some conclusions can be drawn between the different rehabilitation technologies.

- Appendix F suggested HIR consumes less energy than CIR and CIREAM. This finding does not seem to be consistent with the literature because HIR involves heating of asphalt, which would likely result in emissions. Hence, it is believed that the HIR calculation in PaLATE is incorrect. However, other elements of sustainability related to HIR are still considered in this task.
- The results show M&O is the least sustainable alternative available with the highest emissions and highest energy used.
- Adding RAP in the M&O process reduces energy used, and the associated CO_2, NO_x, CO emissions are reduced.

- The PaLATE results for CIR and CIREAM are nearly identical as shown in Appendix F. The difference in the input for the asphalt emulsion for CIR does not significantly affect the PaLATE estimation between the two technologies.
- Between FDR and EAS, FDR uses less energy, releases less CO_2 and CO compared to EAS. Due to the different pavement designs for these two rehabilitations, both techniques are adequate to provide rehabilitation on pavement exhibit structural distresses.
- Overlay material contribute significant energy use and emission in the analysis.
- Concrete overlay consumed less energy and but more greenhouse gas emission as shown from the PaLATE results compared to asphalt overlay.

A numerical comparison of each environmental impact shown in Appendix E was made. Equation 1 was developed to determine the percentage of savings for a pavement rehabilitation alternative relative compared to M&O.

$$\left(1-\frac{Alt\_E.I.}{M\&O\_E.I.}\right)\times 100\% \qquad (1)$$

Where:
Alt_E.I. = Environmental Impact (CO_2, CO, Energy, SO_2, or NO_x) of an alternative
M&O_E.I. = Environmental Impact (CO_2, CO, Energy, SO_2, or NO_x) for mill and overlay rehabilitation

Equation 1 is used on all the environmental impact quantities to determine the relative savings percentages. Table 7 shows the results of equation 1 calculated from Table 41, note that HIR was excluded as the PaLATE output for HIR seems incorrect.

Table 7: Relative Savings of Pavement Rehabilitations

Rehabilitation	**Energy**	**CO_2**	**NO_x**	**SO_2**	**CO**	**Average**
CIR	51%	50%	51%	60%	46%	52%
CIREAM	52%	51%	51%	61%	47%	52%
EAS	28%	25%	34%	58%	13%	32%
FDR	30%	30%	30%	31%	30%	30%
M&O	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
M&O w RAP	16%	17%	9%	0%	19%	12%
Rubblization	22%	21%	18%	23%	20%	21%
Concrete Overlay	44%	-64%	-136%	93%	-234%	-59%
WMA M&O	29%	43%	48%	30%	-[1]	38%

[1] *Note the CO Savings for WMA M&O was not analyzed due to insufficient data available to differentiate CO emission from WMA and HMA; hence it is marked as - in* Table 7.

As shown in Table 7, it is evident that CIR and CIREAM produced half of the environmental impacts as compared to M&O. Hence, it can be concluded that CIR and CIREAM are the most sustainable pavement rehabilitation in the analysis for asphalt pavement. FDR and EAS yield 30% less environmental impact than M&O. WMA saves an average of 38% in environmental impact. Concrete overlays generate more CO_2, NO_x and CO compared to M&O. However, it should be noted that the rehabilitation processes presented in Table 7 have different performance service lives. Therefore, the PaLATE results only account for environmental impact during pavement construction or rehabilitation. Hence, the results from Table 41 should be interpreted as one-dimensional parameters that estimate the environmental impact produced during construction or rehabilitation for a typical one kilometre, 2 lane highway.

For new pavement construction, it is difficult to establish a control option for comparison because asphalt and concrete are two distinct materials that have unique performance characteristics and service lives. The environmental evaluation of new construction compares asphalt pavement and concrete pavement. Emissions and energy output for construction projects are shown in Figure 35 to Figure 39 in Appendix F. The PaLATE results for construction are categorized by material type: concrete, asphalt, OGDL, and granular.

The purpose for compiling PaLATE workbooks for pervious concrete, porous asphalt, and the use of RCA in concrete pavement are to evaluate emission differences during construction between these options versus the conventional asphalt or concrete pavement. Appendix E shows the numerical results from the PaLATE evaluation for pavement new construction.

These results in Appendix E indicate PaLATE output tends to favour asphalt pavements because of the lower energy use and emissions output during construction. However, it is important to note that sustainability is not solely emphasized on the environment. The agency should keep in mind that

- Performance service lives of concrete pavement and asphalt pavement are different.
- The impact of social cost should be considered. For example, traffic loading (ESALs) is an important factor in the selection of asphalt or concrete pavement for new construction. In addition, the frequency of preservation activities over the pavement service life is directly related to social cost.

- In terms of economic cost, life cycle cost of the pavement is also an important consideration for the agency.
- It is observed that concrete material itself generate more emissions and consume more energy that asphalt and granular combined at individual project perspective. Based on the analysis assumption that the transportation distance for all materials is equal, it is concluded PaLATE estimates concrete material manufacturing generate more emissions and consume more energy.

A life cycle analysis using PaLATE was conducted for asphalt and concrete pavements over a life cycle. The purpose of the life cycle analysis is estimating energy and emission quantities over a specific life time of the pavement. Previously, emissions and energy are considered on individual construction or rehabilitation at project level basis. Appendix G shows the result of the life cycle analysis in bar chart form. The life cycle analysis estimates energy and emissions using life cycle schedule suggested in the MTO LCC report 2005 [Lane, 2005]. The life cycle schedule considers a 50 years analysis. Table 8 shows the life cycle schedule that listed the necessary rehabilitations for asphalt and concrete pavement construction over the course of 50 years [Lane, 2005]. Table 9 shows the total energy and emission estimations from PaLATE for a typical 1-kilometre two-lane highway.

Table 8: 50 Years Life Cycle Schedule for Energy and Emissions

Year	Asphalt Pavement	Year	Concrete Pavement
9	Mill 40mm, Patch 40mm Asphalt	18	Full and Partial Depth Concrete Repair
15	Mill 40mm, Patch 40mm Asphalt	28	Full and Partial Depth Concrete Repair
19	Mill 80mm, Patch 80mm Asphalt	38	Patch 40mm Asphalt
27	Mill 40mm, Patch 40mm Asphalt		
31	Mill 80mm, Patch 80mm Asphalt		
38	Mill 40mm, Patch 40mm Asphalt		
42	Mill 80mm, Patch 80mm Asphalt		
48	Mill 40mm, Patch 40mm Asphalt		

Table 9: Total Energy and Emission Estimates for 50 Years

Quantities	Asphalt	Concrete
Energy (MJ)	12,060,054	6,932,881
CO_2 (Mg)	640	545
SO_2 (kg)	5,258	6,638
NO_x (kg)	160,829	23,447
CO (kg)	1,876	3,192

The result from Table 9 is the summation of energy and emission quantities from Figure 40 to Figure 44. The estimation in Table 9 shows concrete consumes less energy, produces less CO_2 and SO_2 over 50 year life cycle. Asphalt emits less SO_2 and CO over the 50 years life cycle. Also concrete pavement has a longer initial service life than asphalt pavement as seen in Table 8 that concrete pavement receives its first rehabilitation at year 38; whereas first asphalt receives its first rehabilitation at year 19.

5.2 Economic Savings

For the economic quantification of pavement rehabilitation and construction, it can be broken down into two sub-quantifications: material savings, and life cycle cost analysis (LCCA).

5.2.1 Hot Mix Asphalt (HMA) Savings in Rehabilitation

For any road rehabilitation project, HMA materials contribute a largest portion to the project cost. Because the virgin aggregate supply in Ontario is limited and the cost of asphalt cement has direct correlation with oil price in the market, the conservation HMA material is one way to improve pavement sustainability. For economic quantification of rehabilitation, M&O is assumed as the control option. Based on the pavement thickness design input in PaLATE, it is possible to quantify HMA material savings associated with different rehabilitations.

Asphalt pavement rehabilitations are generally consisted of two parts: a process, and a HMA overlay. The rehabilitation processes are CIR, CIREAM, FDR, milling, etc. An overlay is adding one or two lifts of HMA on top of existing pavement. Table 10 summarizes the overlay thickness in millimetres requires for each rehabilitation method.

Table 10: Overlay Thickness for Rehabilitation Used in PaLATE Input

Rehabilitation Treatment	**Design Overlay Thickness (mm)**
Hot In-place Recycling (HIR)	50
Cold In-place Recycling (CIR)	50
Cold In-place Recycling with Expanded Asphalt Mix (CIREAM)	50
Full Depth Reclamation (FDR)	90
Expanded Asphalt Stabilization (EAS)	50
Mill and Overlay (M&O)	130
Mill and Overlay with Reclaimed Asphalt Pavement (M&O w RAP)	130
Rubblization	100
Mill and Overlay with Warm Mix Asphalt (WMA M&O)	130

Based on the overlay thicknesses in Table 10, the HMA material and cost savings can be calculated given the dimension of the overlay. In this analysis, the HMA savings are measured in tonnes because tonne is the unit of pricing for HMA material for all MTO projects. The conversion of HMA material from cubic metres to tonnes is shown in equation 2.

$$Tonnes = 2.48 \times \frac{1 Tonnes}{m^3} \times \left(L \times 2W \times \frac{T}{1000} \right) \quad (2)$$

Where:
L = Highway Length in metres
W = 1 Lane Width in metres
T = Pavement Thickness in millimetres

The constant of 2.48 in equation 2 is the averaged conversion factor for HMA material provided by MTO [OPSS 313-1, 2008]. Table 11 shows the result of HMA materials savings.

The percentage HMA saved is calculated by equation 3, which is essentially derived from equation 1.

$$\left(1 - \frac{Rehab\_HMA}{M \& O\_HMA} \right) \times 100\% \quad (3)$$

Where:
Rehab_HMA = Amount of HMA required for the rehabilitation
M&O_HMA = Amount of HMA required for mill and overlay

Table 11: HMA Material Savings

Technique	Tonnes Used	Tonnes Saved	% Saved
HIR: Overlay 50mm	868	1388.8	61.5%
CIR: Overlay 50mm	868	1388.8	61.5%
CIREAM: Overlay 50mm	868	1388.8	61.5%
FDR: Overlay 90mm	1562.4	694.4	30.7%
EAS: Overlay 50mm	868	1388.8	61.5%
Overlay 130mm (No RAP)	2256.8	0	0
Overlay 130mm with 20% RAP	1805.44	451.36	20%
WMA Overlay 130mm	2256.8	0	0

Table 12 converts the results from Table 11 into actual monetary value for HMA material. The economic cost of rehabilitation typically consists of two major components: Process, and Overlay. For the economic quantification in this project, cost data are extracted from MTO HiCO Database [HiCO, 2009]. HiCO stores the bidding cost breakdown for MTO projects. The unit costs in Table 12 are averages calculated from HiCO cost data. HiCO measures rehabilitation processes in m^2 and overlay in tonnes.

Table 12: Typical Economic Savings between Pavement Rehabilitation

Technique	Unit Price	Unit	Quantity	Price	Total	Total Savings	% Savings
HIR Process	$8.86	m^2	7000	$62,020	$165,173	$(143,624)	-47%
HIR: Overlay 50mm	$118.84	T	868	$103,153			
CIR Process	$9.60	m^2	7000	$67,200	$170,353	$(138,444)	-45%
CIR: Overlay 50mm	$118.84	T	868	$103,153			
CIREAM Process	$14.11	m^2	7000	$98,770	$201,923	$(106,874)	-35%
CIREAM: Overlay 50mm	$118.84	T	868	$103,153			
FDR Process	$1.43	m^2	7000	$10,010	$195,685	$(113,112)	-37%
FDR: Overlay 90mm	$118.84	T	1562.4	$185,675			
EAS Process	$4.36	m^2	7000	$74,830	$177,983	$(130,814)	-42%
EAS Overlay 50mm	$118.84	T	868	$103,153			
Rubblization	$4.36	m^2	7000	$30,520	$236,826	$(71,971)	-23%
Overlay 100mm	$118.84	T	1736	$206,306			
Mill Process 2	$5.80	m^2	7000	$40,600	$308,798	$ -	0%
100% V.A. Overlay 130mm	$118.84	T	2256.8	$268,198			
Mill Process 2	$5.80	m^2	7000	$40,600	$262,587	$(46,210)	-15%
80% V.A. Overlay	$118.84	T	1805.4	$214,559			
20% RAP	$16.46	T	451.4	$7,429			
Mill Process 2	$5.80	m^2	7000	$40,600	$316,133	$7,334	2%
WMA 100% V.A. Overlay 130mm	$122.09	T	2256.8	$275,533			

V.A. = Virgin Aggregate

Table 12 shows the comprehensive cost differences of asphalt rehabilitation alternatives. From Table 12, it is observed that WMA M&O is the most expensive alternative since an additional premium of $3.25 per tonne is added to the price of WMA material [Davidson, 2009]. M&O is the second most expensive alternative available. HIR is a 47% less expensive than M&O, it suggested Ontario should reconsider using HIR. CIR and CIREAM save 45% and 35% of the price respectively compared to M&O respectively.

Table 12 also shows adding RAP in the pavement is less expensive than using 100% virgin aggregates. This project purposely chooses 20% RAP content for analysis because RAP content beyond 20% requires adjustment to the asphalt cement gradation as suggested in the literature review.

5.2.2 Life Cycle Cost Analysis for Pavement Rehabilitation and Construction

Life Cycle Cost Analysis (LCCA) is important in the decision-making process for both project and network level pavement management. MTO typically chooses to implement the project alternative that has the lowest life cycle cost (LCC). Sustainable pavement also considers optimizing economic benefit for transportation agency. For LCCA with rehabilitation, typical pavement dimensions from PaLATE analysis are used.

The LCC of an alternative is the sum of pavement construction and preservation costs, minus its salvage value discounted to present worth value over a life cycle horizon. This project uses the deterministic approach to calculate LCC [Lane, 2005]. Equation 4 and 5 shows the equations to compute present worth and salvage value respectively.

$$PW_{TOT} = \left[\sum \left(C \times \left(\frac{1}{1+i}\right)^{n}\right)\right] - SV_{PW} \tag{4}$$

$$SV_{PW} = \left(\frac{L_{REM}}{L_{EXP}}\right) \times C \times \left(\frac{1}{1+i}\right)^{m} \tag{5}$$

Where:

PW_{TOT}	= Total Present Worth
SV_{PW}	= Salvage Value in Present Worth
m	= Analysis Period
n	= n^{th} Year of Implementation
L_{EXP}	= Expected Service Life, see Table 13

L_{REM} = Remaining Service Life = $L_{EXP} - (m - n)$
C = Cost of Rehabilitation/Construction
i = Discount Rate 5.3%

Table 13 summarizes the typical performance service life of the pavement rehabilitations listed in Table 12 [Chan, 2009], [Harrington, 2008].

Table 13: Typical Performance Service Life for Pavement Rehabilitation/Reconstruction

Technique	**Service Life (Years) (L_{Exp})**
HIR → Hot In-place Recycling + 1 lift Asphalt Overlay	12
CIR → Cold In-place Recycling + 1 lift Asphalt Overlay	15
CIREAM → Cold In-place Recycling with Expanded Asphalt + 1 lift Asphalt Overlay	15
M&O → Mill 2 lifts & Asphalt Overlay 2 lifts	14
Resurfacing →Asphalt Overlay 2 lifts	12
FDR → Full Depth Reclamation + 2 lifts Asphalt Overlay	10
EAS → Expanded Asphalt Stabilization + 2 lifts Asphalt Overlay	15
Concrete Overlay → Milling existing surface + 1 lift concrete overlay	15

Historically, M&O has been commonly used for pavement rehabilitation by many agencies. MTO has previously developed LCC schedules for pavement rehabilitation and reconstruction techniques as shown in Table 42 in Appendix H [Chan, 2009]. However, these LCC schedules can be modified to yield a lower LCC. Prior to the discussion of LCC schedule modification, one must understand the relationship of rehabilitation techniques and pavement distresses. Table 14 shows a matrix of different rehabilitations applicability against different distresses [Haas, 1997], [Fung, 2010].

Table 14: Pavement Rehabilitation Matrix against Different Distresses

	Cause of Pavement Distresses			
	Load	**Environmental**	**Material**	**Construction**
Pavement Rehabilitation	Reconstruction	Reconstruction	Reconstruction	Reconstruction
	CIR	CIR	CIR	
	HIR	HIR	HIR	
	CIREAM	CIREAM	CIREAM	
		M&O	M&O	M&O
		Resurfacing	Resurfacing	Resurfacing
	Concrete Overlay	Concrete Overlay	Concrete Overlay	Concrete Overlay

- Note FDR and EAS were not considered in Table 14 explicitly because they are referred as reconstruction
- Resurfacing is also referred as overlay

The costs of rehabilitation used in LCCA computation are shown in Table 12 and Table 45. The LCC schedule modification can be summarized in four steps:

1. Select control rehabilitation for each type of distresses (load, environmental, material, and construction) based on the information from Table 14, and then Table 42 shows the control LCC schedules.
2. Modify the LCC schedule from Table 42 by substituting less expensive rehabilitation alternatives after year zero. The modified LCC schedules are shown in Table 43.
3. Compute the LCC based on the schedules from Table 42 and Table 43.
4. Compare the cost difference from step 3 computation as shown in Table 44. Table 15 and Table 16 are reduced version of Table 44 that summarizes the LCCA.

Table 15: Summary of Net Present Worth Calculation for Asphalt Rehabilitation

Option	Control	M&O	M&O	Control	CIR	Control FDR	FDR	Control EAS	EAS
Rehabilitate with		CIR	O2	M&O	CIR	M&O	CIR	M&O	CIR
Total NPW	$535,234	$431,588	$512,699	$376,036	$228,982	$412,270	$318,476	$393,048	$300,773
Salvage Value	$49,190	$30,615	$28,482	$54,656	$33,167	$50,452	$30,615	$38,259	$30,615
Total – Salvage	$486,043	$400,972	$484,217	$321,379	$225,815	$361,817	$287,860	$354,789	$270,157
Cost Savings		-$85070	-$1825	-$65564		$73,957		$84,631	
% Savings		-18%	0%	-20%		-20%		-24%	

Table 16: Summary of Net Present Worth Calculation for Concrete Rehabilitation

Option	Control (M&O)	M&O
Rehabilitate with		Concrete Overlay
Total NPW	$535,234	$406,561
Salvage Value	$49,190	$27,337
Total – Salvage	$486,043	$379,224
Cost Savings		$106,818
% Savings		-22%

CIR is clearly a more economical alternative than M&O. Table 15 clearly shows using CIR can provide a 20% saving over the pavement service life than using M&O. Table 16 shows concrete overlay on existing mill and overlay asphalt surface also provide economic advantage by 22% savings. Based on the 30 years LCCA, the use of resurfacing instead of M&O to rehabilitate construction related distress does not show any economic advantage. However, there still may be technical reasons to resurface. Overall the LCC of the pavement rehabilitation can potentially provide up to 20% in cost savings. Although CIR and concrete overlay are very sustainable rehabilitation techniques, it should be noted that other constraints such as design, availability, and site conditions could affect the agency's selection of the proposed treatment.

5.2.3 Material Savings in New Construction

For new construction, flexible and rigid pavements are the two primary types of pavement structures managed by MTO. Surface treated roads are also a major type of pavement, but only flexible and rigid were considered in this evaluation. Due to performance and costing methodology difference in flexible and rigid pavements, total aggregates used in each of these pavements are compared. Unlike rehabilitations where the pavement overlay is the major factor, new construction requires consideration of all pavement layers above the subgrade. The total aggregates consumed are the sum of all aggregates used in surface course, granular base, and granular subbase. The aggregate quantities are taken from the PaLATE analysis. Table 17 summarized the aggregates used for each new construction technique. Note that the techniques suggested in Table 17 have different performance service lives. Table 17 is another one-dimensional way to demonstrate the amount of material exhausted for different pavement construction techniques.

Table 17: Total Aggregates for Different Construction Technique

Construction	Layer	Material	Yd^3	Total Yd^3	Total m^3	Rounded
Asphalt Expressway	WC1	HMA	2746	8238	6300	6300
	WC2	OGDL	915			
	SB1	GRAN. A	4577			
Asphalt Arterial	WC1	HMA	1373	6408	4902	5000
	WC2	OGDL	915			
	SB1	GRAN. A	1373			
	SB2	GRAN. B	2746			
Concrete Expressway	WC1	CONC	2380	6042	4622	4700
	WC2	OGDL	915			
	SB1	GRAN. A	2746			
Concrete Arterial	WC1	CONC	1831	4119	3152	3200
	WC2	OGDL	915			
	SB1	GRAN. A	1373			
Pervious Concrete	WC1	CONC	2197	4028	3081	3100
	SB1	GRAN. A	1831			
Concrete with 30% RCA	WC1	CONC	2289	4577	3500	3500
	WC2	OGDL	915			
	SB1	GRAN. A	1373			
Porous Asphalt	WC1	HMA	915	5493	4203	4300
	WC2	OGDL	915			
	SB1	GRAN. A	3662			

Where:

WC1	=	Wearing Course 1
WC2	=	Wearing Course 2
SB1	=	Subbase 1
SB2	=	Subbase 2
HMA	=	Hot Mix Asphalt
GRAN. A	=	Granular A
GRAN. B	=	Granular B
OGDL	=	Open Graded Drainage Layer
CONC	=	Concrete

Based on the pavement design from PaLATE evaluations, Table 17 suggested that concrete pavement construction uses less aggregates than asphalt pavement. Flexible pavement design tends to have a thicker granular base; hence it increases the virgin aggregate content as shown in Table 17.

5.2.4 Life Cycle Cost Analysis for New Construction

A life cycle cost analysis was conducted to compare the economic difference of asphalt versus concrete construction through two equivalent expressway sections. As a side note, MTO initiated the alternative bid criteria in 2001 for new pavement constructions or reconstructions projects that have at least five 2-lane kilometres, one million ESALs within 5 years of construction [Lane, 2005]. The alternate bid criterion is an option for contractors to bid on either asphalt pavement design or concrete pavement design for tender. In the alternate bid criterion, MTO provides bid adjustment factors that correspond to asphalt and concrete pavement design to estimate the cost of maintenance and rehabilitation activities over the pavement life cycle [Lane, 2005]. The contractor then submits the construction bid for either asphalt or concrete pavement construction. The corresponding bid adjustment factor to reflect future pavement preservation activities is added to yield the total adjusted bid [Lane, 2005]. Under most circumstances, the contractor that submitted the bid with the lowest total adjusted bid is awarded the contract. Intuitively, total adjusted bid can be interpreted as a life cycle cost of a project. Because of alternate bid criterion provide flexibility in how funding can be spent during construction, it is important to examine the effect of the life cycle cost for new construction or reconstruction in the economic quantification of this project.

For simplicity of this project, pavement design used in PaLATE asphalt expressway and concrete expressway quantification previously are considered in the LCCA. The LCCA assumes a two lane highway that has pavement length of 1 kilometre and width of 3.5 metres per lane. Table 45 shows the price breakdown for different material used in rigid and flexible pavement construction [Lane, 2005]. Table 46 shows the LCCA results using the life cycle schedule shown in Table 8, material price from Table 45, equation 4, and equation 5. From the LCCA result, it shows the life cycle cost of constructing rigid pavement is approximately half of the flexible pavement equivalent. Rigid pavement can produce a significant life cycle cost saving because concrete pavement construction and rehabilitation have longer service life than asphalt pavement construction and rehabilitation.

5.3 Social Cost Identification

Although social cost is also an important sustainability component, it is difficult to quantify explicitly. For this task, a list of potential social costs was identified based on the output from CPATT/MTO Sustainable Pavement Workshop held on December 2008. This list of social cost does not specifically target any pavement construction or rehabilitation technique. Instead, it provides insights to develop a sustainable pavement rating system for Task 4. In order to achieve socially sustainable pavement, it requires the effort from the stakeholders and users. The numbered list below shows sixteen possible social cost items that should be considered.

1. Control emission in field construction.
2. Control emission in material manufacturing.
3. Long life pavement design (such as 50 years of service life design).
4. Illustrate material conservation.
5. Illustrate fuel conservation.
6. Material management through better stockpile and storage.
7. Material availability and accessibility awareness.
8. Labour availability and accessibility awareness.
9. Innovation such as: Future recyclability, new material, new technique, new design.
10. Investment in research and development, partner with universities.
11. Provide training and leadership role.
12. Quality assurance and quality control.
13. Proactive planning for new construction and rehabilitation.

14. Reduce user delay through proper lane closure, detour, staging design, proper construction access, reduce traffic interruptions.
15. Improve safety for travellers and workers.
16. Noise reduction in construction and traffic.

5.4 MTO Green Pavement Rating System, GreenPave

GreenPave is a separate project carried out by the Material Engineering Research Office of MTO. GreenPave is exclusively used by MTO to rate environmental sustainability at project level. GreenPave resembles GreenLITES, but with a sole emphasis on Ontario pavement experiences and current practices. GreenPave does not operate like LEED® or Greenroads because it is not a third party rating system that acts as a separate project entity. GreenPave also does not resemble the TAC Green Guide for Road Task Force because GreenPave is not a guideline for sustainable practice.

Ultimately, the implementation of GreenPave in the near future essentially marks the basis for design and construction of sustainable pavement practice in Ontario. Therefore, GreenPave is currently being promoted to the pavement industry and MTO senior management. In this project, GreenPave is used for the development of frameworks and indicators that can be used to assess pavement sustainability in the future.

The latest revision of GreenPave being assessed in this project was developed in June 2009. Table 18 shows the credits breakdown for GreenPave [Chan, 2009a]. The distribution of credits as shown in Table 18 is derived by MTO with industry partners during the GreenPave development. Table 19 shows the certification levels breakdown for GreenPave [Chan, 2009a].

Table 18: GreenPave Points Categories

Category	Point ID	Description	Max Credit
Pavement Technologies	PT-1	Long-Life Pavement Designs	3
	PT-2	Permeable Pavements	1
	PT-3	Quiet Pavements	3
	PT-4	Cool Pavements	2
Materials and Resources	MR-1	Recycled Content	6
	MR-2	Reuse of Pavement	3
	MR-3	Local Materials	3
	MR-4	Construction Quality	2
Energy and Atmosphere	EA-1	Reduce Energy Consumption	3
	EA-2	GHG Emission Reduction	2
	EA-3	Improve Rolling Resistance	1
	EA-4	Pollution Reduction	3
Innovation & Design Process	I-1	Innovation in Design	2
	I-2	Exemplary Process	2
Maximum Credits			36

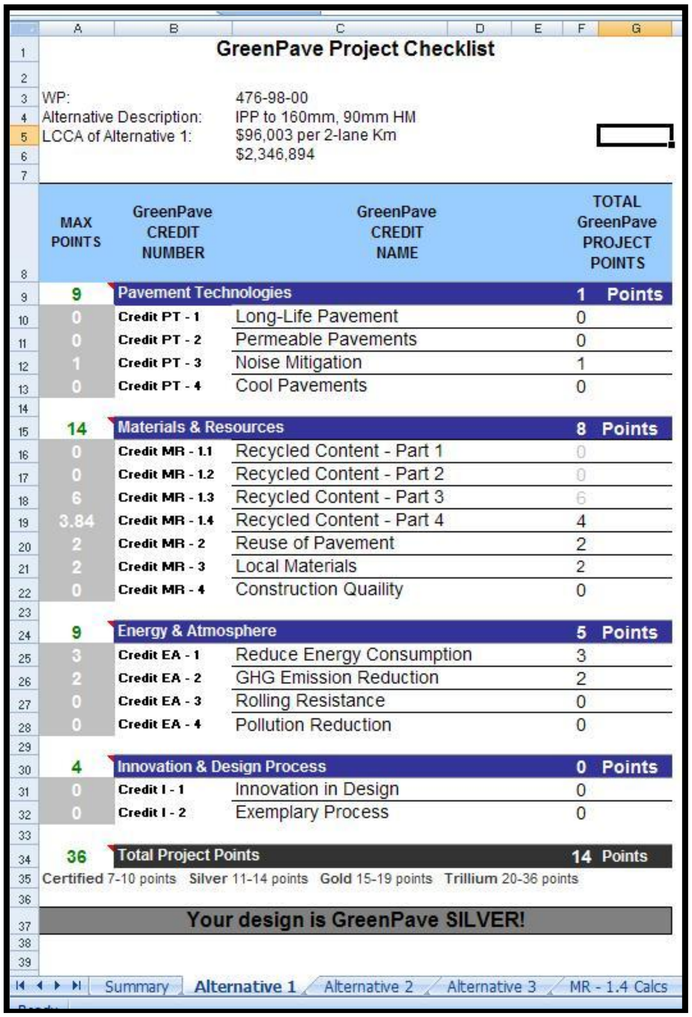
Table 19: GreenPave Certification Level

Level	Credits Required
Not Certified	< 7
Bronze	7-10
Silver	11-14
Gold	15-19
Trillium	20+

Extensive details of all the GreenPave credits will not be addressed in this report and project. In general, GreenPave credits can be divided into three themes: design credits, construction credits, and innovation credits. Design credits are awarded during the assessment of pavement design. Each design alternative proposed in a project will be assessed for design credits in GreenPave. Construction credits are awarded at the end of the construction. Innovation credits are awarded for sustainable practices that are not identified in GreenPave. It is important to note MTO is partnering with industry to ensure GreenPave Certification levels and point categories are appropriate and consistent with industry practices.

In a GreenPave evaluation of a project, the credits from each category are totalled where Table 19 shows five certification levels allowed in GreenPave. The minimum requirement for a project to become GreenPave certified is 7 GreenPave credits and it would result in an associated bronze certification.

From May 2009 to July 2009, CPATT has participated in the evaluations of various pavement designs using GreenPave with MTO. GreenPave evaluations are generally completed by MTO staff using the excel template shown in Figure 6. Individual project evaluations are not discussed in this report because GreenPave is only a tool that aids in developing indicators to measure pavement sustainability for this project. Figure 6 can be interpreted as the GreenPave scorecard in the form of a sample project evaluation result. Each GreenPave credit is shown on the scorecard in Figure 6. A summary of GreenPave project evaluations was compiled in October 2009 as attached in Appendix I [Thornton, 2009]. The information in Appendix I is used to develop indicators for project Task 5. However, some alternatives shown in Appendix I do not contain LCC because they were not proposed in the pavement design by consultants. Note the LCC from Appendix I are from design report, which does not represent contractual prices from MTO tender process. Figure 7 shows a sample GreenPave result from Appendix I [Thornton, 2009].



GreenPave Project Checklist

WP: 476-98-00
Alternative Description: IPP to 160mm, 90mm HM
LCCA of Alternative 1: $96,003 per 2-lane Km
$2,346,894

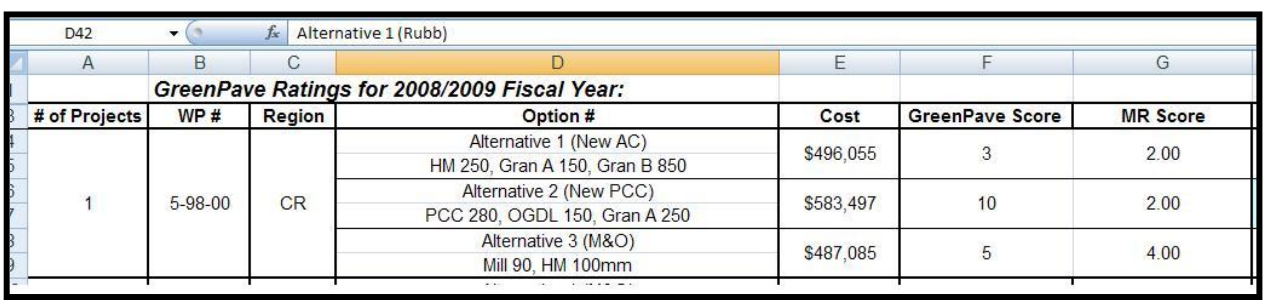
MAX POINTS	GreenPave CREDIT NUMBER	GreenPave CREDIT NAME	TOTAL GreenPave PROJECT POINTS
9	Pavement Technologies		1 Points
0	Credit PT - 1	Long-Life Pavement	0
0	Credit PT - 2	Permeable Pavements	0
1	Credit PT - 3	Noise Mitigation	1
0	Credit PT - 4	Cool Pavements	0
14	Materials & Resources		8 Points
0	Credit MR - 1.1	Recycled Content - Part 1	0
0	Credit MR - 1.2	Recycled Content - Part 2	0
6	Credit MR - 1.3	Recycled Content - Part 3	6
3.84	Credit MR - 1.4	Recycled Content - Part 4	4
2	Credit MR - 2	Reuse of Pavement	2
2	Credit MR - 3	Local Materials	2
0	Credit MR - 4	Construction Quaility	0
9	Energy & Atmosphere		5 Points
3	Credit EA - 1	Reduce Energy Consumption	3
2	Credit EA - 2	GHG Emission Reduction	2
0	Credit EA - 3	Rolling Resistance	0
0	Credit EA - 4	Pollution Reduction	0
4	Innovation & Design Process		0 Points
0	Credit I - 1	Innovation in Design	0
0	Credit I - 2	Exemplary Process	0
36	Total Project Points		14 Points

Certified 7-10 points Silver 11-14 points Gold 15-19 points Trillium 20-36 points

Your design is GreenPave SILVER!

Summary | Alternative 1 | Alternative 2 | Alternative 3 | MR - 1.4 Calcs

Figure 6: GreenPave Excel Template



D42 Alternative 1 (Rubb)

GreenPave Ratings for 2008/2009 Fiscal Year:

# of Projects	WP #	Region	Option #	Cost	GreenPave Score	MR Score
1	5-98-00	CR	Alternative 1 (New AC) HM 250, Gran A 150, Gran B 850	$496,055	3	2.00
			Alternative 2 (New PCC) PCC 280, OGDL 150, Gran A 250	$583,497	10	2.00
			Alternative 3 (M&O) Mill 90, HM 100mm	$487,085	5	4.00

Figure 7: Sample GreenPave Results Summary

Figure 7 shows a MTO project example that has three design options, suggested life cycle cost (LCC), the corresponding GreenPave score, and the material and resource (MR) score achieved during the evaluation.

Chapter 6
Project Level Indicator Development

GreenPave is simply an evaluation system that measures environmental sustainability of a pavement design alternative for a given project design at MTO. GreenPave credits score by an alternative does not consider its economic cost; hence it does not truly cover the entire scope of sustainability. Therefore, economic indicators must be combined with GreenPave credits to get an overall sustainability evaluation.

A simple way to better capture pavement sustainability through GreenPave is developing indicators. Two indicators are proposed to measure pavement sustainability for project level pavement management in this project: Green Discounted Life Cycle Cost (GDLCC) Type P, and Parameter D. Both indicators use mathematics to derive a value that measures pavement sustainability using the comprehensive GreenPave trial results provided in Appendix I. These indicators will act as a decision support tool for two primary purposes: pavement project selection in project level practice, and maintenance and rehabilitation (M&R) priority programming at the network level management.

6.1 Green Discounted Life Cycle Cost (GDLCC) Type P

The concept of GDLCC was originally suggested by MTO with GreenPave. GDLCC Type P is a project level indicator proposed by CPATT designed to measure pavement sustainability to further improve the sensitivity of GDLCC. Hence, the term "Type P" represents project level GDLCC. Equation 6 shows the original GDLCC equation suggested by MTO.

$$GDLCC = LCC - LCC \times 0.2 \times \left(\frac{GP}{36}\right) \tag{6}$$

Where:
LCC = Life cycle cost of an alternative suggested in a pavement design report
GP = GreenPave credits scored by an alternative

Equation 6 suggests that GDLCC is a discounted life cycle cost of an alternative. The amount of discount that an alternative can achieve is directly proportional to the amount of GreenPave credits (GP) scored on the alternative. The constant of 0.2 in equation 6 is suggested by MTO as a factor that controls the sensitivity of GDLCC. GDLCC demonstrates the economic aspect of sustainability by considering LCC of an alternative; and the environmental aspect of sustainability by considering the GreenPave credits of an alternative. Equation 6 demonstrates a linear mathematical relationship between LCC and GP credits. The lower the GDLCC of an alternative, the more sustainable the pavement practice.

The weakness of equation 6 is the low sensitivity of GDLCC suggested by the constant 0.2. For example, if a project has two alternatives where alternative 1 is more than 20% less expensive than alternative 2 in proposed LCC, then the GreenPave credits score by these two alternatives become irrelevant to make an impact in the GDLCC calculation because the cheaper alternative will always produce a smaller GDLCC from equation 6. Also, it is realistic in a pavement project to have design alternatives with a LCC difference of 20% or more. Therefore, equation 6 must be modified to improve sensitivity of GDLCC.

CPATT proposed the change to improve the sensitivity of GDLCC at the project level, as presented in equation 7 named GDLCC Type P.

$$GDLCC\_Type\_P = LCC - LCC \times \left(\frac{Min(10, MR)}{10}\right) \times \left(\frac{GP}{36}\right) \qquad (7)$$

Where:
MR = Materials and Resources credits achieve for an alternative in GreenPave

In equation 7, the 0.2 from equation 6 is removed and replaced with a 10% of Material and Resources (MR) credit of the design alternative from GreenPave. MR is a subset of GreenPave credits as illustrated in Table 18. A maximum of 14 credits can be achieved in the MR category as suggested in Table 18. In general, an environmentally friendly pavement design alternative should score high GreenPave (GP) credits in the evaluation with a high recycled and reused content. As a result, an alternative with a high GP score should correlate a high MR score of a project. Therefore, the high GP score alternative should yield a lower GDLCC using equation 7 than using equation 6. Appendix J contains plots that use information from GreenPave trials in Appendix I to demonstrate the difference between equation 6 and 7.

It is arguable that equation 7 is double counting the MR score component in GreenPave. Therefore, a regression analysis is conducted to determine the correlation between GP score and MR score in Excel as verification for this argument. Based on the assumption that a GP score is dependent on its MR score of a design alternative, linear, quadratic and cubic regression models were tested using Excel. The goal of regressions analysis is to find the best-fit correlation coefficient, R^2, value. Table 20 shows the regression result using the data given from Appendix I. Appendix J shows the regression plots from Excel.

Table 20: R-Square Result for Regression Analysis

Regression Model	**R^2**
Linear (1st Degree)	0.76
Quadratic (2nd Degree)	0.76
Cubic (3rd Degree)	0.81

The results in Table 20 show an increase in the R^2 value as the degree of the regression model increases. This phenomenon represents the data can be fitted better with a higher degree polynomial regression. However, it is more important to observe how the regression model fits the data visually through examining the shape of the trendlines in Appendix J. Nevertheless, the results in Table 20 do not provide a very strong correlation result with a R^2 value of approximately 0.80. Therefore, it can be concluded that GP score is not strongly dependent on MR score even though MR score is a subset of GP score.

6.1.1 Calculation Example for GDLCC Type P

This section shows a numerical example for the computation of GDLCC Type P. Consider an asphalt rehabilitation project with the data given in Table 21 from project WP# 403-98-00 [Thornton, 2009]:

Table 21: GDLCC Type P Data for Asphalt Rehabilitation

Alternative	**Description**	**LCC**	**GreenPave**	**MR**
1	50mm Hot Mix Overlay	$169,000	6	5
2	FDR + 60mm HM Overlay	$189,300	16	9.8
3	150mm EAS + 50mm HM Overlay	$156,900	16	9.5
4	Remove HM, add 50mm Gran. A + 100mm HM	$226,800	5	4

By observing the pavement design data from Table 21, it shows:

- Alternative 1 seems to provide quick and easy solution, low GreenPave and low MR credits
- Alternative 2 seems to utilize in-place recycling, high GreenPave and MR Scores
- Alternative 3 seems to utilize in-place recycling and has the lowest LCC
- Alternative 4 seems to utilize most material, low GreenPave and MR Scores

GDLCC Type P is computed for all four alternatives using equation 7.

For Alternative 1, start from equation 7

$$GDLCC\_Type\_P \;= LCC - LCC \times \left(\frac{Min(10, MR)}{10}\right) \times \left(\frac{GP}{36}\right)$$

$$GDLCC\_Type\_P \;= \$169000 - \$169000 \times \left(\frac{Min(10,5)}{10}\right) \times \left(\frac{6}{36}\right)$$

$$GDLCC\_Type\_P \;= \$154916$$

For Alternative 2

$$GDLCC\_Type\_P \;= \$189300 - \$189300 \times \left(\frac{Min(10,9.8)}{10}\right) \times \left(\frac{16}{36}\right)$$

$$GDLCC\_Type\_P \;= \$106849$$

For Alternative 3

$$GDLCC\_Type\_P \;= \$1569000 - \$1569000 \times \left(\frac{Min(10,9.5)}{10}\right) \times \left(\frac{16}{36}\right)$$

$$GDLCC\_Type\_P \;= \$90653$$

For Alternative 4

$$GDLCC\_Type\_P \;= \$226800 - \$226800 \times \left(\frac{Min(10,4)}{10}\right) \times \left(\frac{5}{36}\right)$$

$$GDLCC\_Type\_P \;= \$214200$$

From the above calculation, it is observed that:

- Clearly, alternative 3 is the most sustainable alternative in the calculation with the lowest GDLCC Type P.
- Alternative 2 is more expensive than alternative 3 for LCC in Table 21, but it still deemed to be a sustainable option.

- Alternative 2 suggests that it is a more sustainable than alternative 1 as show by the lower value of GDLCC, though the original LCC of alternative 1 is less expensive than alternative 2.

6.2 Parameter D

Parameter D is an indicator developed by the CPATT research team to measure pavement sustainability at the project level. It also utilizes LCC and GP credits of a design alternative. The development of D is initiated by the weak sensitivity of GDLCC in equation 6 during the early stage of GreenPave trials. The ultimate goal of D is essentially the same as GDLCC: to provide a simple and sensitive way to assess pavement sustainability at project level for MTO.

D is again developed using simple mathematics, namely through the Pythagorean Theorem. The original parameter D is calculated by transforming GP credits and LCC into x and y Cartesian coordinates using equation 8 and 9 respectively.

$$x = 1 - \left(\frac{GP}{36}\right) \tag{8}$$

$$y = \frac{alt\_LCC}{Max(alt\_LCC)} \tag{9}$$

Where:
Alt_LCC = Life cycle cost of an alternative in a project (taken from pavement design report)
Max(alt_LCC) = Alternative that has the highest life cycle cost in a project (taken from pavement design report)

Equation 8 and 9 convert GP credits and LCC into fractions with arithmetic. Equation 8 suggests the smaller value of x is calculated from a higher GP credits. On the other hand, equation 9 suggests the smaller value of y is resulted from lower LCC in a project alternative. Then parameter D is calculated using Pythagorean Theorem using x and y as shown in equation 10.

$$D = \sqrt{x^2 + y^2} \tag{10}$$

D value is simply the distance of x and y coordinates from the origin, or often referred as square-root of the sum of the squares. From a mathematical perspective, the smaller value of

D suggests the alternative has a higher degree of pavement sustainability. Moreover, D may be plotted using a spreadsheet to determine how different alternatives are ranked in terms of sustainability. By computing D using the results in Appendix I, a series of D value can be plotted as shown in Figure 8. Note Figure 8 only shows four asphalt rehabilitation alternatives from Appendix I to illustrate the graphical representation of D. Table 22 shows the corresponding x, y, and D value for Figure 8.

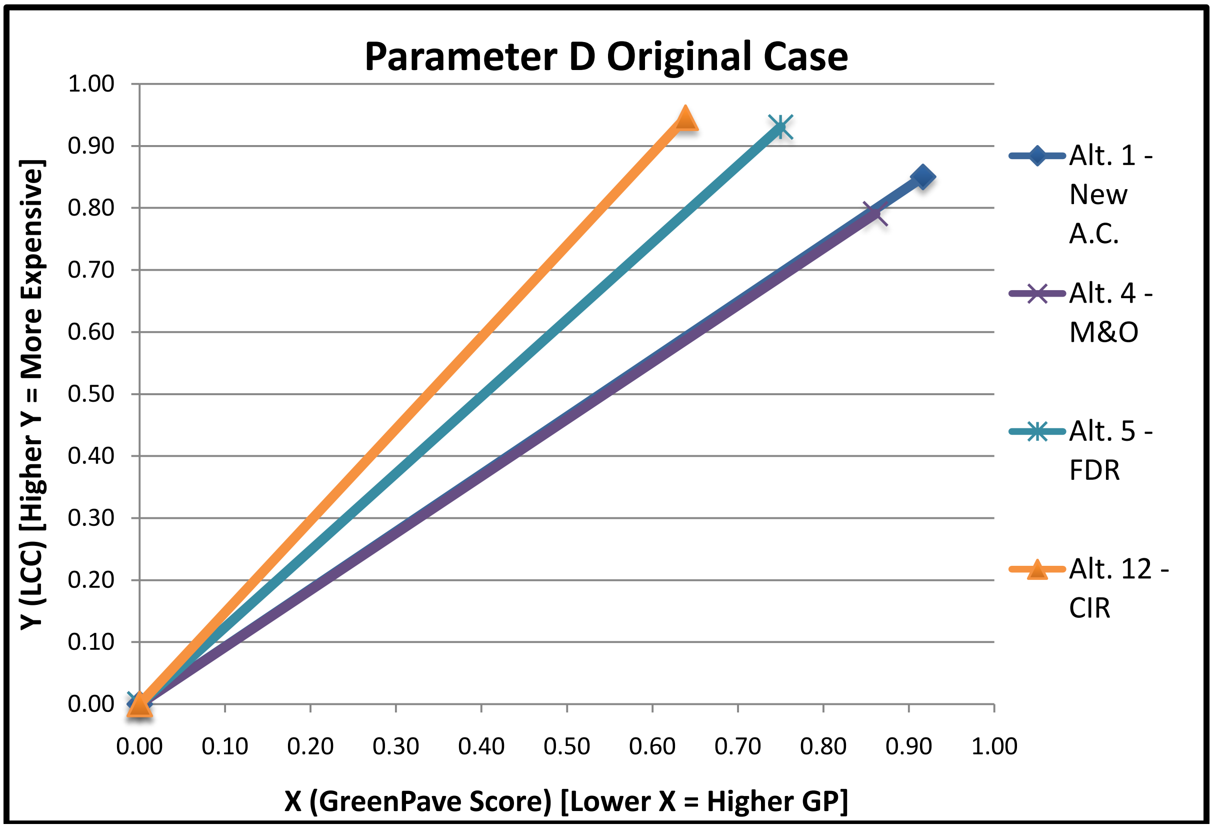


Figure 8: Graphical Representation of Parameter D

Table 22: Data Table for Figure 8

Vector Name	X (Equation 8)	Y (Equation 9)	D (Equation 10)
Alt. 1 – New A.C.	0.917	0.850	1.250
Alt. 4 – M&O	0.861	0.791	1.169
Alt. 5 – FDR	0.750	0.931	1.195
Alt. 12 - CIR	0.639	0.946	1.141

Where:
A.C. = Asphalt Concrete

As shown by the four alternatives in Figure 8 and Table 22, it is not evident which alternative is most sustainable. Overall, Figure 8 suggests equation 8 and 9 are not very sensitive because they under-utilize the entire spectrum on the vertical and horizontal axis. Modifications to increase the sensitivity of equation 8 and 9 are necessary to further distinguish the sustainability of the alternatives.

Based on the information provided in Table 18 and equation 8, a project alternative with 18 GP credits would yield an x value of 0.5. Although no evidence suggests it is impossible to score 18 GP credits for an alternative, Table 19 suggests the trillium level certification only requires minimum of 20 GP credits. In addition, it is impossible for an alternative to score all 36 GP credits because there are credits in GreenPave that specifically target construction or rehabilitation project components [Chan, 2009a]. Therefore, it may be inappropriate to use 36 as the denominator in equation 8.

However, this denominator from equation 8 can be changed to different values to better reflect the project information. For sensitivity analysis, proposed denominators of 20 and 25 as shown in equation 11 and 12 respectively as a revised equation 8.

$$x = 1 - \left(\frac{Min(GP, 20)}{20} \right) \tag{11}$$

$$x = 1 - \left(\frac{Min(GP.25)}{25} \right) \tag{12}$$

Equation 11 suggests if a project alternative achieves a 20 GP credits or more, the x value that will be substituted into equation 10 becomes 0. The value 20 is selected as the denominator because minimum of 20 GP credits allow a trillium certification, which is the highest certification level that can be achieved in GreenPave.

Equation 12 works in the same manner as equation 11 but x only becomes 0 if a minimum of 25 GP credits are scored. The value 25 is chosen as a second sensitivity analysis scenario is because silver and gold level of certification are staggered by 5 GP credits difference suggested in Table 19. Table 23 shows results of x using equation 8, 11, and 12.

Table 23: Revised x Values

Equation Use	Equation 8	Equation 11	Equation 12
Parameter	**x**	**x**	**x**
Alt. 1 – New A.C.	0.917	0.850	0.880
Alt. 4 – M&O	0.861	0.750	0.800
Alt. 5 – FDR	0.750	0.550	0.640
Alt. 12 – CIR	0.639	0.350	0.480

Table 23 shows equation 11 that it produces the lowest x values and largest range of x values from the proposed equations. Therefore, equation 11 produces the most diverse result in rating the environmental aspect for a project alternative.

Figure 8 previously showed y values of the alternative computed by equation 7 ranges from 0.8 to 1.0. This phenomenon demonstrates the LCC range of pavement design alternatives in a project would likely to be within 20% difference, even though the alternatives suggested in Figure 8 come from different projects. Therefore, a modification to equation 9 is necessary to utilize the entire y-axis. Two scenarios are proposed to improve the sensitivity of y. Equation 13 and 14 demonstrate these two scenarios.

$$y = \left(\frac{alt\_LCC}{Max(alt\_LCC)} \right)^2 \tag{13}$$

$$y = \left(\frac{alt\_LCC}{Max(alt\_LCC)} \right)^4 \tag{14}$$

Equation 13 and 14 raise the exponent of equation 9 by 2 and 4 respectively. Since equation 9 always result a fraction less than 1, the exponent raises by equation 13 or 14 causes the lower LCC to produce a smaller y value. Table 24 shows y values using equation 9, 13, and 14.

Table 24: Revised y Values

Equation Use	Equation 9	Equation 13	Equation 14
Parameter	**y**	**y**	**y**
Alt. 1 – New A.C.	0.850	0.723	0.522
Alt. 4 – M&O	0.791	0.625	0.391
Alt. 5 – FDR	0.931	0.866	0.791
Alt. 12 – CIR	0.946	0.895	0.800

Table 24 shows that equation 14 is the most sensitive scenario for y represented by the largest range of y values. Although the maximum y value in Table 24 is calculated using equation 9 with value of 0.946, it is irrelevant because the agencies rarely choose the alternative with highest LCC.

Figure 9 shows the revised graphical representation of D using equation 11 and 14 for horizontal and vertical axis respectively. It clearly shows the sensitivity improvement as the different length for the D vectors are clearly distinguishable. Table 25 shows the corresponding numerical results for Figure 9.

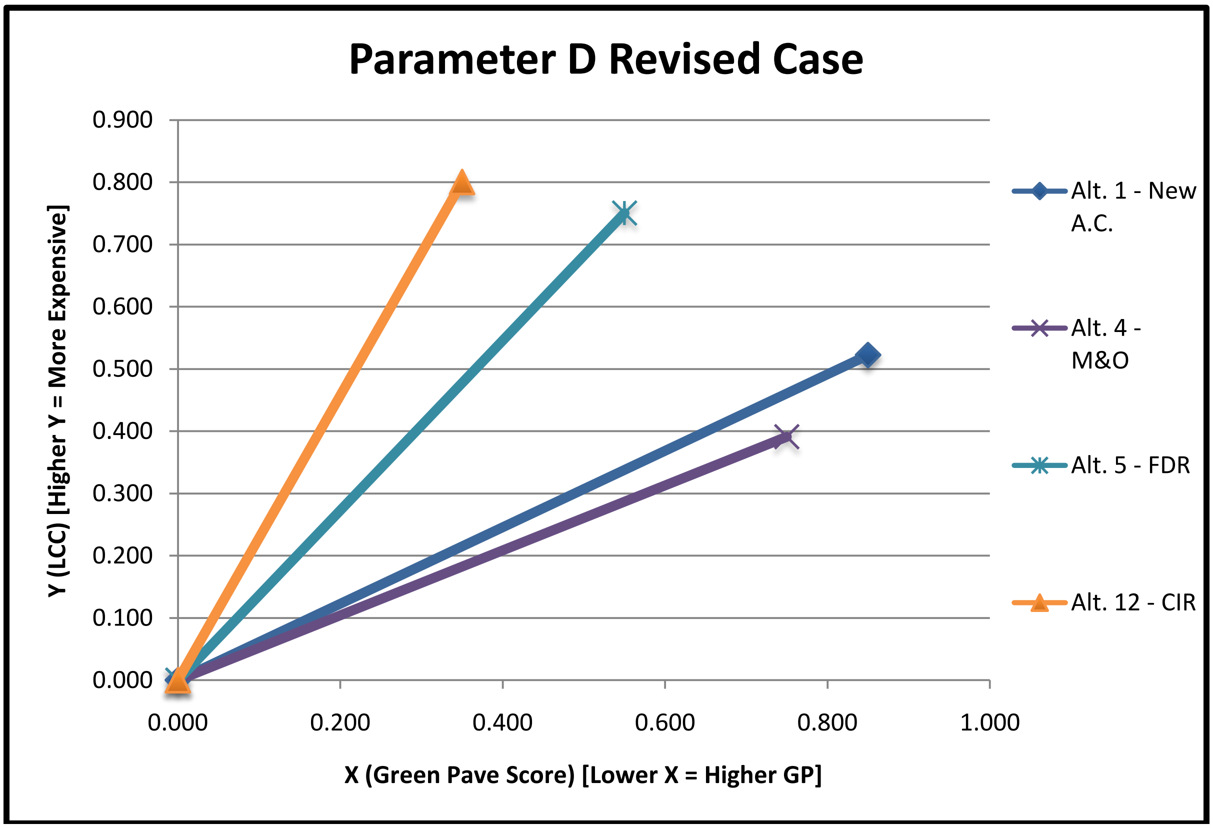


Figure 9: Revised Parameter D Results

Table 25: Revised D Values

Parameter	D
Alt. 1 – New A.C.	0.998
Alt. 4 – M&O	0.846
Alt. 5 – FDR	0.931
Alt. 12 – CIR	0.874

6.2.1 Calculation Example of Parameter D

The calculation of parameter D considers equation 10, 11, and 14 together. The example for the parameter D computation uses the same data as GDLCC Type P given in Table 21. First, the x component relating to GreenPave credits is calculated using equation 11.

$$x = 1 - \left(\frac{Min(GP, 20)}{20} \right)$$

Alternative 1

$$x = 1 - \left(\frac{Min(6, 20)}{20} \right) = 0.7$$

Alternative 2 and 3

$$x = 1 - \left(\frac{Min(16, 20)}{20} \right) = 0.2$$

Alternative 4

$$x = 1 - \left(\frac{Min(5, 20)}{20} \right) = 0.75$$

Second, the y component regarding LCC is calculated using equation 14.

Alternative 1

$$y = \left(\frac{169000}{226800} \right)^4 = 0.308$$

Alternative 2

$$y = \left(\frac{189300}{226800} \right) = 0.485$$

Alternative 3

$$y = \left(\frac{156900}{226800} \right) = 0.229$$

Alternative 4

$$y = \left(\frac{226800}{226800}\right) = 1.00$$

Table 26 summarizes the x and y components of the given project data. The data are substitute into equation 10 to calculate D.

Table 26: Parameter D data values

Alternative	**X**	**Y**
1	0.7	0.308
2	0.2	0.485
3	0.2	0.229
4	0.75	1.000

$$D = \sqrt{x^2 + y^2}$$

Alternative 1

$$D = \sqrt{0.7^2 + 0.308^2} = 0.765$$

Alternative 2

$$D = \sqrt{0.2^2 + 0.485^2} = 0.524$$

Alternative 3

$$D = \sqrt{0.2^2 + 0.229^2} = 0.304$$

Alternative 4

$$D = \sqrt{0.75^2 + 1.00^2} = 1.250$$

From the calculation of D, alternative 3 is the most sustainable alternative with the lowest D value. Figure 10 shows the visual representation of D for the alternatives from Table 21.

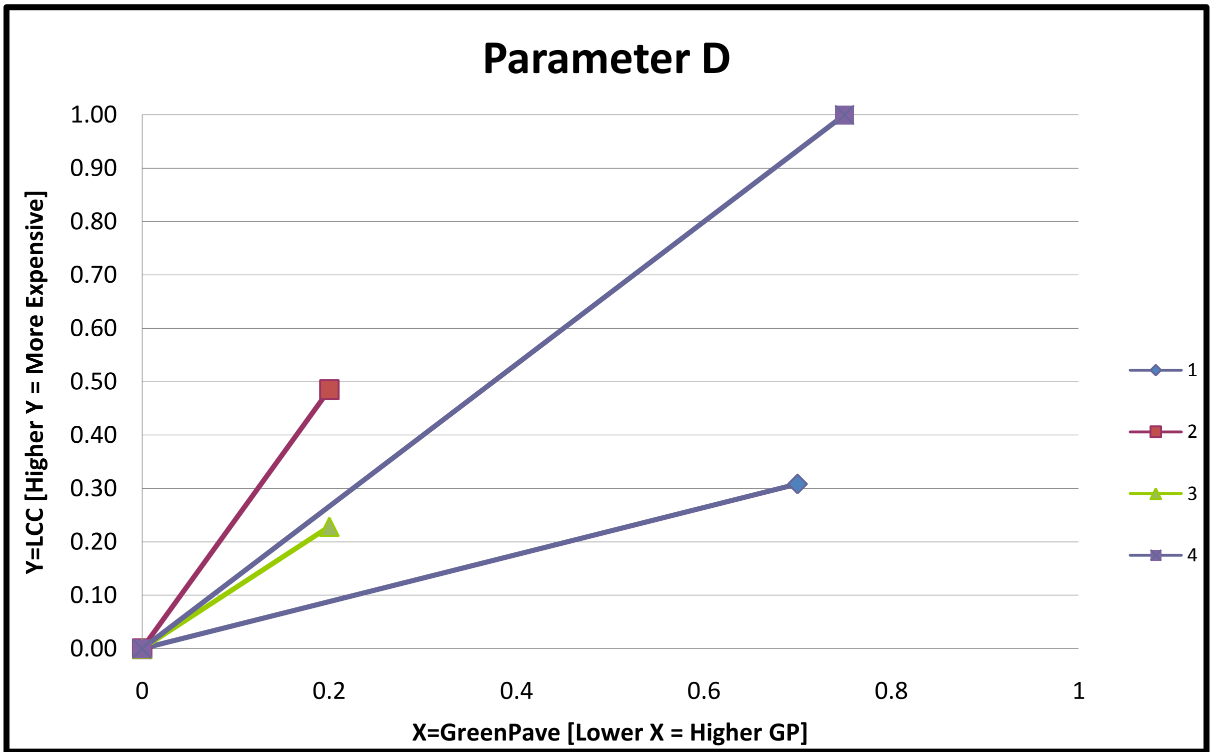


Figure 10: Parameter D plot for Project 403-98-00

Clearly, from Figure 10 above, alternative 4 has the longest vector and alternative 3 has the shortest vector. The numerical value of D is a one-dimensional indicator that is unable to capture the entire picture for pavement sustainability. A fictitious example can demonstrate the importance of visual representation of D. Table 27 considers a different set of data for a fictitious example of parameter D. The corresponding x, y, and D values are shown in Table 28.

Table 27: Fictitious Example for Parameter D

Alternative	*Description*	*LCC*	*GreenPave*
1	*CIR +50mm Hot Mix Overlay*	*$207450*	*14*
2	*FDR+60mm HM Overlay*	*$180367*	*13*
3	*150mm EAS + 50mm HM Overlay*	*$168407*	*21*
4	*Remove HM, add 50mm Gran. A + 100mm HM*	*$226,800*	*5*

Table 28: Results for D by fictitious example

Alternative	*X*	*Y*	*D*
1	*0.3*	*0.700*	***0.762***
2	*0.35*	*0.400*	***0.532***
3	*0*	*0.304*	***0.304***
4	*0.75*	*1.000*	***1.250***

The D value from Table 28 shows in the fictitious case is the same as the original case in Table 26. However, Figure 11 shows the graphical representation of the fictitious case, which demonstrates the difference between the alternatives.

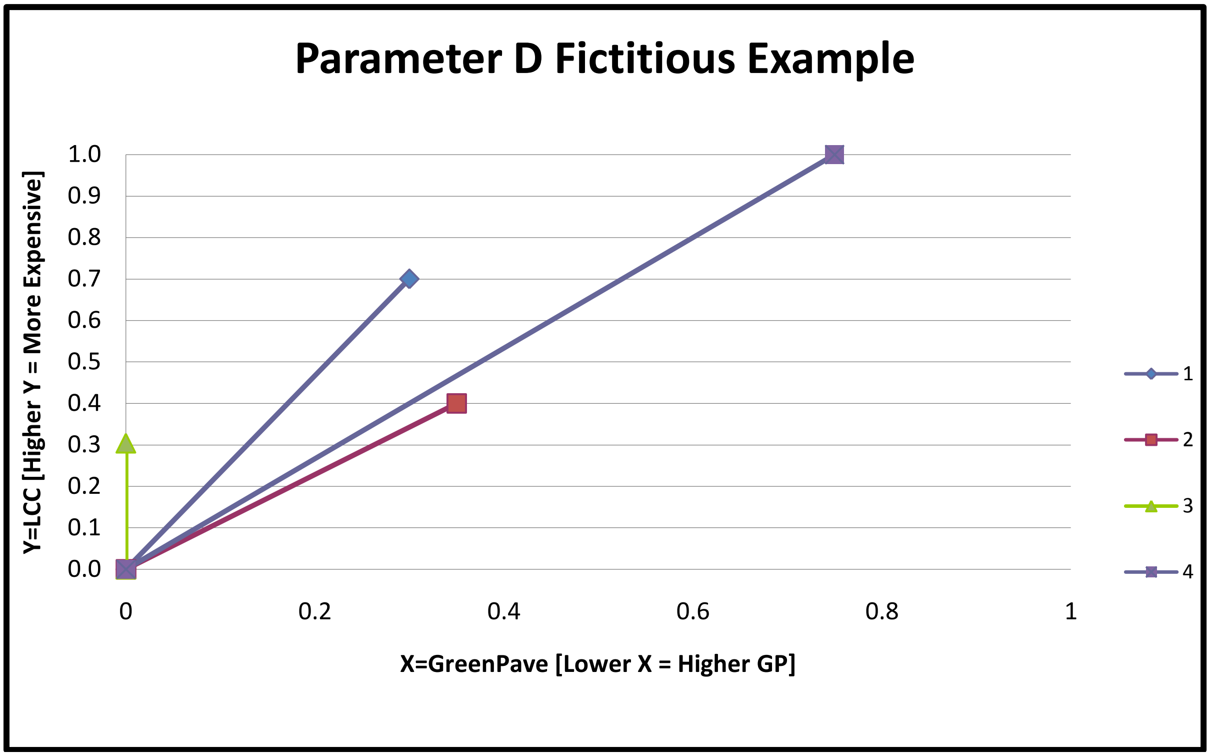


Figure 11: Fictitious Case of Parameter D

As shown in the plot above, alternative 4 was kept the same as a control alternative. All other alternatives lie in different regions of the plot compared to Figure 10. Although alternative 3 is still the most sustainable option available as shown in Figure 11, users of parameter D should plot the vectors for the alternatives to truly reflect the sustainability performance of different alternatives.

6.3 Interpretation of Sustainable Pavement Indicator in Project Level

Both GDLCC Type P and parameter D attempt to provide a simple measure of sustainability for a project alternative. These indicators are decision support tools the agency should consider in their project level decision making, budget planning, and priority programming activities. GDLCC Type P and parameter D work using different basis of mathematics to correlate economic and environmental aspects of a pavement design alternative. In an everyday project level decision making process, social costs are very implicit and difficult to quantify numerically. Therefore, numerical social costs at the project level would require additional research effort that is beyond the scope of this research.

Users should also be aware of the differences between GDLCC Type P and parameter D when calculating these indicators. The advantages of GDLCC Type P include:

- Simple arithmetic computation allows for easy changes of the equation to improve sensitivity of results or programmed into software.
- Results can be compared to LCC of the project.
- The sensitivity can be adjusted through manipulating GP and MR credits simultaneously.
- GDLCC Type P of alternatives are comparable within the same project only.

The advantages of parameter D include:

- It provides a balanced approach for comparing economic and environmental aspects of an alternative.
- It involves slightly more complex computation compared to GDLCC, yet it is still simple to program into the computer software.
- It is a standalone indicator, not a representation of life cycle cost. Therefore, economic aspect of the indicator (y component of parameter D) can be changed to represent other cost item such as tender price.
- The potential to develop thresholds between sustainable and not sustainable alternatives is possible as more evaluations are completed.
- A graphical representation can be presented for comparing among the alternatives.
- It is capable of assessing design alternatives within different projects in a given highway network.

Chapter 7
Network Level Pavement Sustainability and Indicator

In order to discuss the network level framework, the current state of the network level working practices and its relation to sustainable pavement are examined. The majority of the network level work at MTO revolves around MTO's pavement management system, PMS2. The role of PMS2 in this project is providing suggestions in maintenance and rehabilitation (M&R) alternatives for highway sections. Again, PMS2 is only a decision support tool that helps pavement engineers and managers at MTO in selecting a maintenance or rehabilitation alternative. PMS2 contains comprehensive databases that store many types of data. For this project, the relevant data in PMS2 can be categorized into two types:

1. Highway section data (location, stationing, highway class, direction, sectional, traffic)
2. Pavement data (rehabilitation need year, rehabilitation implementation year, rehabilitation cost, possible treatment models, effectiveness, ESALs, deterioration models)

In this research, the role of PMS2 focuses in generating M&R analysis for sustainable pavement practice at network level. The discussion of PMS2 in network level activities in this thesis is divided into two main parts: Conventional M&R Analysis; and Sustainable M&R Analysis. Conventional M&R analysis examines the state-of-practice of PMS2 by MTO. Sustainable M&R analysis proposes ideas to PMS2 to improve sustainability in network level planning and programming process.

7.1 Conventional M&R Analysis

This section discusses M&R Analysis practiced by MTO at network level using PMS2. In general, a M&R analysis in PMS2 operates in three main environments as shown in Figure 12. The next subsections discuss the work in each environment.

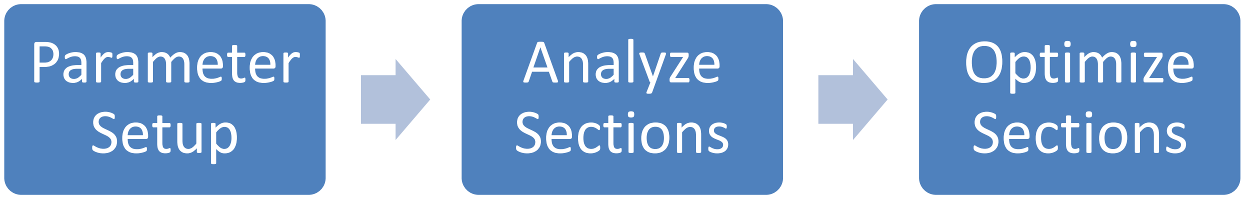


Figure 12: Work Environment in PMS2

7.1.1 Parameter Setup

The first step in the M&R analysis is to establish the constraints required for the M&R analysis. Figure 13 shows a screen capture of the necessary constraints for PMS2 M&R analysis.

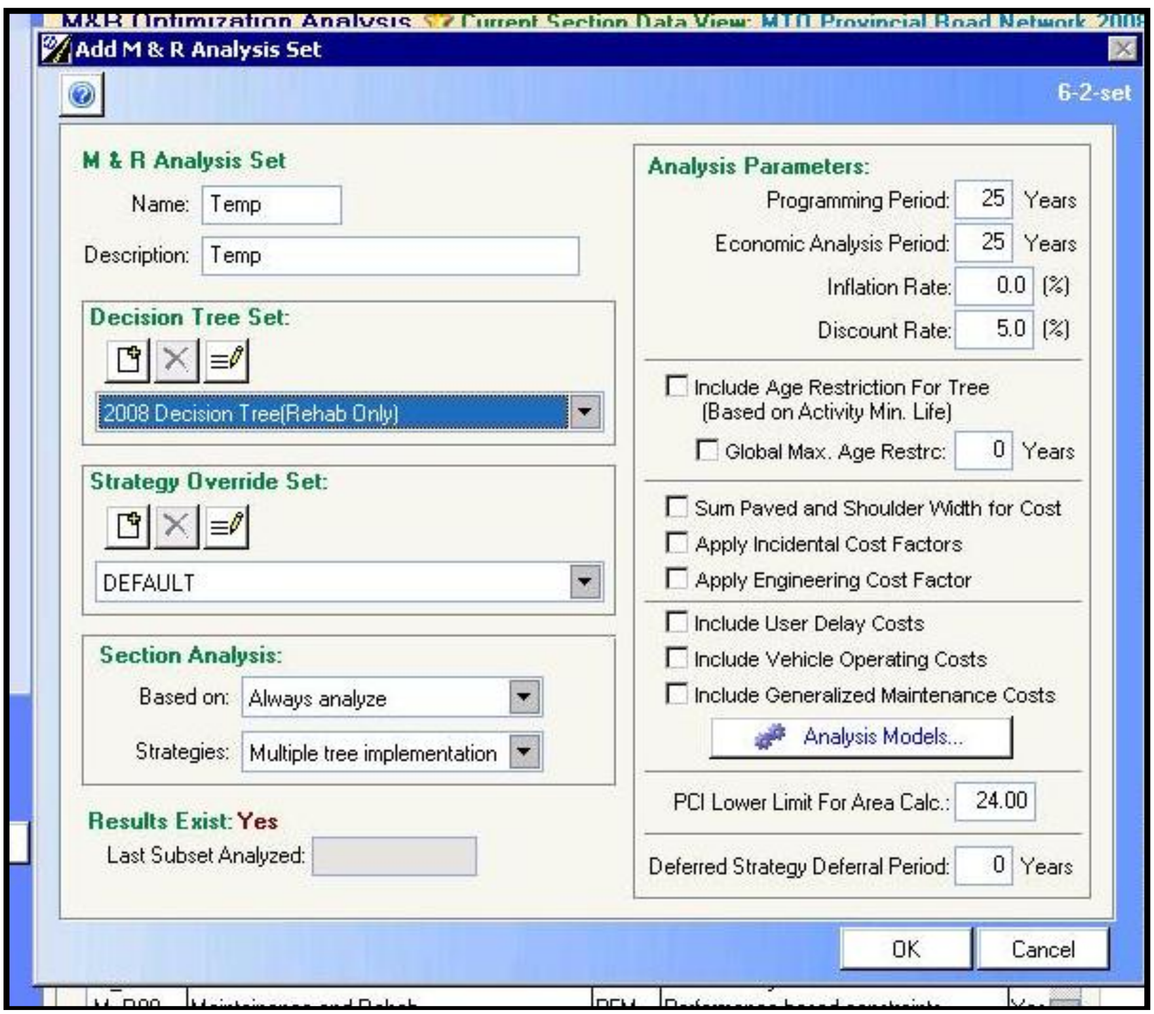


Figure 13: PMS2 Parameter Setup Screen

There are three main categories of information that are important in completing M&R analysis in PMS2: Decision Tree Set, Section Analysis, and Analysis Parameter.

Various decision tree sets are available in PMS2 to select for M&R analysis. These decision trees dictate what alternatives in PMS2 can be considered in the analysis. A decision tree set is a group of individual decision trees that based on a unique combination of road functional class and pavement type. For example, a decision tree set that considers four functional classes (freeway, arterial, collector, and local) and four pavement types (asphalt, concrete, composite, and surface treated) would have maximum of 16 individual decision trees. The default decision tree set in PMS2 is the "2008 Decision Tree (Rehab Only)".

For the section analysis, Figure 13 shows two combo boxes that need to be selected: Based On, and Strategies. These combo boxes control how the sections will be analyzed. For the "Based On" combo box, typically choose the "always analyze" option, which would consider all the sections in the selected highway regardless of pavement condition. For the "Strategies", there are three options available [MERO, 2006]:

1. Single Implementation – Considers rehabilitation only occurs once during the analysis period at a given section.
2. Repeated Implementation – Considers rehabilitation on a section that can occur more than once during the analysis period. The second treatment and initial treatment are the same. PMS2 interprets this type of implementation as one treatment that either implements together or discards together.
3. Multiple Tree Implementation – Similar to repeated implementation except PMS2 can considers a different treatment from the decision if the threshold is reached for a second rehabilitation.

Multiple Tree Implementation option should always be used as it considers more rehabilitation possibilities in the analysis.

Several analysis parameters can be set in PMS2 prior to the analysis of a highway section. The main inputs for analysis parameters are programming period, economic period, and discount rate. These parameters dictate the LCC proposed by PMS2 as shown in Table 29. Programming period in PMS2 represents the number of years considered for the M&R analysis [PMS2, 2009]. The economic analysis period in PMS2 dictates how many years the pavement deterioration models are considered in the M&R analysis [PMS2, 2009]. Table 29 summarizes the initial constraints for a typical M&R analysis in PMS2.

Table 29: Initial Constraints Setup for Typical M&R Analysis

Constraint Type	**Use**
Decision Tree	MTO 2008 Decision Tree
Section Analysis	Based on "Always Analyze" Strategy use "Multiple Tree Implementation"
Analysis Parameter	25 years Programming Period 25 years Analysis Period 5% Discount Rate

PMS2 begins the analysis once the constraints are defined. The analysis takes a few minutes to complete. Users should be aware that the duration of the analysis is affected by five factors:

1. Number of alternatives in the decision tree
2. Single Implementation versus Multiple Tree Implementation
3. Number of distinct highway sections selected for analysis
4. Programming and analysis period
5. Computer processing power and computer network stability

7.1.2 Analysis Sections

M&R analysis assesses different pavement rehabilitation alternatives available for a given highway section. The basic protocol of the M&R analysis in PMS2 is shown in Figure 14.

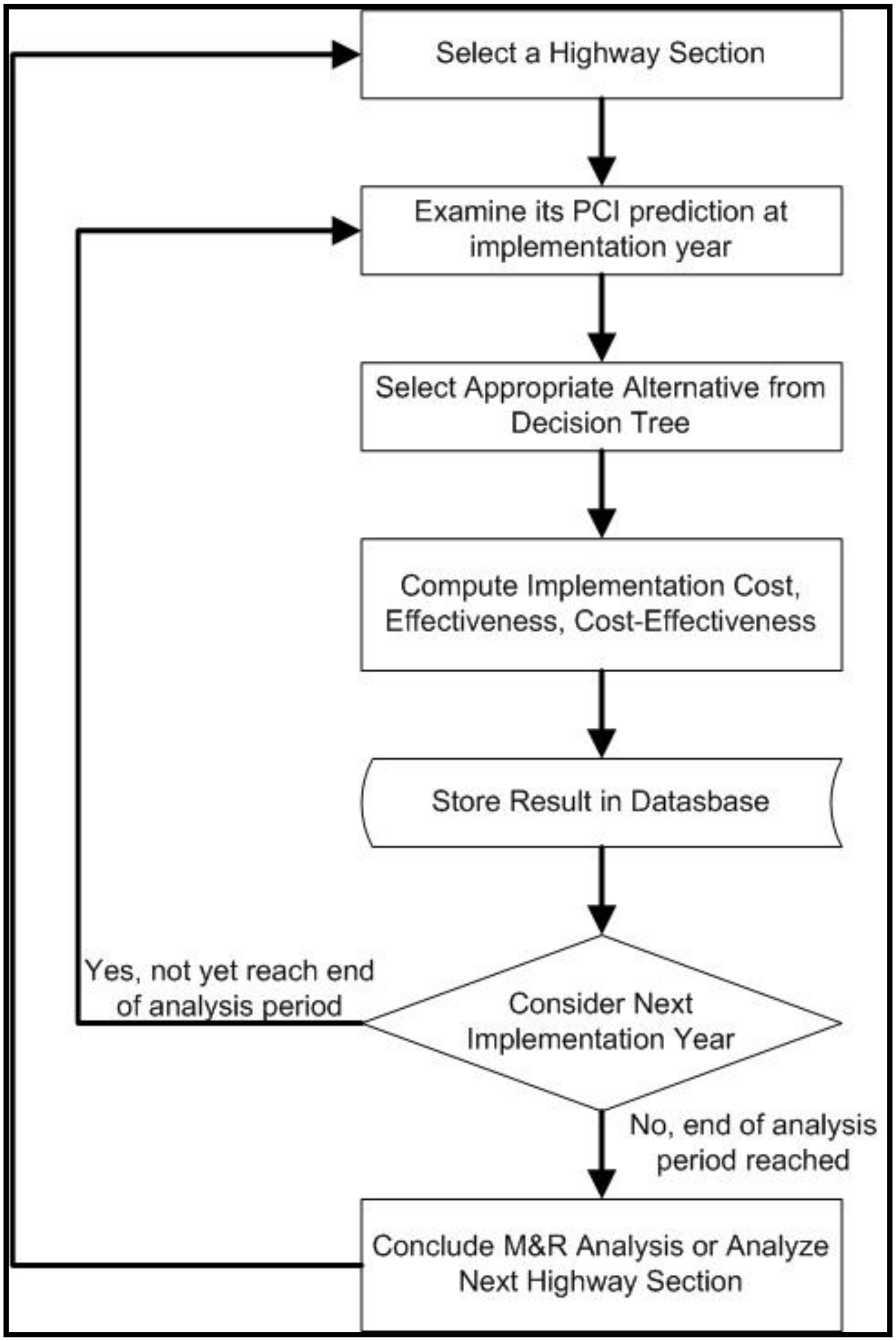


Figure 14: PMS2 Analysis Framework

PMS2 processes the sections using the protocol shown in Figure 14 internally and reports the results. The results are stored in PMS2 and it can be exported to Excel to produce a more user-friendly output for storage or future computations.

7.1.3 : Optimize Sections

PMS2 can optimize the analysis results in conventional M&R analysis. PMS2 has primarily two methods to optimize alternative: Performance Target, and Budget Constraints. Table 30 shows the comparison between the two optimization methods based on CPATT's experience working with PMS2.

Table 30: Breakdown of Optimization Methods

Method	Performance Target	Budget Constraint
Description	• Use PCI as governing factor • Select treatment based on highest cost-effectiveness given the chosen treatment satisfy PCI threshold	• Attempt to use up all available budget • Select treatment based on largest marginal cost-effectiveness until budget is exhausted given the treatment satisfy PCI threshold
Advantage	• Simple to understand and configure	• Good way to verify how to spend the funds available
Disadvantage	• May not be realistic without consideration of budget constraint	• Difficult to estimate budget available over analysis period • PMS2 effectiveness calculation not transparent or easily understood by user

Table 30 shows a comparison of the two optimization methods in PMS2. For this project, the budget constraints optimization will not be used because it is inappropriate for CPATT to propose budget constraints to MTO. Therefore, CPATT would only examine PMS2 optimization through performance target optimization. The performance target optimization method would typically select the alternative with the highest cost-effectiveness (CE) that was calculated in the analysis section phase. Cost-effectiveness is the quotient of effectiveness and cost as shown in equation 15.

$$CE = \frac{Effectiveness}{Cost} \qquad (15)$$

Effectiveness is the product of the area under curve of a PCI vs. Time plot, and an effectiveness factor. Internally, PMS2 has pavement deterioration models that predict the performance of different pavement treatments based on PCI and time for a given rehabilitation alternative. Figure 15 shows a sample graphical illustration of effectiveness from PCI vs. Time plot for a given pavement treatment.

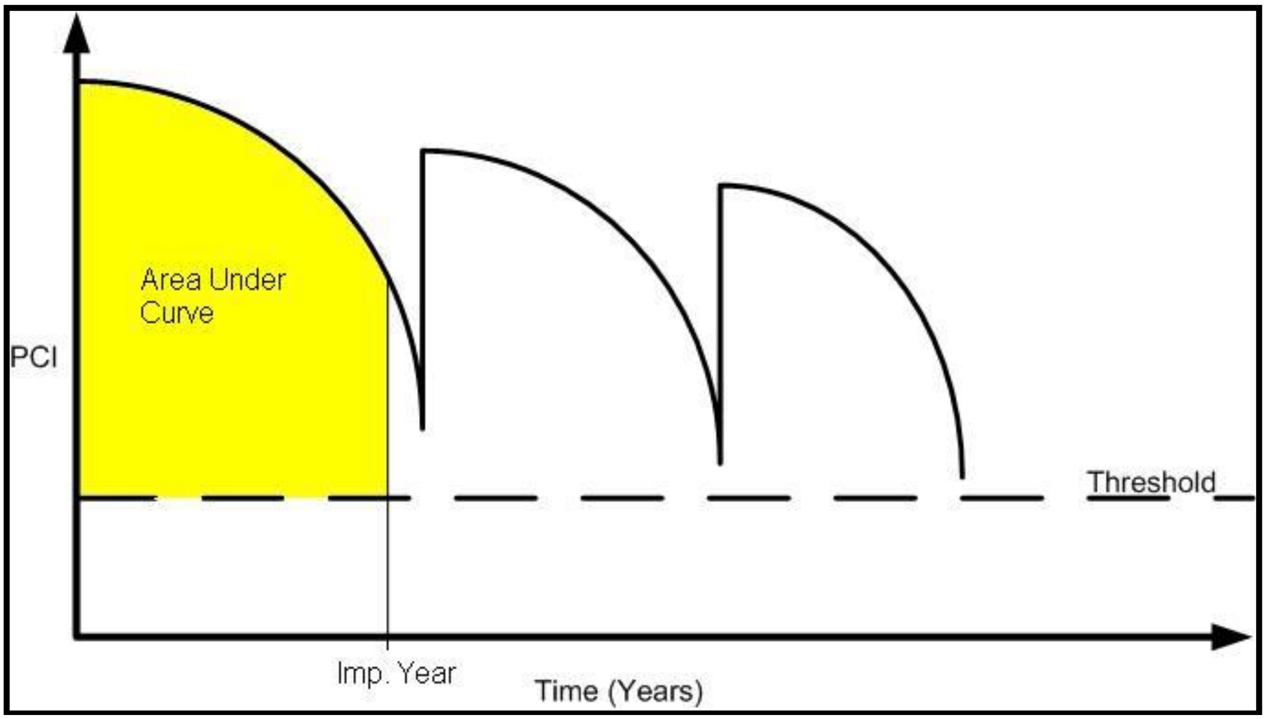


Figure 15: Sample Pavement Deterioration Model and Effectiveness

The area under curve from Figure 15 is multiplied by an effectiveness factor to arrive at the final effectiveness value. The effectiveness factor is a value that accounts for the annual average daily traffic (AADT) of a highway section. A highway section with a large AADT corresponds to a larger effectiveness factor. For example, if Highway A and Highway B have the same performance as shown in the area under curve suggested in Figure 15 but Highway A has more AADT than Highway B. Then it is more effective to rehabilitate Highway A before Highway B.

The cost in equation 15 is the implementation cost suggested by PMS2. The interpretation of implementation cost from PMS2 should be cautious. Implementation cost in PMS2 is the cost to implement initial treatment plus all the associated preservation activities throughout the analysis period. PMS2 expresses this implementation cost in terms of present worth value. If a zero percent discount rate is used in the M&R analysis, a highway section's implementation cost will be the same regardless of the implementation year within the analysis period given the same treatment is being implemented. This phenomenon contradicts the common belief that rehabilitation cost increases as the rehabilitation treatment is delayed due to worse pavement condition.

The performance distribution in PMS2 is another optimization constraint that needs to consider when working with performance target. Performance distribution controls the optimization result for the alternative based on PCI index. Figure 16 shows the screen capture of optimization constraints in PMS2 [PMS2, 2009].

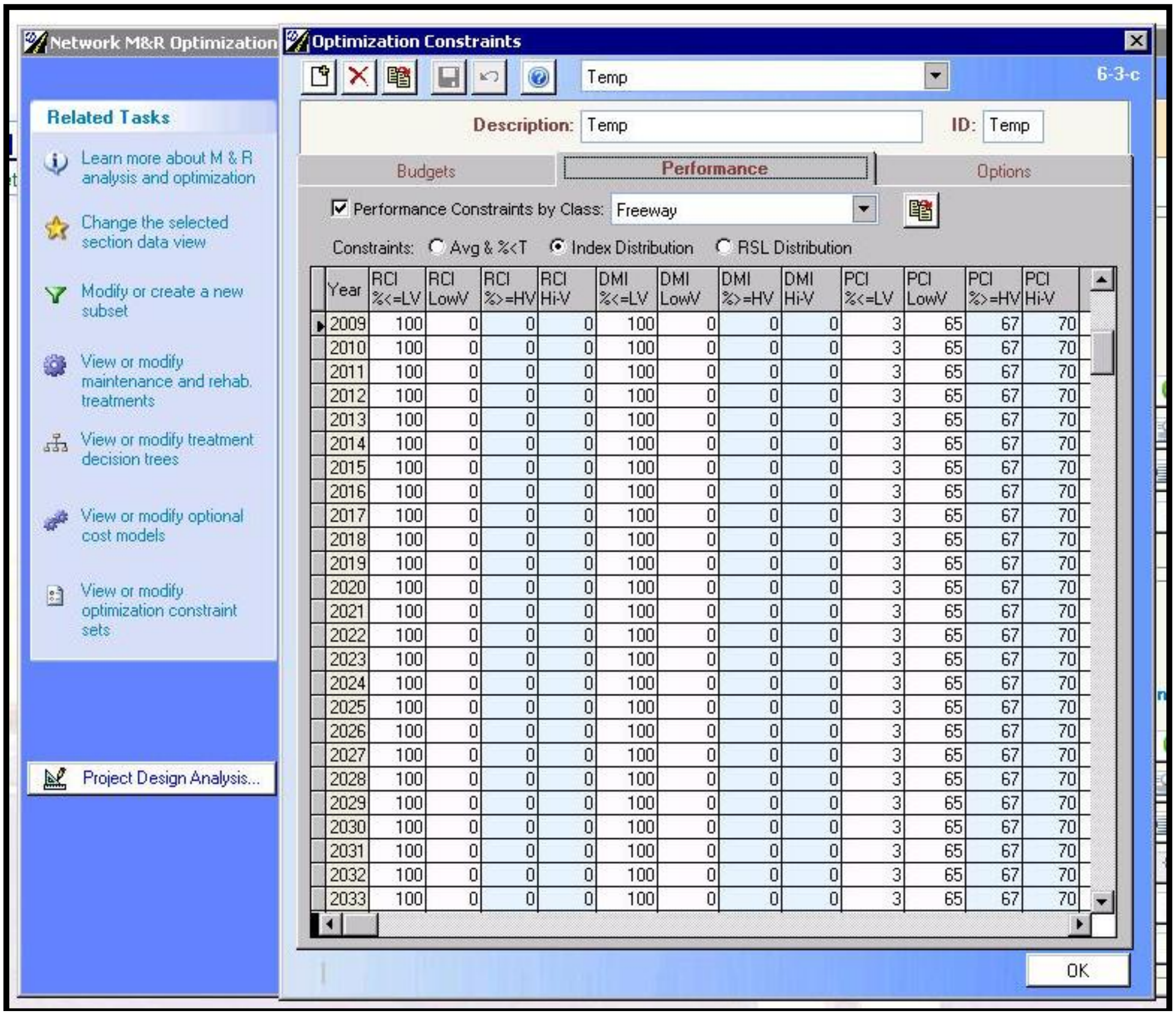


Figure 16: Performance Distribution of PMS2

Performance distribution provides flexibility in the optimization. The optimization in M&R analysis provides alternative suggestions based on the PCI distribution every year. Nevertheless, MTO uses three different terms to describe PCI value:

- Target value: All highway sections should have condition rating above the target value given sufficient (or unlimited) funds optimistically.
- Trigger value: When a pavement section reaches its trigger value, rehabilitation should take place. Trigger value can be equal or lower than target value.
- Threshold value: When a highway section reaches its threshold value, it suggests the section has failed and immediate reconstruction is necessary.

Performance distribution essentially allows a small percent of the highway network can be below the target value. For roads and highways under provincial jurisdiction, Table 31 shows the typical target performance PCI value [Chan, 2009b].

Table 31: Target Performance PCI Value

Road Class	Good		Fair		Poor	
	%	PCI	%	PCI	%	PCI
Freeway	70	75	30	74-66	0	65
Arterial	65	75	30	64-56	5	55
Collector	65	70	30	64-51	5	50
Local	60	65	30	59-46	10	45

Table 31 shows a sample case regarding how the performance target upper bound and lower bound should be set in PMS2 for different classes of road. For example, Table 31 suggested at any given year, 5% of arterial road in the network can have a PCI less than or equal to 55. The benefit of having the performance distribution provides more flexibility regarding how the money can be distributed to different highway sections. Performance distribution in PMS2 is also a tool that can be used to assess how the different overall network PCI affects the cost.

After completing the setup for performance distribution and the method of optimization, PMS2 can run the optimization for the highway section. PMS2 then suggests a rehabilitation alternative for each highway section based on the optimization constraints and M&R analysis result for the highway network selected. The optimized results are stored in the PMS2 database and it can be exported to Excel for analysis. These results are used in network level planning and budget allocation by MTO.

7.2 : Sustainable M&R Analysis

The previous sections reviewed the process MTO typically uses to generate M&R analysis for a given highway network through PMS2. However, with emphasis on sustainable pavement technologies, it seems reasonable that minor tweaks in the PMS2 would encourage sustainable maintenance and rehabilitation practices. This section proposes modifications to

PMS2 in order to produce a sustainable M&R analysis. CPATT proposes four suggestions that can improve the sustainability of the current M&R analysis.

1. Proactive Planning
2. Sustainable Decision Trees
3. Implementation Strategies
4. Discount Rate Suggestions and GDLCC Type N

7.2.1 Proactive Planning

In terms of sustainable M&R analysis, proactive planning is a concept that involves the following activities:

- Continuous update of pavement condition for highway sections from field data.
- Continuous calibration and addition of pavement deterioration models for different treatment alternatives.
- Routinely run M&R analysis in PMS2 to understand the current status of highway sections versus field data obtained.
- Provide budget allocation based on forecasted result from PMS2
- Rehabilitate sections as close to the needed year to optimize benefits

The above list summarizes activities that MTO should consider. PMS2 plays an important role in the proactive planning process because it suggests when, what, and where a rehabilitation is needed. Therefore, the accuracy of field data, cost data and the reliability of performance models in PMS2 are crucial components to ensure good pavement performance predictions. Despite MTO has limited accessibility for PMS2 user, PMS2 is a powerful pavement management system that MTO should utilize to achieve maximum benefit using the available funds.

7.2.2 Sustainable Decision Tree

The 2008 decision tree set in PMS2 are reviewed and revised to create a sustainable M&R analysis. For the 2008 decision tree set, there exists a decision tree for each unique combination of functional class and pavement type in PMS2. These decision trees are modified based on three main concepts:

- Emphasis on practical decisions
- Environmental Impact

- Priority

The goal of the modification was to examine PMS2 whereby only sustainable alternatives were available and those where the trigger level by MTO is met. Figure 17 and Figure 19 show screen captures of PMS2 decision tree [PMS2, 2009]. Figure 18 and Figure 20 translates the decision tree in Figure 17 and Figure 19 in terms of hierarchy respectively. The acronyms shown in Figure 19 and Figure 20 are presented in more detail in Appendix K.

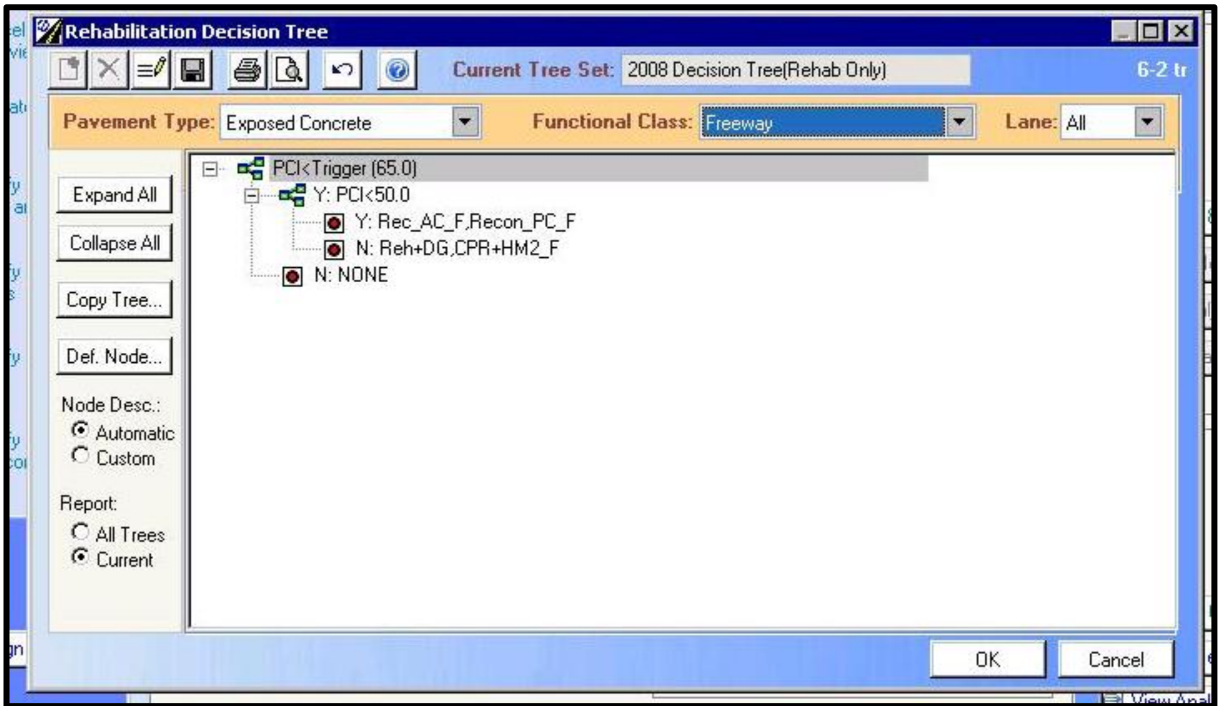


Figure 17: PMS2 2008 Decision Tree for Concrete Freeway

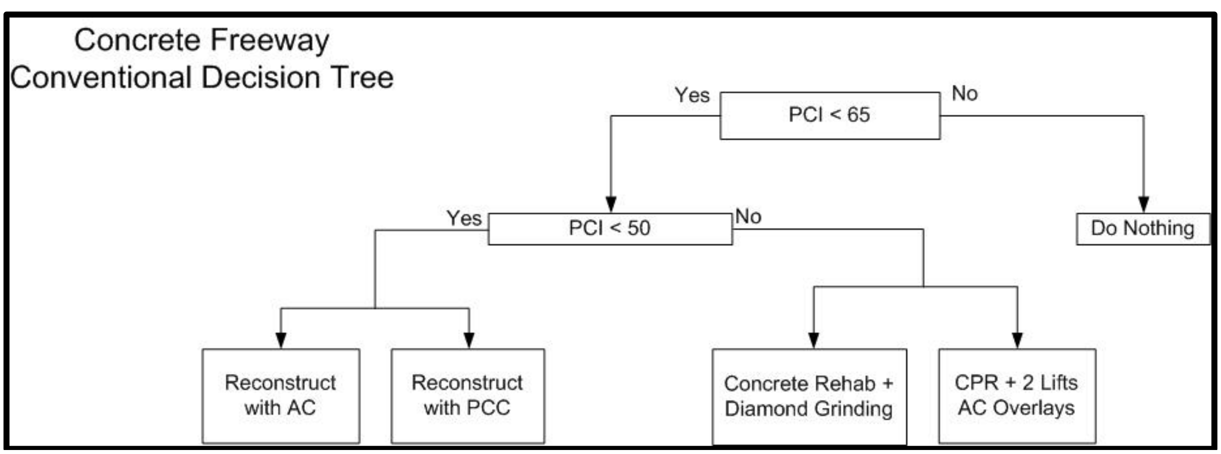


Figure 18: Decision Tree in Hierarchy Form for Concrete Freeway

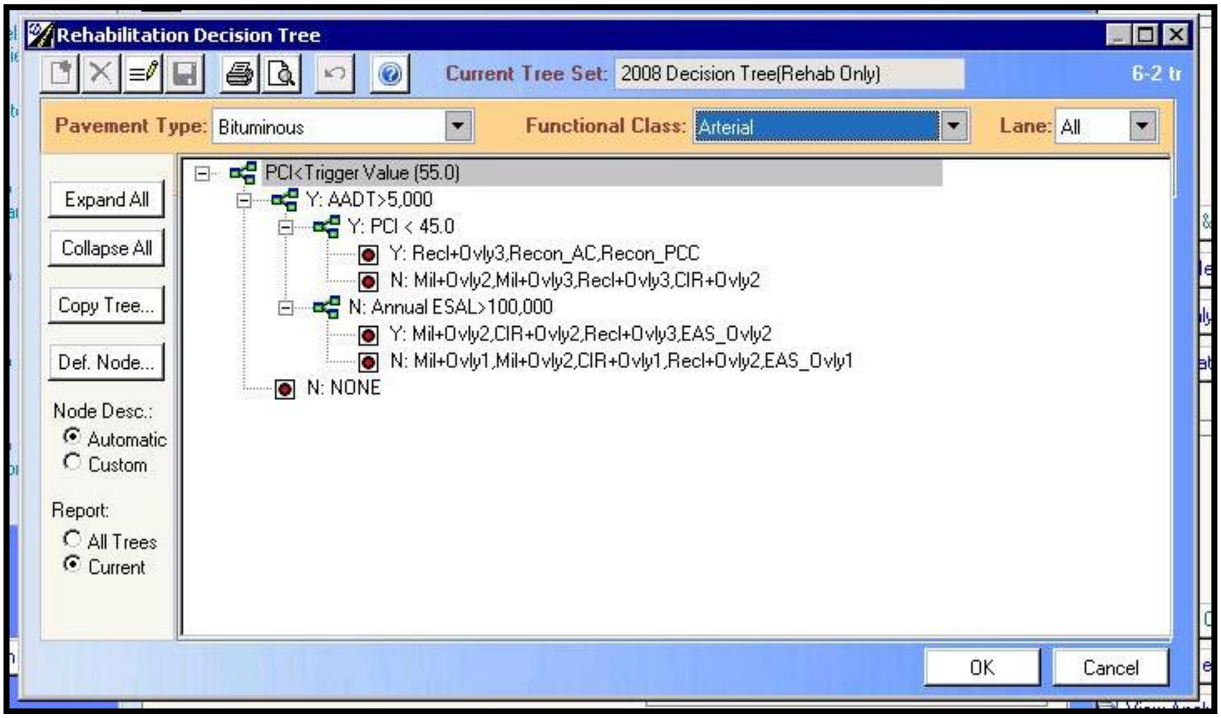


Figure 19: PMS2 2008 Decision Tree for Asphalt Arterial

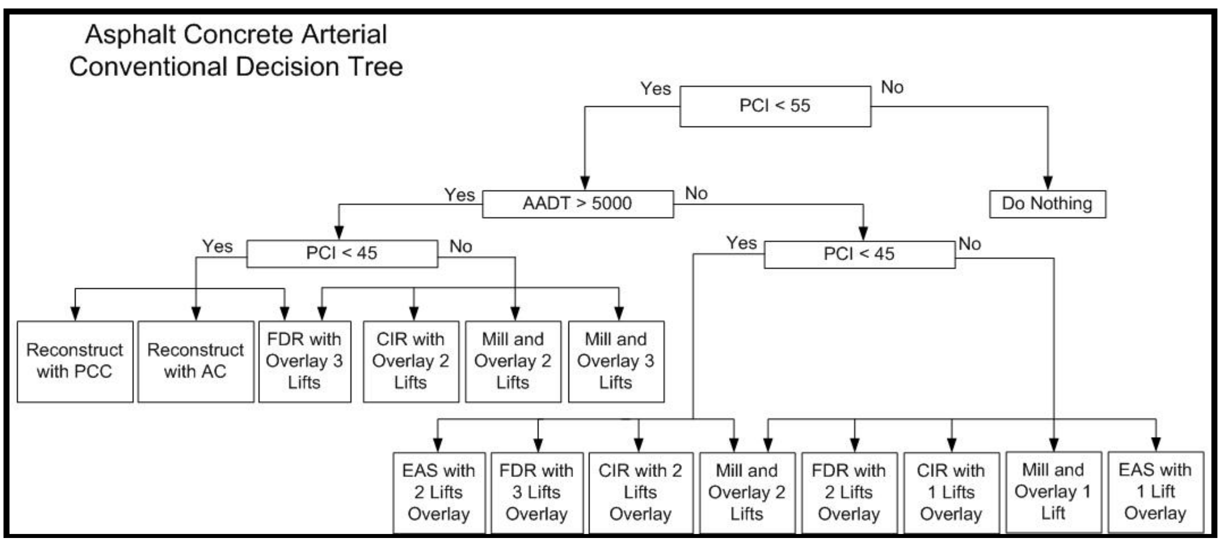


Figure 20: Decision Tree in Hierarchy Form for Asphalt Arterial

For this research, the treatments available in the decision trees were examined and any treatments that were felt to be impractical were eliminated. The meaning of practical decisions considers the economic, social, and environmental aspects of a treatment's applicability to the type of pavement. For example in Figure 20, the treatment of

“Reconstruct with portland cement concrete (PCC)” on asphalt arterial is not a very practical option because:

- Full depth reclamation can be utilized for high reused content.
- Construction duration with PCC may deem this treatment not practical, design of detour for the arterial traffic may not be economically feasible.

In terms of the environmental impact, the decision trees are modified to eliminate treatments that are not environmentally friendly. In other words, users can restrict PMS2 to choose the more environmentally friendly alternative if desirable. Another example in Figure 19 is if an arterial has AADT less than 5000 and PCI greater than 45, it is not environmentally friendly to consider mill and overlay rehabilitation when in-place recycling techniques are in the same consideration.

Overall, the intent of sustainable decision tree is also to reduce the number of alternatives available in a decision tree. As shown in Figure 20, PMS2 considers three to five alternatives based on the condition of the pavement and the section’s AADT. At the end of the analysis, the most sustainable alternative available should be selected. For example from Figure 20, an arterial has AADT greater than 5000 and PCI greater than 45, PMS2 suggests mill and overlay with 2 lifts or 3 lifts would both be adequate rehabilitation. The reduction of the total alternatives available would also improve the analysis duration in PMS2.

The sustainable decision tree for asphalt arterial is shown in Figure 21 as an example.

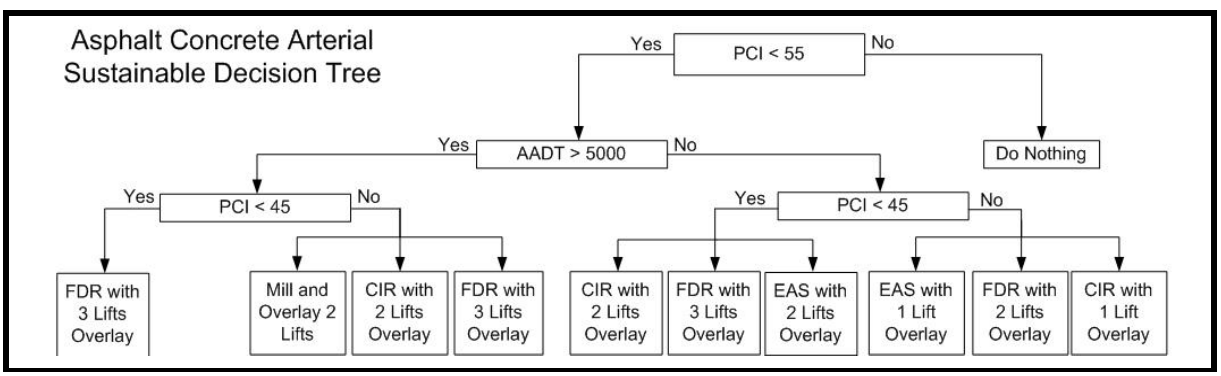


Figure 21: Sustainable Decision Tree for Asphalt Arterial

Appendix K presents an alternate sustainable decision trees based on the functional classification and pavement type (i.e. asphalt or concrete pavement). The composite pavement decision trees were not analyzed by CPATT because:

- Insufficient data models and dedicated treatments were not available in the PMS2.
- Insufficient composite pavement sections in Ontario.
- Interpretation of composite pavement by MTO is vague.

Surface treated roads were also not considered.

7.2.3 Implementation Strategies in PMS2

The implementation strategies setting in PMS2 also affect the sustainability of the analysis in PMS2. For a sustainable M&R analysis, the "always analyze" and "multiple tree implementations" strategies together should be used together as suggested previously. The "always analyze" strategy analyzes all the sections within the selected corridor regardless of their PCI condition [MERO, 2006]. The analysis of the entire corridor provides us the following benefits:

- Provide the entire picture for the pavement condition of the corridor.
- Indicate which section(s) are above or below the performance target.
- Since the "always analyze" option will provide the needed year for rehabilitation, it is one way to aid proactive planning for MTO to prepare budget at the needed year.

The "multiple tree implementations" strategy allows multiple rehabilitations throughout the analysis period if the PCI of a section reaches below the trigger level as per the PMS2 model. This option provides the flexibility for PMS2 to choose the most suitable treatment available based on the pavement PCI.

7.2.4 Discount Rate Suggestion and GDLCC Type N

In a sustainable M&R analysis, a 25 year programming period with a 5% discount rate has been selected for this project. A 25 year programming period would be sufficient to allow all the pavement sections in the analysis to receive at least one rehabilitation. A 5% discount rate is an acceptable typical value used in MTO LCC calculations in 2009, though the LCCA in Task 3 uses 5.3% discount rate. Although one may argue that a 5% discount rate may not be appropriate for a long programming period for 25 years, due to uncertainty in the economy. However, a discount rate is needed in order to complete M&R analysis and GDLCC Type N calculation. The GDLCC Type N is an indicator that measures pavement sustainability at the network level. It maintains the same concept as GDLCC, but with additional modification as shown in equation 16.

$$GDLCC\_Type\_N = [LCC \times (A/P\,, i, PCI_{MIN})] \times \left[1 - \left(\frac{GP}{36}\right) \times \left(\frac{MR}{10}\right)\right] \quad (16)$$

Where:

LCC	= Implementation Cost Proposed by PMS2 in Present worth
(A/P, i, PCI_{min})	= Factor to convert present worth to equivalent annual worth, see equation 17 [Fraser et al., 2000]
i	= Discount rate
PCI_{min}	= Minimum service life based on PCI as suggested by PMS2 (dependent on treatment)

$$(A/P\,, i, PCI_{MIN}) = \frac{i(1+i)^{PCI_{MIN}}}{(1+i)^{PCI_{MIN}} - 1} \quad (17)$$

GP = Typical GreenPave credits for the treatment, derived from project level GreenPave evaluation
MR = Typical Material and Resources credits for the treatment, derived from project level GreenPave evaluation

Equation 16 suggests that GDLCC Type N considers the economic aspect of sustainability by maintaining the final GDLCC value as a cost. However, at the network level, the GDLCC is expressed in terms of an equivalent annual worth and not the present worth. PMS2 M&R analysis result provides the LCC estimate in terms of present worth. Note the discount rate is needed in equation 17 to convert from present worth to equivalent annual worth. Therefore, in the PMS2 setup, it should be implemented using the same discount rate for sustainable M&R analysis.

The conversion of GDLCC into an equivalent annual worth can be related to the social aspect of sustainability because pavement serviceability affects user costs such as road safety and delays. By presenting GDLCC as an equivalent annual worth rather than as a present worth, a comparison can be made across the different pavement treatments that have different service lives. It also can be an easier comparison for comprehension. The service life considered in the sustainable M&R analysis is the typical minimum service life based on PCI. The minimum PCI service life of a treatment is based on the PMS2 model (if available) as shown in Appendix L. The minimum PCI value is chosen to allow for a more proactive planning and conservative calculation. On the other hand, at the project level, a decision is made based on the available pavement design suggested by the consultants. It is not appropriate to apply a minimum PCI service life as a social cost discount at the project level because often it is difficult to match the consultants' pavement design with the model available in PMS2. In addition, it is difficult to predict the service life of a design that is proposed by a consultant.

Again, the GreenPave (GP) credits and Material and Resources (MR) credits are considered for GDLCC Type N calculation as shown in equation 16. At the network level, the typical GP credits and MR credits for the treatment are considered. Table 32 shows the typical values suggested by CPATT to be used at network level based on the treatment type. At the end of the GreenPave evaluations by CPATT and MTO in project Task 4, the project alternatives were grouped together based on the treatment type on the pavement. By grouping the evaluations based on treatment type, it is possible to estimate the average credits an alternative would achieve given the alternative's pavement rehabilitation or construction method. Appendix M shows data that are used to derive Table 32. As more GreenPave trials are completed and analyzed over time, the values in Table 32 will need to be updated to improve the accuracy of the estimation. CPATT recommends a yearly revision on these typical GP and MR values. Unfortunately, as shown in Appendix M, no GreenPave evaluation was made on concrete pavement rehabilitation due to the small amount of concrete pavement available in Ontario. Therefore, Table 32 does not have any typical GP credits or MR credits suggestion for concrete rehabilitation treatment at this moment. However, when GreenPave starts to be implemented in 2010, then typical GP credits, material and resources credits can be computed with higher confidence.

Table 32: Typical GreenPave values for sustainable network evaluation

Treatment	Average Assumed at Network Level	
	GP Credits	**MR Credits**
Mill and Overlay	6.11	4.41
Full Depth Reclamation or In-Place Processing	12.44	7.44
Expanded Asphalt Stabilization	14.8	8.46
Cold In-Place Recycling (Cold In-Place Recycling with Expanded Asphalt)	14	8
New Asphalt Reconstruction	3	2
Overlay	5.5	4.5
Rubblization and Overlay	9	5.6
New Concrete Reconstruction	6	2

GDLCC Type N is computed for all the treatment alternatives generated in the sustainable M&R analysis using equation 16 as a network level sustainability assessment. From the network level perspective, CPATT believes that the alternative with the lowest GDLCC Type N in a section is the most sustainable option available.

7.2.5 GDLCC Type N Computation

The calculation of GDLCC Type N is completed using equation 16. Consider an example based on the data given below for asphalt pavement [PMS2, 2009]:

Project information: Highway 417
From Quebec-Ontario Boundary to Highway 17 Interchange 9
Eastbound, 2-Lane section, A.C. Pavement
Assumed 25 years programming period with 5% discount rate

Table 33: Extracted PMS2 Data for Highway 417

Alt. #	From PMS2				PCI_{min} [1]	GP (TYP.) [2]	MR (TYP.) [2]
	Description	**Need Year**	**Imp. Year**	**Imp. Cost**			
1	FDR+HM Overlay3F	2013	2013	$3990782	13	12.44	7.44
2	Mill+HM Overlay2 FWY	2013	2013	$2645575	10	6.11	4.41
3	CIR+HM Overlay 2F	2013	2013	$3176540	12	14	8
4	FDR+HM Overlay3F	2013	2014	$3990782	13	12.44	7.44
5	Mill+HM Overlay2 FWY	2013	2014	$2645575	10	6.11	4.41
6	CIR+HM Overlay 2F	2013	2014	$3176540	12	14	8

Where
Imp. Year = Implementation Year
Imp. Cost = Implementation Cost
[1] – From Appendix L, Table 49
[2] – From Table 32

From Table 33 it is observed that

- 3 treatment methods (FDR, M&O, and CIR) are proposed by PMS2 for this highway section.
- 2 different implementation years (2013 or 2014).
- Same implementation cost for the treatment **regardless** of implementation year, therefore implementation year does not affect GDLCC Type N calculation. Moreover, it should interpret that GDLCC Type N (Equation 16) only suggests which alternative is most sustainable. It does not suggest when will be a good implementation year for the treatment, primarily because the actual implementation year is governed by budget constraint. GDLCC Type N helps select the most sustainable alternative in PMS2, but it does not suggest how funding should be invested in the network.
- Therefore, the GDLCC Type N result for alternative 1 will equal to alternative 4, same results for 2 and 5; 3 and 6.
- Again the programming period does not influence in GDLCC Type N calculation.
- PCI_{min} values for this example are taken from Table 49, not Table 13. The values from either table are acceptable as long as only one table is use for the analysis to ensure consistency in the calculation.

The computation of GDLCC Type N begins with equation 16 and 17:

$$GDLCC\_TypeN = [LCC \times (A/P\,, i, PCI_{MIN})] \times \left[1 - \left(\frac{GP}{36}\right) \times \left(\frac{MR}{10}\right)\right]$$

$$(A/P\,, i, PCI_{MIN}) = \frac{i(1+i)^{PCI_{MIN}}}{(1+i)^{PCI_{MIN}} - 1}$$

First, the A/P factor should be computed using equation 17 for the alternatives in Table 33

For Alternative 1 (*and 4*)

$$(A/P, 5\%, 13) = \frac{0.05 \times (1+0.05)^{13}}{(1+0.05)^{13} - 1} = 0.1064$$

For Alternative 2 (*and 5*)

$$(A/P, 5\%, 10) = \frac{0.05 \times (1+0.05)^{10}}{(1+0.05)^{10} - 1} = 0.1295$$

For Alternative 3 (*and 6*)

$$(A/P, 5\%, 12) = \frac{0.05 \times (1+0.05)^{12}}{(1+0.05)^{12} - 1} = 0.1128$$

Substitute the above A/P factors into equation 16

For Alternative 1 (*and 4*)

$$GDLCC\_TypeN = [\$3990782 \times (0.1064)] \times \left[1 - \left(\frac{12.44}{36}\right) \times \left(\frac{7.44}{10}\right)\right]$$

$$GDLCC\_TypeN = \$315452$$

For Alternative 2 (*and 5*)

$$GDLCC\_TypeN = [\$2645575 \times (0.1295)] \times \left[1 - \left(\frac{6.11}{36}\right) \times \left(\frac{4.41}{10}\right)\right]$$

$$GDLCC\_TypeN = \$316959$$

For Alternative 3 (*and 6*)

$$GDLCC\_TypeN = [\$3176540 \times (0.1128)] \times \left[1 - \left(\frac{14}{36}\right) \times \left(\frac{8}{10}\right)\right]$$

$$GDLCC\_TypeN = \$246838$$

From the calculation above alternative 3 shows the lowest GDLCC Type N value for the given alternatives generated by PMS2 M&R analysis. Although PMS2 suggest mill and overlay has the lowest implementation cost, it is not the most sustainable alternative in this example.

7.2.6 New Optimization Scenario

This section discusses how the optimization protocol should be utilized to develop a sustainable M&R analysis. In the previous discussion on optimization, PMS2 select the treatment that has the highest cost-effectiveness. It also utilizes performance distribution to ensure the performance target is satisfied at the end of the optimization. In a sustainable M&R analysis, the performance target optimization method is adequate and can be used as a basis to compare the conventional practice versus the sustainable practices.

An alternate way to approach the optimization is to program PMS2 to select the treatment that has the lowest GDLCC Type N. The lower GDLCC Type N value suggests higher degree of pavement sustainability as demonstrated in the previous calculation example. In conventional or sustainable M&R analysis for a highway, thousands of alternatives can be generated based on different combinations of implementation year, treatment, highway section, and highway direction. Therefore, it will be convenient for PMS2 to have an optimization protocol that selects a treatment based on the lowest GDLCC Type N.

Network performance distribution is another factor that would affect sustainable M&R analysis. For example, if Highway 404 is being optimized using performance target criteria suggested in Table 31, PMS2 would produce 70% of the highway sections with good PCI standing; and 30% of the highway section with fair PCI standing. The optimization result in PMS2 does not distinguish sections satisfy the performance target, but the result simply suggests a treatment for a section. Therefore, it is difficult for the user to detect whether there is a specific pattern in the distribution of fair PCI highway versus good PCI highway through PMS2 result. Optimistically, all sections should be above the performance target as suggested in Table 31. In a sustainable M&R analysis, the user can also establish stricter performance targets through performance distribution.

Furthermore, PMS2 is only a decision support tool for the MTO network level pavement management and the results from PMS2 must be interpreted carefully prior to implementing any decision.

Chapter 8
Sustainable Pavement Framework

From the previous discussion on project and network level pavement sustainability, it is possible to formalize how to integrate and where sustainability comes into actual practice. There are two framework proposed in this research, one framework for project level applications, the other for network level applications. At the end of this chapter, the connection between project and network level pavement sustainability is presented to demonstrate the entire picture of pavement engineering.

8.1 Project Level Framework

The framework for sustainable pavement practice at project level revolves around GreenPave. Figure 22 provides a visual representation of the project level framework.

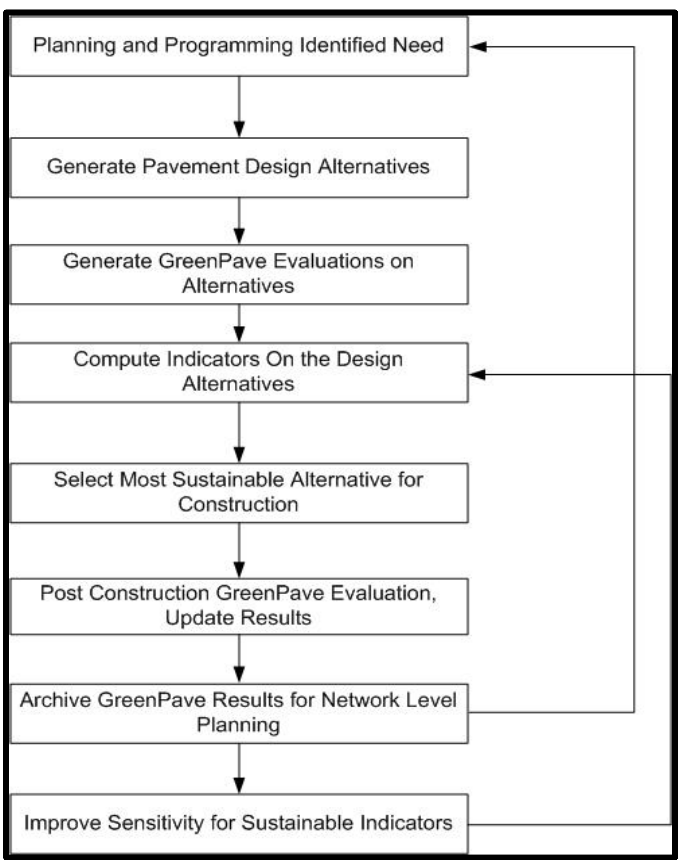


Figure 22: Sustainable Pavement Framework at Project Level

Figure 22 demonstrates a proposed eight steps framework that MTO could follow to achieve sustainable pavement decision making at the project level. First, MTO determines the need to build or rehabilitate a road or highway. The need is determined by various factors such as poor PCI, a high roughness or International Roughness Index (IRI) value, available budget, user complaints, etc, whereby the road repair becomes an identified need.

In most cases, MTO hires consultants to generate design alternatives for a section of road. The actual pavement design and its LCC are essential at this stage because they are used to compute the sustainability indicators. Pavement design should contain information such as pavement thicknesses, recycling usage, material recommendations, that will be considered in GreenPave evaluation. LCC of a pavement design is also required in order to compute GDLCC Type P or parameter D. The consultant's life cycle cost as suggested in the pavement design shall follow MTO's LCCA protocols [Lane, 2005]. Within MTO internally, GreenPave evaluation and pavement sustainability indicators are computed. MTO selects the most sustainable design alternative for tender.

At the completion of construction, the MTO will evaluate the project for GreenPave construction and innovation related credits where appropriate. Indicator values are adjusted as per the post-construction GreenPave credits.

GreenPave results for a given section roadway should be archived in the database such as the pavement management system for network level maintenance and rehabilitation programming purposes. Furthermore, as more data on GreenPave and its indicators are collected, the sensitivity of the indicators can be improved to reflect the pavement sustainability among different regions in Ontario.

8.2 Network Level Framework

The sustainable network level framework demonstrates the sequence of activities that MTO should do to promote network level pavement sustainability. The sustainable network level framework proposed by CPATT to MTO is shown in Figure 23.

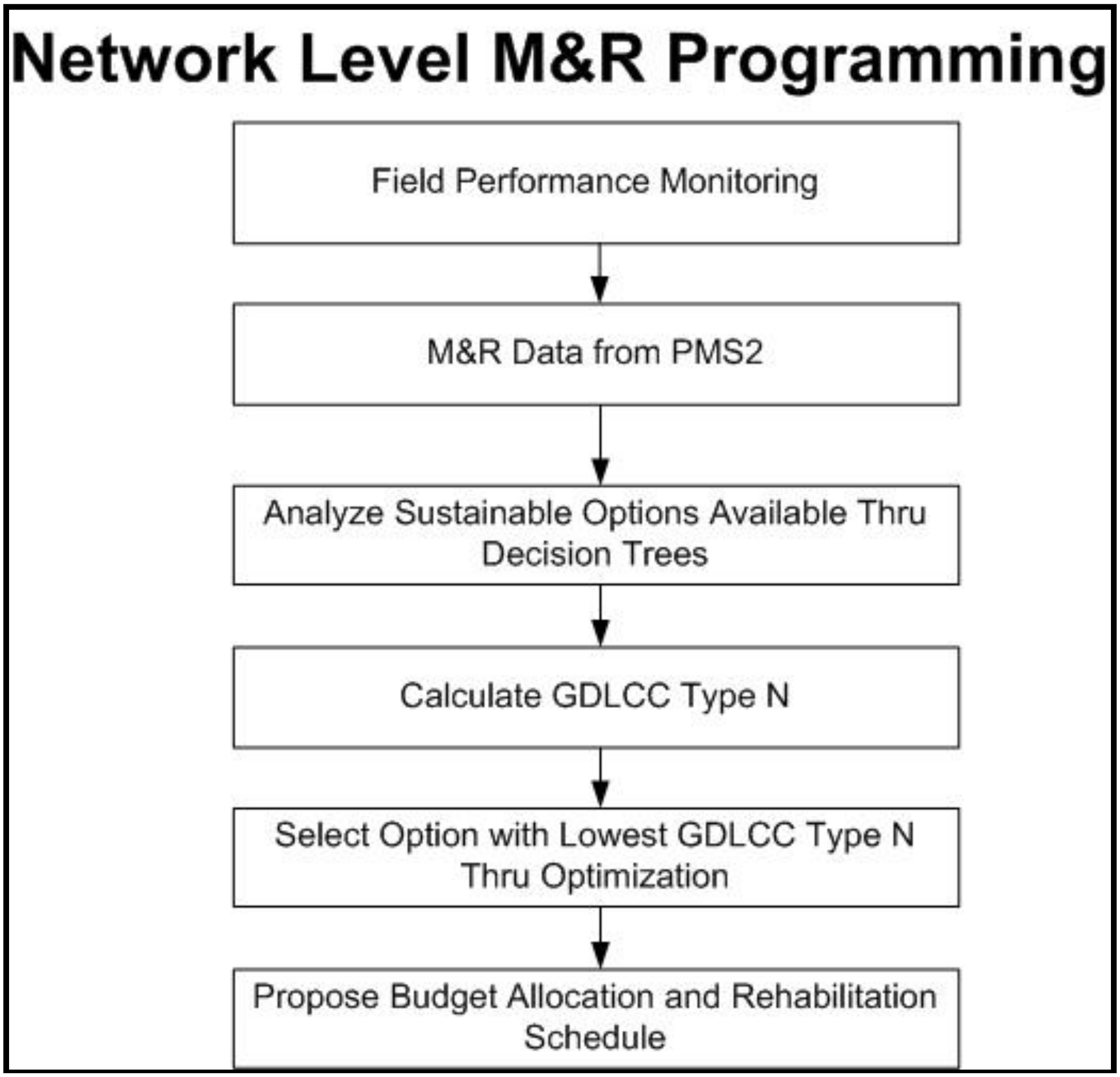


Figure 23: Sustainable Network Level Framework

From a sustainability perspective, the field performance monitoring and continuous update of pavement condition data are initial steps toward network level pavement sustainability. Various data serve as the working platform of any network level M&R analysis. MTO should proactively monitor pavement performance and collect pavement condition data in their highway network. Given reliable pavement data, sustainable M&R analysis can be initiated through PMS2. The sustainable M&R analysis involves three main activities in PMS2 as shown in Figure 23:

1. Analyze sustainable options available through usage decision trees.
2. Compute GDLCC Type N.
3. Select the option with lowest GDLCC Type N through optimization in PMS2 (in the future).

The result of a sustainable M&R analysis suggests the most sustainable option for the given highway section. Given the results from sustainable M&R analysis, MTO can prepare and analyze the budget required and rehabilitation schedule for the highway network in order to achieve their sustainability goals.

8.3 Connection Between Project and Network Level Framework

The project level and network level framework for pavement sustainability are introduced previously. Nevertheless, sustainable pavement in the future requires a joint effort between project level and network level activities. The framework suggested in this project outlines the necessary actions to arrive at a sound sustainable decision. However, the connection between project level and network level activities in sustainable practice must work together to achieve pavement sustainability in the future. Figure 24 shows the connection between project level and network level framework.

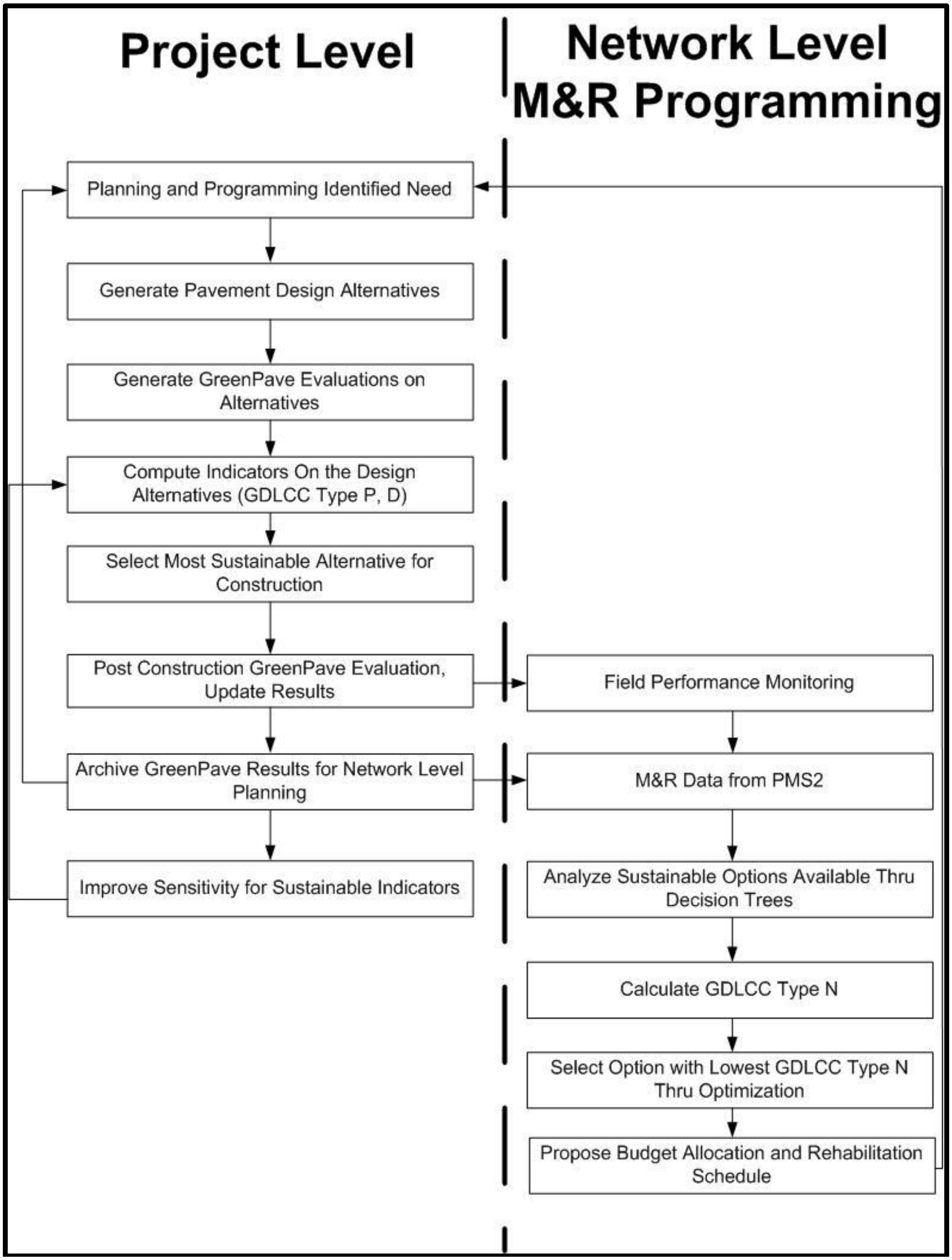


Figure 24: Combined Sustainable Pavement Framework

In terms of pavement sustainability, Figure 24 suggested that a crucial connection between the project level and the network level is transferring GreenPave results to PMS2 in long term pavement management. The results from GreenPave evaluation shall be archived in a centralized database such as PMS2 for pavement performance evaluation and prediction. As GreenPave becomes mature in Ontario, there will be potential to develop computation protocols in PMS2 for sustainable indicator calculation such as GDLCC or parameter D.

Chapter 9
Conclusions

Transportation infrastructure ages and deteriorates with time. With limited resources and funding, transportation agencies such as MTO face challenges in maintaining infrastructure which meets the needs of the users. As the concept of sustainable development gains more momentum, the consideration of economy, society and environment in pavement engineering practices is a crucial step toward sustainable transportation. The research in quantifying pavement sustainability demonstrates MTO is in the state of implementing sustainable transportation infrastructures in Ontario.

The thesis summarized all research involved in quantifying pavement sustainability. The main goal of this research was to develop a framework for MTO to quantify sustainable pavement practices. This framework considered the sustainability in project and network level practices by MTO.

The development of the framework was initiated with a comprehensive literature review. The intent of the literature review was to understand the state-of-the-art pavement engineering practices available. The literature review of this project considered material, design, construction and rehabilitation techniques that could be used in project level applications at MTO. Various green initiatives were reviewed in this project as well. These green initiatives provided MTO insights regarding how a green pavement rating system could work as a platform to quantify sustainable practices and influence decision making. A sustainable pavement workshop was held in December 2008 to invite key stakeholders in the pavement industry around Ontario. The intent of the workshop was to discuss the current state of sustainable pavement practice in Ontario and potential ways to step forward with sustainable pavement. Many useful findings and directions came out of this workshop, which were subsequently included in this research.

The research emphasized the use of a new innovative program, GreenPave to achieve sustainable pavement practices. The quantification of typical environmental and economic savings between different pavement technologies helped in the development of GreenPave. Economic and environmental savings of different project alternatives were examined from both a project perspective and life cycle perspective. The typical savings quantification demonstrated the relationship of economic, social, and environmental elements in a pavement technology. The environmental quantification was completed using the PaLATE software to estimate energy and greenhouse gas emissions. The PaLATE results showed that in-place recycling processes were the most environmentally friendly. At a life cycle perspective, rigid pavement provided energy, CO_2 and NO_x savings compared to flexible pavement.

From an economic perspective, rigid pavement construction and rehabilitation provided economic advantage in comparison to conventional flexible pavement construction and rehabilitation. Concrete overlay rehabilitation provided 20% savings in economic cost compare to asphalt mill and overlay. Furthermore, concrete pavement provided approximately 50% life cycle cost savings in the economic quantification for two equivalent concrete and asphalt pavement design options.

GreenPave evaluations addressed environmental aspect of pavement design and construction, but it did not completely represent pavement sustainability. Pavement sustainability should consider economic, social and environmental aspects of pavement performance simultaneously.

In order to measure pavement sustainability with the aid of GreenPave, this research proposed two indicators to measure pavement sustainability at project level. These indicators assessed pavement sustainability by combining GreenPave credits achieved by a project and life cycle cost simultaneously. The indicators proposed in this project provide a balanced way to represent pavement sustainability through simple mathematics. The project level sustainable pavement framework involves integrating GreenPave and sustainable pavement indicators as part of MTO daily decision practice.

The project also developed a network level sustainable pavement framework by utilizing MTO’s pavement management system, PMS2. The role of PMS2 in this project was generating M&R analysis for Ontario highways. Different ideas were proposed to improve the sustainability at the network level such as proactive planning, use of sustainable decision trees in PMS2, selection of the correct implementation strategies, and computation of GDLCC Type N as a pavement sustainability indicator at the network level. The network level framework also required conducting sustainable M&R analysis and potentially using PMS2 as the central database for storing GreenPave credits and sustainability indicators.

In conclusion, the framework for pavement sustainability involves the cooperation of project level and network level work. GreenPave and sustainable indicators allows MTO to fully understand sustainability of an alternative. PMS2 aids in network level pavement treatment suggestion as well as central data storage. This project represents MTO's intention to move forward to sustainable pavement practices.

References

[ACPA, 1998] No author given, Rubblization of Concrete Pavement, A Discussion of Its Use. American Concrete Pavement Association, 2006.

[Ahammad, 2008] Ahammed, M. Alauddin and Tighe, Susan L., "Quiet Pavements: A Sustainable and Environmental Friendly Choice". Transportation Association of Canada. Ontario, 2008.

[Arnold et al., 2008] Arnold, Greg., Werkmeister, Sabin., Alabaster, David., The Effect of Adding Recycled Glass On the Performance of Basecourse Aggregate. Nz Transport Agency, 2008.

[Bairagi, 1993] Bairagi, P., Kishore Ravande and V.K. Pareek, "Behaviour of concrete with different proportions of natural and recycled aggregates," Resources, Conservation and Recycling, V. 9, No.1-2, 1993, pp 109-126.

[Cable, 2004] Cable, Jame K and Frentress, Daniel P., "Two Lift Portland Cement Concrete Pavements to Meet Public Needs". Centre for Transportation Research and Education Iowa State University, Iowa, 2004.

[CAC, 2008] No author given, " Road Rehabilitation using FDR-PC Point Michaud Beach Road, L'Ardoise Nova Scotia". Cement Association of Canada. Ottawa, Ontario, 2008.

[Cahill, 2004] Cahill, Thomas H., Michele Adams and Courtney Marm, "Asphalt – the right choice for porous pavements," Better Roads, V. 74, No. 11, pp. 60-66, November 2004.

[CaGBC, 2008] Canada Green Building Council, "What is LEED®?" http://www.cagbc.org. Accessed March 2, 2010.

[Chan et al., 2010] Chan, Peter., Chan, Susanne., and Tighe, Susan. "Exploring Sustainable Pavement Rehabilitation: Cold In-Place Recycling With Expanded Asphalt Mix," Transportation Research Board Conference. Washington D.C., 2010.

[Chan, 2009] Chan, Susanne. "Typical Service Lives", Ministry of Transportation Ontario, Ontario, 2009.

[Chan, 2009a] Chan, Susanne, Hidalgo, Mireya and Lane, Becca. GreenPave. Ministry of Transportation Ontario Material Engineering Research Office, 2009.

[Chan, 2009b] Chan, Susanne, *MTO Pavement Design and Rehabilitation Manual, second edition. Chapter 5: Evaluation and Pavement Management. Draft Version.* Ministry of Transportation Ontario Material Engineering Research Office, 2009.

[Davidson, 2009] Davidson, Keith, Warm Asphalt Price. Emailed to Peter Chan February 13, 2009.

[Delatte, 2007] Delatte, Norbert, Dan Miller and Aleksandar Mrkajic, “Portland Cement Pervious Concrete Pavement – Field Performance Investigation on Parking Lot and Roadway Pavements,” RMC Research and Education Foundation, December 1, 2007.

[El-Hakim et al., 2008] El-Hakim, Mohab., Tighe, Susan., and Galal, Khaled., “M-E Performance Evaluation and LCCA of a Conventional Asphalt Pavement and a Perpetual Asphalt Pavement Sections, “ University of Waterloo, 2008.

[El-Hakim et al., 2009] El-Hakim, Mohab. Tighe, Susan., and Galal, Khaled., "Performance Prediction and Economic Analysis of Perpetual and Conventional Pavement Designs Using Mechanistic Empirical Models," University of Waterloo. Waterloo, Ontario, 2009.

[Elvik, 2005] Elvik, Rune and Poul Greibe, “Road safety effects of porous asphalt: a systematic review of evaluation studies,” Accident Analysis and Prevention, V. 37, 2005, pp. 515–522.

[EPA, 1999] “Stormwater Technology Fact Sheet – Porous Pavement,” Office of Water, Washington DC, September 1999.

[Erwin, 2008] Tara Erwin and Susan Tighe, 2008. "Safety Effects of Preventive Maintenance Microsurfacing Case Study", National Academy of Sciences, Washington, D.C.,Transportation Research Record No. 2044, pp. 79-85

[Fraser et al., 2000] Fraser, Niall M., Bernhardt, Irwin., Jewkes, Elizabeth M., and Tajima, May. *Engineering Economics in Canada Second Edition.* Prentice-Hall Canada Inc., Scarborough, Ontario, 2000.

[Fung, 2010] Fung, Rico and Smith, Tim. “Concrete Overlays – Sustainable Pavement Preservation Techniques Helping DOT’s Adjusting to New Realities of Shrinking Resources”. Transportation Association of Canada. Halifax, Nova Scotia, 2010.

[Fwa, 1999] Fwa, T.F., S.A. Tan and Y.K. Guwf, “Laboratory Evaluation of Clogging Potential of Porous Asphalt Mixtures,” In *Transportation Research Record 1681*, TRB, National Research Council, Washington DC, 1999, pp. 43-49.

[GGRTF, 2010] No author given, "Green Guide for Roads", Transportation Association of Canada. Www.tac-atc.ca/english/projects/greenguide.cfm, accessed March 3, 2010.

[GreenLITES, 2009] No author given, "GreenLITES Project Environmental Sustainability Rating System Scorecard v2.0.1," New York State Department of Transportation, 2009.

[Haas, 1997] Haas, Ralph. “Pavement Design and Management Guide,” Transportation Association of Canada, 1997.

[Harrington, 2008] Harrington, Dale. “Guide to Concrete Overlay, Sustainable Solutions to Resurfacing and Rehabilitating Existing Pavements.” Snyder and Associates Inc. Iowa, 2008.

[Hassan, 2009] Hassan, Marwa M. "Life-Cycle Assessment of Warm-Mix Asphalt: Environmental and Economic Perspective" Transportation Research Board Paper #09-0506, Washington D.C., 2009.

[Hein, 2006] Hein, David., Hajek, Jerry., “Life-Cycle Cost 2006 Update Final Report” Applied Research Associates Inc., Toronto, 2006.

[Hein, 2007] Hein, David and Robert Burak, “Development of A Pavement Condition Rating Procedure For Interlocking Concrete Pavements,” Prepared for Session of Cost-Effective Assessment Rehabilitation of the Condition of Materials for Transportation Association of Canada Fall 2007 meeting, Saskatoon, Saskatchewan, 2007.

[Henderson, 2008] Henderson, Vimy., Tighe, Susan., Norris, Jodi., “Pervious Concrete Pavement: An Integrated Laboratory and Field Study,” University of Waterloo, 2008.

[HiCO, 2009] No author given, HiCO Search Results For Material, Ministry of Transportation, 2009.

[Horvath, 2009] Horvath, Arpod., “Pavement Life-cycle Assessment Tool for Environmental and Economic Effects. http://www.ce.berkeley.edu/~horvath/palate.html. Accessed April 2, 2009.

[Huang et al., 2007] Huang, Yue, Roger N. Bird and Oliver Heidrich, “A review of the use of recycled solid waste materials in asphalt pavements,” Resources, Conservation and Recycling, V. 52, No.1, November 2007, pp. 58-73.

[ICPI, 1997] No author given, *Renovation of Interlocking Concrete Streets and Sidewalks in North Bay, Ontario*. Interlocking Concrete Pavement Institute, 1997.

[ICPI, 2004] No author given, *Case Study in Engineered Interlocking Concrete Pavement Hong Kong International Airport*. Interlocking Concrete Pavement Institute, Interpave, 2004.

[ICPI, 2008] No author given, *University Curriculum for Civil Engineers on Interlocking Concrete Pavements Chapter 9*. Interlocking Concrete Pavement Institute, Burlington, 2008.

[Infraguide, 2005] Infraguide, "Reuse and Recycling of Road Construction and Maintenance Materials," Federation of Canadian Municipalities and National Research Council, 2005.

[Kenter, 2010] Kenter, Peter, "Ontario Ministry of Transportation Getting Concrete Results from Pre-cast Tests". Reed Construction Data. Markham, Ontario, 2010.

[Kosmatka et al., 2002] Kosmatka, Steven H., Kerkhoff, Beatrix., Panarese, William C., MacLeod, Norman F., and McGrath, Richard J. *Design and Control of Concrete Mixtures Seventh Edition*. Cement Association of Canada, Ottawa, 2002.

[Lane, 2005] Lane, Becca and Kazierowski, Tom. Guidelines for the Use of Life Cycle Cost Analysis on MTO Freeway Projects. Materials Engineering and Research Office, Engineering Standards Branch, Ontario Ministry of Transportation, 2005.

[Lane, 2010] Lane, Becca. Chan, Susanne., Kazmierowski, Tom., Raymond, Chris., and Lee, Warren. "Comparative Performance of Conventional Cold In-place Recycling and Cold In-place Recycling with Expanded Asphalt - Ontario's Experience," Transportation Research Board, Washington D.C., 2010.

[LEED®, 2008] No author given, "LEED Green Building Rating System for New and Major Renovations Version 1.0". Canada Green Building Council, Canada, 2008

[Leung, 2007] Leung, Yuen-Ting Fiona, "Evaluation of Sound Attenuation Abilities of Various Asphalt Pavements," University of Waterloo, 2008.

[Liang et al., 2007] Liang, Hong., Zhu, Huiying., and Byars, Ewan A. "Use of Waste Glass as Aggregate in Concrete" 7^{th} UK CARE Annual General Meeting, Greenwich, England, 2007.

[Mahboub, 1996] Mahboub, K. C., and P.R. Massies. "Use of scrap Tires in Asphaltic Membrane", In Transportation Research Record 1530, TRB, National Research Council, Washington, D.C., 1995, pp. 59-63.

[MacLeod, 2005] MacLeod, Norman. "A Synthesis of Data On the Use of Supplementary Cementing Materials (SCMs) In Concrete Pavement Applications Exposed to Freeze/Thaw and Deicing Chemicals". Cement Association of Canada, Canada, 2005.

[Mallick et al., 2009] Mallick, Rajib., Bergendahl, John., and Pakula, Margaret. "Laboratory Study on CO2 Emission Reductions Through Use of Warm-Mix Asphalt". Transportation Research Board Paper #09-1951. Washington D.C., 2009.

[Maupin, 1996] Maupin, G.W. “Hot Mix Asphalt Rubber Applications”, In Transportation Research Record 1530, TRB, National Research Council, Washington, D.C., 1996, pp 18 - 24.

[Mehta, 2001] Mehta, P. Kumar, “Reducing the Environmental Impact of Concrete”, Concrete International, V.23, No.10, October 2001, pp.61-66.

[MERO, 2006] Material Engineering and Research Office MTO, “Applying PMS2 In Corridor Investment Planning (CIP)”. Ministry of Transportation Ontario. Downsview. November 2006.

[Miller, 2010] Miller, Heather. et al., "Field Evaluation of Reconstructed Roadways Incorporating Full Depth Reclamation," Transportation Research, Washington D.C., 2010.

[Moore, 2007] Moore, Lucinda M., R.G. Hicks and David F. Rogge, “Design, Construction, and Maintenance Guidelines for Porous Asphalt Pavements,” In Transportation Research Record 1778, TRB, National Research Council, Washington DC, 2007, pp. 91-99.

[MTAG, 2006] No author given. "Maintenance Technical Advisory Guide - Rigid Pavements," State of California Department of Transportation, Sacramento, CA., 2006.

[Muench, 2010] Muench, Stephen, "Greenroads v1.0 Rating System", University of Washington, 2010.

[NRC, 2005] No author given, "Road Rehabilitation Energy Reduction Guide for Canadian Roads Builders". Natural Resources Canada, Ottawa, 2005.

[NYSDOT, 2009] No author given, “GREENLITES Project Design Certification Program”, New York State Department of Transportation, 2009.

[OPSS 1002, 2004] No author given, “Material Specification for Aggregates – Concrete,” Ministry of Transportation Ontario, 2004.

[OPSS 1010, 2004] No author given, “Material Specification for Aggregates – Base, Subbase, Select Subgrade, and Backfill Material,” Ministry of Transportation Ontario, 2004.

[OPSS 1150, 2008] No author given, “Material Specification for Hot Mix Asphalt”, Ministry of Transportation Ontario, 2002.

[OPSS 1151, 2007] No Author given, “Material Specification for Superpave and Stone Mastic Asphalt Mixtures”, Ministry of Transportation Ontario, 2007.

[OPSS 1301, 2007] No author given, “Material Specification for Cementing Materials,” Ministry of Transportation Ontario, 2007.

[OPSS 1350, 2007] No author given. “Material Specification for Concrete – Materials and Production”. Ministry of Transportation Ontario, 2007.

[OPSS 313-1, 2008] No author given. Detail Estimating 313-1 Hot Mix Asphalt. Ontario Provincial Standard, 2008.

[OPSS 333, 2007] No author given, “Construction Specification for Cold In-place Recycling,” Ministry of Transportation Ontario, 2007.

[OPSS 335, 2005] No author given, “Construction Specification for Cold In-place Recycling with Expanded Asphalt,” Ministry of Transportation Ontario, 2005.

[OPSS 336, 2005] No author given, “ Construction Specification for Microsurfacing,” Ministry of Transportation, 2005.

[OPSS 361, 2005] No author given, “Construction Specification for Rubblizing Concrete Pavement and Concrete Base,” Ministry of Transportation Ontario, 2005.

[PaLATE, 2009] Horvath, Arpod., “Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE). University of California at Berkeley. 2009.

[PMS2, 2009] Ministry of Transportation Ontario., “Pavement Management System 2 (PMS2)”. Stantec Consulting Limited, accessed October 26, 2009.

[Rizvi et al., 2010] Rizvi, Rabiah., Tighe, Susan., Henderson, Vimy., and Norris, Jodi. "Evaluating the Use of Recycled Concrete Aggregate in Pervious Concrete Pavement" Transportation Research Board. Paper#10-3151. Washington D.C., 2010.

[Senior et al., 1994] Senior, S.A., Szoke, S.I., Rogers, C.A. “Ontario’s Experience with Reclaimed Materials for Use as Aggregates” Ministry of Transportation Ontario, 1994.

[Smith, 2008] Smith, James T., et al. "Coarse Recycled Aggregate Concrete Pavements - Design, Instrumentation, and Performance," Transportation Association of Canada, Ottawa, 2008.

[Soderlund, 2007] Soderlund, Martina “Sustainable Roadway Design – A Model for an Environmental Rating System” Master of Science Thesis, University of Washington, Washington DC, 2007.

[Thornton, 2009] Thornton, Tara. GreenPave Trial Result Fiscal Year 2008-2009. Ministry of Transportation Ontario, Ontario, 2009.

[Tighe, 2008] Tighe, Susan and Davidson, Keith, "Environmental/Structural Evaluation of Warm Asphalt in the Canadian Climate" ISAP, 2008.

[Tighe, 2008a]Tighe, Susan., Essex, Ryan., Damp, Stephen., Who Thought Recycled Asphalt Shingles (RAS) Needed to Be Landfilled; Using RAS in Asphalt. CTAA, 2008.

[Uzarowski, 2007] Uzarowski, Ludomir., "A Rational Approach for Selecting the Optimum Preventive and Rehabilitation Treatments – Two Practical Examples from Ontario," Golder Associates, 2007.

[Yildirim, 2007] Yildirim, Yetkin., Dossey, Terry., Fults, Kenneth., and Trevino, Manuel. "Winter Maintenance Issues Associated with New Generation Open-Graded Friction Courses," Center for Transportation Research at The University of Texas at Austin, 2006.

[Zanzotto, 1996] Zanzotto, Ludo and Gerhard Kennepohl. "Development of Rubber and Asphalt Binders by Depolymerization and Devulcanizatin of Scrap Tires in Asphalt," In Transportation Research Record 1515, TRB, National Research Council, Washington, D.C., 1995, pp. 51-58.

Appendix A

Acronym List

Table 34: Acronyms Used in This Thesis

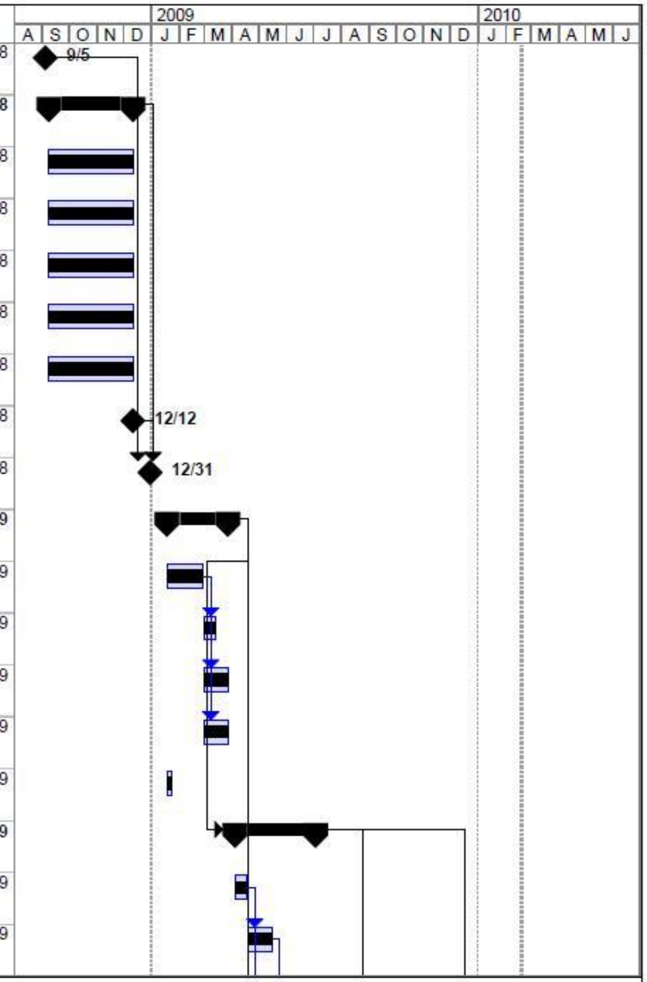
Acronym	Full Name
A.C.	Asphalt
AADT	Average Annual Daily Traffic
CaGBC	Canada Green Building Council
CE	Cost Effectiveness
CIR	Cold In-place Recycling
CIREAM	Cold In-place Recycling with Expanded Asphalt Mix
CO_2	Carbon Dioxide
CO	Carbon Monoxide
EAS	Expanded Asphalt Stabilization
EPA	Environmental Protection Agency
ESAL	Equivalent Standard Axle Load
FDR	Full Depth Reclamation
GGRTF	Green Guide for Road Task Force
GDLCC	Green Discounted Life Cycle Cost
GHG	Greenhouse Gas
GP	GreenPave
HIIFP	Highway Innovation Infrastructure Funding Program
HIR	Hot In-place Recycling
HL3	Hot Laid 3
HMA	Hot Mix Asphalt
ICPI	Interlocking Concrete Pavement Institute
IMP.	Implementation
IRI	International Roughness Index
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LEED®	Leadership in Energy and Environmental Design
M&O	Mill and Asphalt Overlay
M&R	Maintenance and Rehabilitation
MR	Material and Resources
MTO	Ministry of Transportation Ontario
NGOGFC	New Generation Open Graded Friction Course
NO_x	Nitrous Oxides
NYSDOT	New York State Department of Transportation
OGDL	Open Graded Drainage Layer
OGFC	Open Graded Friction Course
OPSS	Ontario Provincial Standards and Specification

PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PICP	Permeable Interlocking Concrete Pavement
PMS2	Pavement Management System 2
PW	Present Worth
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RCA	Recycled Concrete Aggregates
rOFC	Rubberized Open Friction Course
rOGC	Rubberized Open Graded Course
SCM	Supplementary Cement Material
SMA	Stone Mastic Asphalt
SO_2	Sulphur Dioxide
SV	Salvage Value
TAC	Transportation Association of Canada
UW CPATT	University of Waterloo Centre for Pavement and Transportation Technology
WMA	Warm Mix Asphalt

Appendix B

Project Schedule

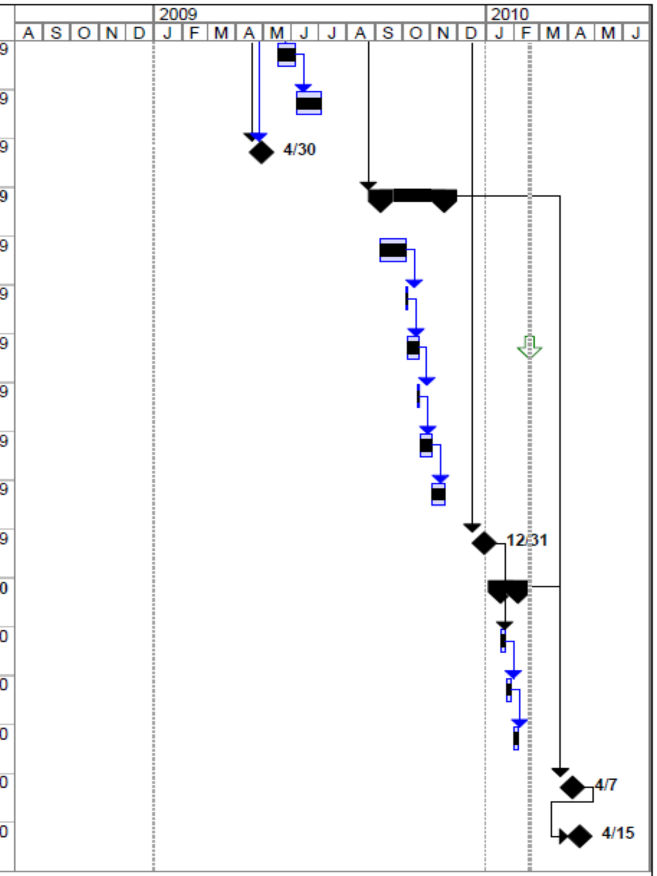
ID		Task Name	Duration	Start	Finish
1	✓	Project Kick-off Meeting	1 day	Fri 9/5/08	Fri 9/5/08
2	✓	**Literature Review**	**68 days**	**Tue 9/9/08**	**Thu 12/11/08**
3	✓	Asphalt Materials	68 days	Tue 9/9/08	Thu 12/11/08
4	✓	Concrete Materials	68 days	Tue 9/9/08	Thu 12/11/08
5	✓	Construction Technologies	68 days	Tue 9/9/08	Thu 12/11/08
6	✓	Rehabilitation Technologies	68 days	Tue 9/9/08	Thu 12/11/08
7	✓	Green Initiatives	68 days	Tue 9/9/08	Thu 12/11/08
8	✓	**CPATT/MTO Sustainable Pavement Workshop**	1 day	Fri 12/12/08	Fri 12/12/08
9	✓	**Submission 1: Progress Report 1**	1 day	Wed 12/31/08	Wed 12/31/08
10	✓	**Quantifying Typical Savings**	**50 days**	**Mon 1/19/09**	**Fri 3/27/09**
11	✓	Environmental Savings: PaLATE Analysis	30 days	Mon 1/19/09	Fri 2/27/09
12	✓	Draft PaLATE Manual	10 days	Mon 3/2/09	Fri 3/13/09
13	✓	Life Cycle Cost Quantification	20 days	Mon 3/2/09	Fri 3/27/09
14	✓	Materials Savings	20 days	Mon 3/2/09	Fri 3/27/09
15	✓	Social Cost Identification	5 days	Mon 1/19/09	Fri 1/23/09
16	✓	**Green Pavement Rating System**	**65 days**	**Sun 4/5/09**	**Fri 7/3/09**
17	✓	Preliminary Review	10 days	Sun 4/5/09	Fri 4/17/09
18	✓	Trial Evaluations	20 days	Mon 4/20/09	Fri 5/15/09



Project: Quantifyir
Date: Thu 2/18/10

Task		Milestone	◆	External Tasks	
Split		Summary		External Milestone	◆
Progress		Project Summary		Deadline	⇩

ID	Info	Task Name	Duration	Start	Finish
19	✓	Project Level Indicator Development	15 days	Mon 5/18/09	Fri 6/5/09
20	✓	Project Level Indicator Applications	20 days	Mon 6/8/09	Fri 7/3/09
21	✓	**Submission 2: Progress Report 2**	1 day	Thu 4/30/09	Thu 4/30/09
22	✓	**Network Level Pavement Sustainability**	**50 days**	**Tue 9/8/09**	**Mon 11/16/09**
23	✓	Review PMS2 M&R Analysis	20 days	Tue 9/8/09	Mon 10/5/09
24	✓	Generate PMS2 M&R Data 1	2 days	Tue 10/6/09	Wed 10/7/09
25	✓	PMS2 Decision Trees Modifications	8 days	Thu 10/8/09	Mon 10/19/09
26	✓	Generate PMS2 M&R Data 2	2 days	Mon 10/19/09	Tue 10/20/09
27	✓	Network Level Indicator Development	10 days	Wed 10/21/09	Tue 11/3/09
28	✓	Network Level Indicator Applications	10 days	Tue 11/3/09	Mon 11/16/09
29	✓	**Submission 3: Progress Report 3**	1 day	Thu 12/31/09	Thu 12/31/09
30	✓	**Use of Pavement Sustainabilty Indicator**	**15 days**	**Mon 1/18/10**	**Fri 2/5/10**
31	✓	Green Discounted Life Cycle Cost Type P	5 days	Mon 1/18/10	Fri 1/22/10
32	✓	Green Discounted Life Cycle Cost Type N	5 days	Mon 1/25/10	Fri 1/29/10
33	✓	Parameter D	5 days	Mon 2/1/10	Fri 2/5/10
34	✓	**Final Presentation to MTO**	1 day	Wed 4/7/10	Wed 4/7/10
35	✓	**Submission 4: Final Report**	1 day	Thu 4/15/10	Thu 4/15/10



Project: Quantifyir
Date: Thu 2/18/10

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

Page 2

Figure 25: Project Gantt Chart

Appendix C

Concrete Sampling Calculation

Reference: Design and Control of Concrete Mixture 7th Edition. Page 161 Example 1
Special Thanks to Dr. Jeff West

Note this example is done in **METRIC** units

Cement: Type 10 (As per OPSS 1301)

Coarse Aggregate: Nominal Maximum Size = 19.0mm (As per OPSS 1002)

Fine Aggregate: (Suggested by CAC)
Natural Sand,
Oven dry Density = 2.64
Absorption = 0.7%
Lab Moisture Content = 6%
Fineness Modulus = 2.80

Wood Resin Type Air Entraining Admixture (Suggested by CAC)

Water Reducer ASTM C494 (Suggested by CAC)

Strength = 30 MPa OPSS 350, C-2 Exposure Class According to CAC
f'_c = 35MPa
f'_{cr} = 35+8.5 = 43.5MPa (Use Table 9-11)

Water Cement Ratio
According to Table 9-1, max water cement ratio allows is 0.45
Based on f'_{cr} = 35+8.5 = 43.5MPa for air entrained concrete, we use table 3 and interpolate.
The governing W/C ratio is 0.31

Air Content
According to OPSS 1002,
Nominal Maximum Size = 19mm
Air Content = 6% ±1.5%
OPSS 350 Suggest
Slump = 70mm ± 25mm

Water Content
For Air Entrained Concrete, Category 1, Max Nominal Size 20mm, Slump 75, Table 9-5 suggest 184 kg for 1 cubic metre of concrete hence 184kg/m^3
Round gravel should reduce water content by 25 kg/m^3
Water reducer reduces water content by 10%
Therefore
Water Content = (184kg – 25kg)*0.9 = 143.1kg/m^3

Cement Content

= $\frac{143.1kg/m^3}{0.31} = 461.41kg/m^3$ Governs

> 335kg/m^3 (suggested by table 9-7)

Coarse Aggregate Content

(Suggested by CAC)

Assumed bulk density 1600kg/m^3

Fineness modulus = 2.80

Max Nominal Size = 19mm

Bulk volume of coarse aggregate per unit volume of concrete recommended = 0.62

Therefore mass of dry coarse aggregate = 1600*0.62 = 992kg

Admixture content

6% air content (As per OPSS 350)

Assume 0.5g per kg of cement for air entraining admixture
3g per kg of cement for water reducer

For air entraining admixture

0.5g*461.61 = 231g = 0.231kg

For water entraining admixture

3g*461.61 = 1.385kg

Fine aggregate content volume

Water = $\frac{143.1kg/m^3}{1 \times 1000} = 0.143m^3$

Cement = $\frac{416.1kg/m^3}{3.15 \times 1000} = 0.146m^3$

Air = $\frac{6}{100} = 0.06m^3$

Coarse Aggregate = $\frac{992kg/m^3}{2.68 \times 1000} = 0.370m^3$

Fine Aggregate = $1-(0.143+0.146+0.06+0.370)=0.281\text{m}^3$

Appendix D

PaLATE Documentation

Background and Introduction

This document explains how to use PaLATE to quantify environmental impacts in pavement constructions and rehabilitations for MTO projects. PaLATE stands for Pavement Life-cycle Assessment Tool for Environmental and Economic Effects. It is a Microsoft Excel workbook that contains several worksheets. Dr. Arpod Horvath and his research team at the University of California Berkeley, develops PaLATE as a freeware. It is important to note that PaLATE only provides preliminary estimate of environmental results. PaLATE user should occasionally check for updates to improve accuracy of results. This document does not explain the mathematical derivation of quantities calculated by PaLATE, but provides simple instruction for first time PaLATE user.

PaLATE General Setup

The PaLATE workbook can be broken down into three general categories: Input, Output, and Assumptions. Table 35 provides a brief explanation of the three categories.

Table 35: PaLATE General Categories

Category	Worksheet names	Explanation
Input	Intro Design Initial Construction Maintenance Equipment Cost $	These worksheets allow user to enter pavement dimensions, construction material, processes, equipment used, and unit prices to calculate costs.
Output	Cost $ Results Environmental Results	The two worksheets provide monetary results and environmental results
Assumptions	References Data Densities Equipment Details EMF Transport Fumes Leachate Cost Data Conversions Diagram	These worksheets contain the assumptions, values, and data that are used to process the input to produce the output. Most of the data are from various research data.

For quantifying pavement sustainability at MTO, PaLATE will be solely used to estimate the environmental impact or Life Cycle Analysis (LCA). The Life Cycle Cost Analysis (LCCA) component will not be used for this project or discussed in this Appendix.

The worksheets that are required for LCA in this project are summarized in Table 36

Table 36: Worksheets Requires for LCA

Category	Worksheet Name	Explanation
Input	Design	Input desire pavement depth, length and width, in imperial units. Breakdown the input by different pavement layers Adjustment for material densities
	Initial Construction	Only use this worksheet for new construction or reconstruction LCA. Input required material volume in each pavement layer in imperial units
	Maintenance	Use the worksheet if any pavement rehabilitation processes are being quantified (CIR, CIREAM, FDR, etc...) Input required material volume in each pavement layer in imperial units Input total volume for which the material undergo pavement rehabilitation process
Output	Environmental Results	This worksheet present environmental results numerically and in bar chart

It is suggested that the worksheets ***not*** listed in Table 36 be locked or protected to prevent unexpected changes. Other sheets contain cost information, or equipment properties that should left unchanged in the analysis.

Do not use the “cut” and “paste” command in Excel, by doing this you are changing the referencing in the embedded calculation sheet. So it is preferred to use “copy” and “paste special as values”.

The next step is to examine what to input in each worksheet.

Design Worksheet

This section discusses the components in the design worksheet that needs our attention. Two main inputs are required for the design worksheet: pavement dimensions, and densities.

Figure 26 shows the general layout for the Design worksheet

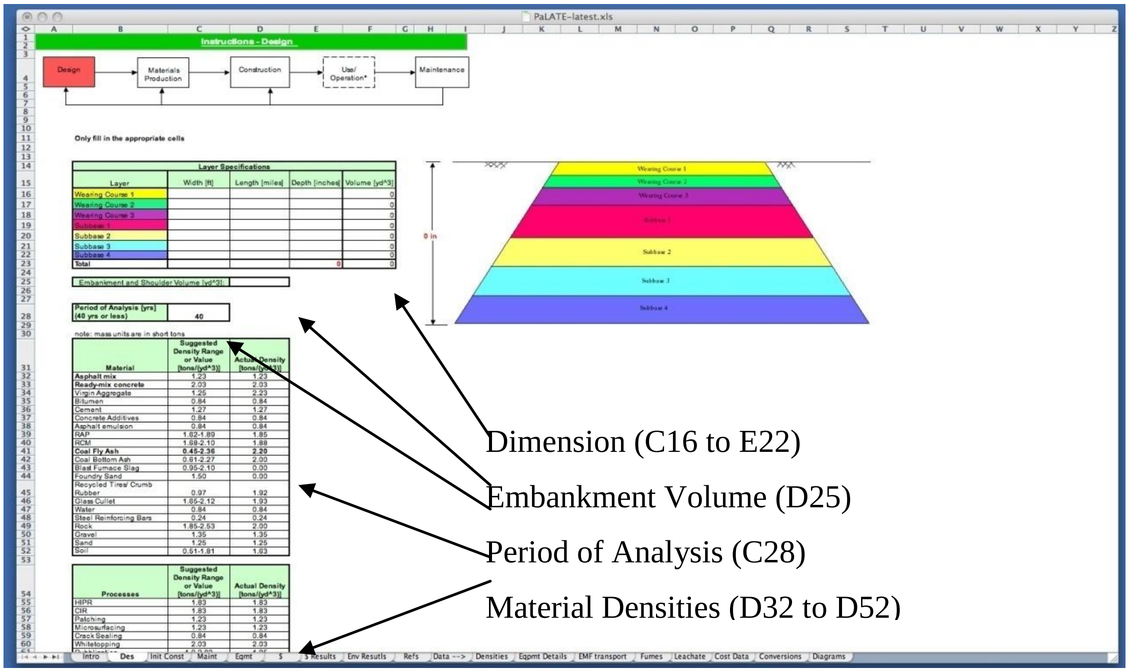


Figure 26: Design Worksheet

Pavement dimensions are the input for length, width and depth of each pavement layer in the structure. PaLATE can account a maximum of seven pavement layers (three for wearing courses and four for subbases). For pavement construction or rehabilitation, the pavement dimension must be entered in the design worksheet. Pavement dimensions are input in imperial units. For pavement dimensions, we will modify ***cells C16 to cells E22.***

For embankment volume **(D25)**, you can input if available from your design calculation. For a typical section, you can assume cell D25 = 0.

For period of analysis **(C28)**, PaLATE will accept from value 1 to 40, where 1 equals to one year cost analysis; 40 equals to forty years cost analysis. It is irrelevant for LCA analysis.

For material densities **(D32 to D52)**, check for any discrepancy and make changes if necessary. Default values are used.

For process densities **(D55 to D62)**, these are value related to the equipment that drives the process. Default values are used.

Initial Construction Worksheet

The Initial Construction worksheet allows user to input the pavement material volumes, transportation distances, and method of transportation. PaLATE separates the input by pavement layers from wearing course 1 to wearing course 3 and from subbase 1 to subbase 4. Figure 27 shows the layout of the Initial Construction worksheet.

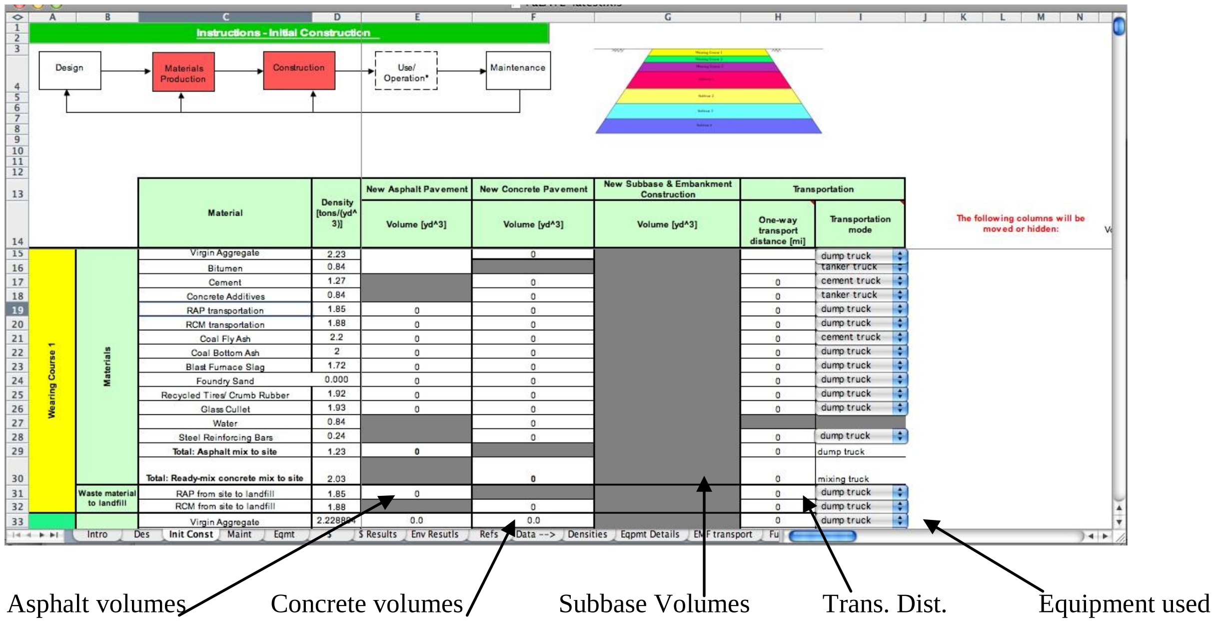


Figure 27: Initial Construction Worksheet

Cells ***E15 to E67*** are input related new asphalt pavement construction in yd^3

Cells ***F15 to F68*** are input related new concrete pavement construction in yd^3

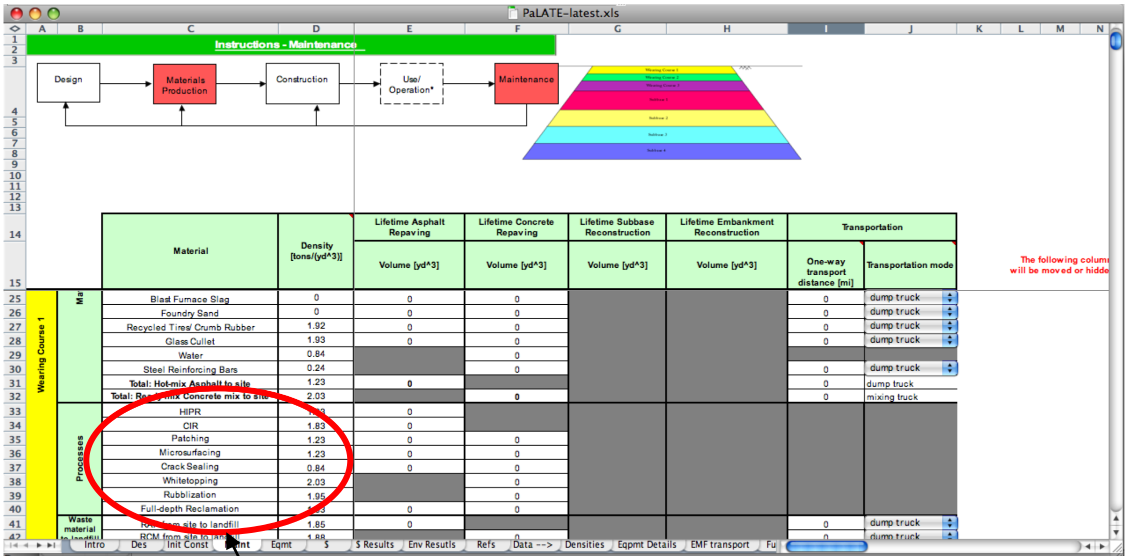
Cells ***G69 to G158*** are input related to subbase and embankment construction in yd^3.

Cells ***H15 to H158*** are input for transportation distance in miles.

Cells ***I15 to I158*** are combo boxes for transportation method. These can be left in default value.

Maintenance Worksheet

The maintenance worksheet has a very similar layout compared the initial construction sheet. However, the maintenance worksheet has an additional component for each pavement layer: *processes*. This maintenance worksheet is designed to incorporate pavement maintenance and rehabilitation processes such as HIPR, CIR, FDR, microsurfacing, whitetopping, etc. Figure 28 shows the layout of maintenance worksheet.



Maintenance & Rehabilitation Processes

Figure 28: Maintenance Worksheet (Only Show Wearing Course 1)

It shall be note that rehabilitation processes for each layer is input in either ***column E or F***. The other input can be treated the same manner as in Initial Construction worksheet.

Environmental Results

The Environmental Results is a worksheet that summarized all the LCA quantities numerically and in bar chart. There is no input required on this worksheet. It can be locked if user desired to prevent accidental changes. The environmental impacts that PaLATE can estimate are summarized in Table 37.

Table 37: Environmental Results Available in PaLATE

Environmental Result	Measurement Unit
Energy	Megajoule (MJ)
Water Consumption	Kilograms (kg)
CO_2	Megagram (Mg)
NO_x	Kilogram (kg)
PM_{10}	Kilogram (kg)
SO_2	Kilogram (kg)
CO	Kilogram (kg)
Hg	Gram (g)
Pb	Gram (g)
RCRA Hazardous Waste Generated	Kilogram (kg)
Human Toxicity Potential (Cancer)	HTP
Human Toxicity Potential (Non-Cancer)	HTP

Figure 29 shows a sample result from a PaLATE analysis. I used cold in-place recycling (CIR) for demonstration here.

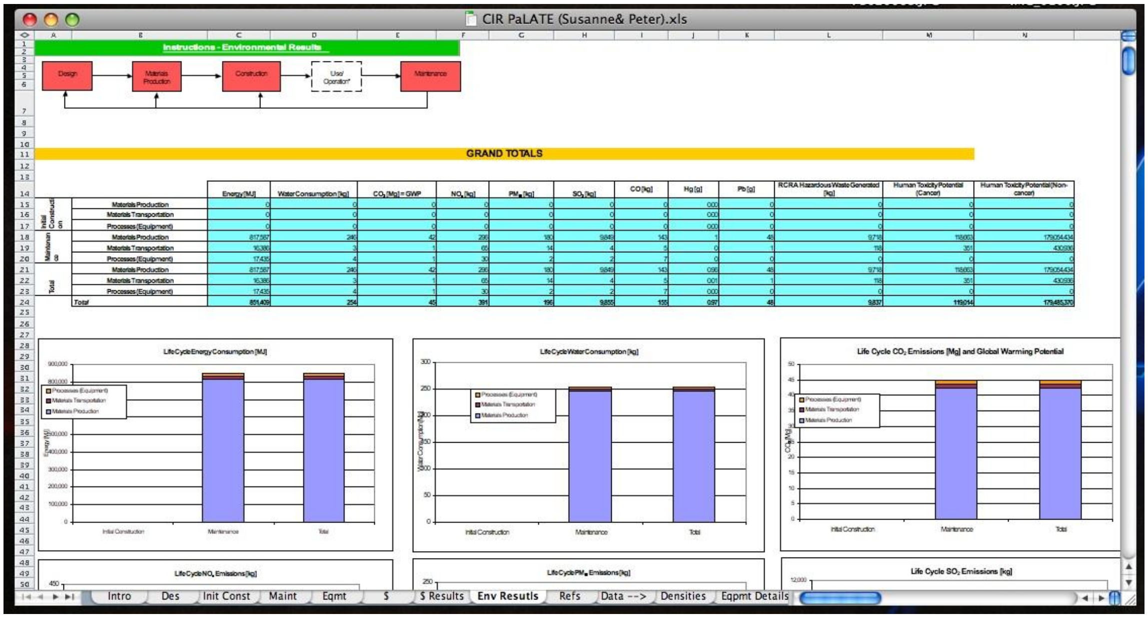


Figure 29: PaLATE Environmental Results for CIR

Define Typical Savings with PaLATE

For the quantifying pavement sustainability project, there are assumptions used to derive the typical savings. The remainder of this document discusses the assumptions made in the PaLATE input.

Design Input

For typical savings, the length and the width for all pavement layers will be the same for the entire structure. It is assumed that we have pavement length of 1km (0.621 miles), a two-lane highway with lane width 3.5m (11.48 ft). The depth of the pavement varies between different layers. Table 38 shows the typical thickness used in new pavement construction. Table 38 shows the typical thickness used in different pavement rehabilitation processes.

Table 38: Pavement Thickness in New Construction (in inches & millimetres)

Layer	Asphalt Express-way	Asphalt Arterial	Porous Asphalt	Pervious Concrete	Concrete Pavement with RCA	Concrete Arterial	Concrete Express-way
WC1	11.81 in 300mm	5.90 in 150 mm	3.94 in 100 mm	9.45 in 240 mm	9.85 in 250 mm	7.88 in 200 mm	10.23 in 260 mm
WC2	3.94 in 100mm	3.94 in 100mm OGDL	3.94 in 100mm OGDL		3.94 in 100 mm OGDL	3.94 in 100 mm OGDL	3.94 in 100 mm OGDL
WC3							
SB1 (Granular A)	19.69 in 500mm	5.90 in 150 mm	15.74 in 400 mm	7.88 in 200 mm	5.90 in 150 mm	5.90 in 150 mm	11.81 in 300 mm
SB2 (Granular B)		11.81 in 300 mm					

Table 39: Pavement Thicknesses in Rehabilitation (in inches & millimetres)

Layer	HIR	CIR	CIREAM	FDR [C]	Mill & Overlay	EAS [C]	Concrete Overlay
WC1[A]	1.97 in 50 mm	1.97 in 50 mm	1.97 in 50 mm	3.546 in 90 mm	5.122 in 130 mm	1.97 in 50 mm	4.92in 125mm Concrete
WC2	1.97 in 50 mm	3.94 in 100 mm	3.94 in 100 mm	3.546 in 90 mm	3.94 in 100 mm	2.955 in 75 mm	
WC3				3.546 in 90 mm		2.955 in 75mm	
SB1[B]							

[A]: WC1= Wearing Course 1
[B]: SB1 = Subbase 1, did not use in quantifying typical savings for rehabilitations since it is not an added component
[C]: Wearing Course 3 (WC3) in FDR and EAS are actually the base layer. However, bitumen is added to this base layer in FDR or EAS. It is impossible to incorporate this bitumen in the SB1 layer, hence we treat WC3 layer as the base layer for the quantification.

Maintenance Input

This section summarizes the required input for the pavement rehabilitations discussed in Table 39.

An assumption was that all asphalt wearing course will be consist of 95% virgin aggregate and 5% bitumen by volume calculated in the design worksheet.

The one-way transport distance for aggregate is assumed to be 6.21 miles or 10km; for bitumen is assumed to be 186.3 miles or 300km; for cement is assumed to be 50km or 31 miles.
Concrete was assumed to be consisted of 65.1% aggregates, 14.3% water, 14.6% cement.
Granular A was assumed to be 30% RAP, 30% RCM, and 40% Gravel
Granular B was assumed to be 30% RAP, 30% RCM, 20% Gravel, and 20% Rock

Hot In-place Recycling (HIR)
As suggested in Table 39, HIR involves 50mm of recycling existing pavement and adding 50mm new asphalt pavement top of existing surface to provide smooth riding pavement. Therefore, the inputs are
Virgin Aggregate →**Cell E16 = 0.95 * Wearing Course 1 Volume**
Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**
HIPR → **Cell E60 = Wearing Course 2 Volume**

Cold In-place Recycling (CIR)
From Table 39, CIR recycles the existing surface course by 100mm and adds 1.2% asphalt emulsion by volume to provide additional strength. A 50mm layer of new asphalt pavement is added on the existing surface.
It should be note that the existing surface course is considered in wearing course 2. It is assumed that no existing material is leaving or adding in the site. Therefore the inputs are
Virgin Aggregate →**Cell E16 = 0.95 * Wearing Course 1 Volume**
Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**
Asphalt Emulsion → **Cell E47 = 0.012 * Wearing Course 2 Volume**
CIR → **Cell E61 = Wearing Course 2 Volume**

Cold In-place Recycling with Expanded Asphalt MIX (CIREAM)
CIREAM follows the exact same pavement design as CIR. The only difference in CIREAM is in wearing course 2. CIREAM requires 1% by volume bitumen in wearing course 2. Therefore the input for CIREAM becomes
Virgin Aggregate →**Cell E16 = 0.95 * Wearing Course 1 Volume**
Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**
Bitumen → **Cell E44 = 0.01 * Wearing Course 2 Volume**
CIR → **Cell E61 = Wearing Course 2 Volume**

Full Depth Reclamation (FDR)
FDR involves adding a new 90mm overlay, pulverizing the existing asphalt surface and 90mm base layer. Therefore the input for FDR becomes
Virgin Aggregate →**Cell E16 = 0.95 * Wearing Course 1 Volume**
Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**
FDR → **Cell E63 = Wearing Course 2 Volume**
FDR → **Cell E86 = Wearing Course 2 Volume**

Expanded Asphalt Stabilization (EAS)

The process of EAS is similar to FDR. The only difference is that EAS adds 2.5% bitumen to wearing course 2 and 3. EAS also uses a different pavement thickness: 50mm HMA and 150 EAS. Therefore the input for EAS

Virgin Aggregate →**Cell E16 = 0.95 * Wearing Course 1 Volume**

Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**

FDR → **Cell E63 = Wearing Course 2 Volume**

Bitumen → **Cell E67 = (Wearing Course 1 AND 2 Volume)*0.025**

FDR → **Cell E86 = Wearing Course 2 Volume**

Note the 2.5% bitumen is added into one cell (E67 only) instead of two is to avoid the double counting of the transport distance, since realistically all the bitumen will deliver by one truck to the site from one plant.

Mill and Overlay

Mill and overlay is most common asphalt pavement rehabilitation available. It is simply milled 100mm of existing pavement and adding 130mm of new pavement. Two cases were assumed: Using RAP and Not Using RAP. The assumed disposal distance is 6.21m or 10km. The input for mill and overlay

Virgin Aggregate →***Cell E16*** **= 0.95 * Wearing Course 1 Volume**

Bitumen → **Cell E17 = 0.05 * Wearing Course 1 Volume**

RAP Disposal → **Cell E64 = Wearing Course 2 Volume**

If using RAP then the % use in Cell E16 and E21 have to be adjusted accordingly

RAP Transportation → Cell E21 = RAP% * Wearing Course 1 Volume

Concrete Rubblization

Rubblization is a concrete pavement rehabilitation method. It pulverized the existing concrete pavement as a base layer then adding new HMA pavement as a finishing surface. The inputs for rubblization are

Virgin Aggregate → **Cell E16 = 0.95*Wearing Course 1 Volume**

Bitumen → **Cell E17 = 0.05*Wearing Course 1 Volume**

Rubblization → **Cell F62 = Wearing Course 2 Volume**

Side Note: Consider SCM in PaLATE using above volume proportions for concrete overlay and concrete construction

From OPSS 1350, maximum fly ash content is 10% by mass, slag content is 15% by mass.

Density of slag = 1.53 tons/yd^3 *Density of fly ash = 2.20 tons/yd*^{3}

*Cement Volume = 0.146*Wearing Course 1 Volume*

*Cement Mass = Cement Density*Cement Volume*

*Slag Mass = 0.15*Cement Mass*

*Slag Volume = (Slag Mass / Slag Density)*Concrete Volume*

*Fly Ash Mass = 0.10*Cement Mass*

*Fly Ash Volume = (Fly Ash Mass / Fly Ash Density)*Concrete Volume*

Concrete Overlay
Concrete overlay involves overlaying a layer of concrete on existing pavement to provide a smooth riding surface. The input for concrete overlay is
Virgin Aggregate (For Concrete) →**Cell F16 = 0.651*Wearing Course 1 Volume**
Cement →**Cell F18 = 0.143*Wearing Course 1 Volume**
Fly Ash → **Cell F23 = 0.00809*Wearing Course 1 Volume**
Slag → **Cell F25 = 0.0178*Wearing Course 1 Volume**
Water →**Cell F29 =0.146 Wearing Course 1 Volume**

New Construction Input
For new construction of an alignment, PaLATE quantification of asphalt expressway, asphalt arterial, concrete expressway, concrete arterial, pervious concrete, porous asphalt, and concrete with 30% RCA mix are considered. For open graded drainage layer, it is assumed to have 2% bitumen content in the input.

Asphalt Expressway Construction
This is building a new asphalt expressway on subgrade. It requires 300mm HMA, 200mm Granular A, and 200mm Granular B. The required New Construction input are:
Virgin Aggregate →**Cell E15 = 0.95*Wearing Course 1 Volume**
Bitumen →**Cell E16 = 0.05 * Wearing Course 1 Volume**
RAP to Site →**Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site →**Cell G81 = 0.95*Subbase 1 Volume**
RAP to Site →**Cell G88 = 0.05*Subbase 1 Volume**
Rock to Site →**Cell G98 = 0.5*Subbase 1 Volume**
Gravel to Site →**Cell G99 = 0.45*Subbase 1 Volume**

Asphalt Arterial Construction
This is building a new asphalt arterial on subgrade. It requires 150mm HMA, 100mm OGDL, 150mm Granular A, and 300mm Granular B. The required New Construction input are:
Virgin Aggregate →**Cell E15 = 0.95*Wearing Course 1 Volume**
Bitumen →**Cell E16 = 0.05 * Wearing Course 1 Volume**
Virgin Aggregate →**Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen →**Cell E34 = 0.02 * Wearing Course 2 Volume**
RAP to Site →**Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site →**Cell G81 = 0.95*Subbase 1 Volume**
RAP to Site →**Cell G88 = 0.05*Subbase 1 Volume**
Rock to Site →**Cell G98 = 0.5*Subbase 1 Volume**
Gravel to Site →**Cell G99 = 0.45*Subbase 1 Volume**

Porous Asphalt Construction

For porous asphalt construction, it has a slight modification compared to new asphalt construction for the PaLATE input in terms of wearing course and subbase. The required inputs for porous asphalt are

Virgin Aggregate → **Cell E15 = 0.942*Wearing Course 1 Volume**
Bitumen → **Cell E16 = 0.055 * Wearing Course 1 Volume**
Virgin Aggregate → **Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen → **Cell E34 = 0.02 * Wearing Course 2 Volume**
Rock → **Cell E80 = 0.95*Subbase 1 Volume**
Gravel → **Cell E81 = 0.05*Subbase 1 Volume**

Concrete Expressway Construction

This is building a new concrete roadway on subgrade. It requires 260mm Concrete, 100mm OGDL, and 300mm Granular A. Note 6% air volume is neglected in PaLATE input. The required New Construction inputs are

Virgin Aggregate → **Cell F15 = 0.651*Wearing Course 1 Volume**
Cement → **Cell F17 = 0.146*Wearing Course 1 Volume**
Fly Ash → **Cell F21 = 0.0178*Wearing Course 1 Volume**
Slag → **Cell F23 = 0.00809*Wearing Course 1 Volume**
Water → **Cell F27 = 0.143*Wearing Course 1 Volume**
Virgin Aggregate → **Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen → **Cell E34 = 0.02*Wearing Course 2 Volume**
RAP to Site → **Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site → **Cell G81 = 0.95*Subbase 1 Volume**

Concrete Arterial Construction

This is building a new concrete roadway on subgrade. It requires 200mm Concrete, 100mm OGDL, and 150mm Granular A. Note 6% air volume is neglected in PaLATE input. The required New Construction inputs are

Virgin Aggregate → **Cell F15 = 0.651*Wearing Course 1 Volume**
Cement → **Cell F17 = 0.146*Wearing Course 1 Volume**
Fly Ash → **Cell F21 = 0.0178*Wearing Course 1 Volume**
Slag → **Cell F23 = 0.00809*Wearing Course 1 Volume**
Water → **Cell F27 = 0.143*Wearing Course 1 Volume**
Virgin Aggregate → **Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen → **Cell E34 = 0.02*Wearing Course 2 Volume**
RAP to Site → **Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site → **Cell G81 = 0.95*Subbase 1 Volume**

Pervious Concrete Construction

This is pervious concrete roadway. It is essentially composed of 200mm of granular, 100mm OGDL, and 240mm of pervious concrete. Please note that the proportions of concrete ingredients are not the same as for new concrete construction.

Virgin Aggregate → **Cell F15 = 0.634*Wearing Course 1 Volume**
Cement → **Cell F17 = 0.092*Wearing Course 1 Volume**
Blast Furnace Slag → **Cell F23 = 0.0388*Wearing Course 1 Volume**
Water → **Cell F27 = 0.09*Wearing Course 1 Volume**
Virgin Aggregate → **Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen → **Cell E34 = 0.02*Wearing Course 2 Volume**
RAP to Site → **Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site → **Cell G81 = 0.95*Subbase 1 Volume**

Concrete Construction with 30% RCA
This alternative contains 30% RCA by coarse aggregate volume. Therefore, a new concrete mix proportion must be calculated to account for the environmental impact of this material. A of transportation distance 31 miles (50km) was assumed for RCA because if the transportation distance greater than 50km will deem RCA to be a not sustainable aggregate substitute.
Virgin Aggregate → **Cell F15 = 0.5429*Wearing Course 1 Volume**
Cement → **Cell F17 = 0.0784*Wearing Course 1 Volume**
RCM Transportation → **Cell F20 = 0.142*Wearing Course 1 Volume**
Blast Furnace Slag → **Cell F23 = 0.0322*Wearing Course 1 Volume**
Water → **Cell F27 = 0.143*Wearing Course 1 Volume**
Virgin Aggregate → **Cell E33 = 0.98*Wearing Course 2 Volume**
Bitumen → **Cell E34 = 0.02*Wearing Course 2 Volume**
RAP to Site → **Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site → **Cell G81 = 0.95*Subbase 1 Volume**
RAP to Site →**Cell G88 = 0.05*Subbase 2 Volume**
Rock to Site→ **Cell G98 = 0.5*Subbase 2 Volume**
Gravel to Site→ **Cell G99 = 0.45*Subbase 2 Volume**

Warm Asphalt Quantification
There is no specific function in PaLATE to quantify the environmental impact associated with the use of warm mix asphalt. The current quantification will only provide a preliminary estimate. For the purpose of this quantification, a brief literature review of different warm asphalt technologies. It is found out that at the current technologies, warm asphalt have significant impact in asphalt production. This section summarizes the assumption use in PaLATE to come up with the preliminary estimate.

Based on the literature review, the environmental impacts that were assessed are energy savings, CO_2, NO_x, CO, and SO_2. Note the results shown in the references are derived from lab and mix design criteria with WMA is neglected in the quantification. Table 40 shows some suggested percentage of environmental savings from literature.

Table 40: WMA VS HMA Environmental Impact Reduction Summary

Reference	1 WAMfoam	2 LEA Half Warm Mix	3 Sasobit	4 Evotherm	Conclusion
Energy	35%	55% (fuel)		54% (fuel)	30%
CO_2	35%	64.5%	32%	45.8%	45%
NO_x	60%	73%		58%	60%
SO_2	25%			41.2%	30%
CO	8%	NC		63.1%	??
5 Natural Resource Canada suggest WMA saves 30% energy compared to HMA					

1 - *Life-Cycle Assessment of Warm-Mix Asphalt: Environmental and Economic Perspective*., Hassan, Marwa. TRB Paper #09-0506
2 - *Environmental Comparison at Industrial Scale of Hot and Half-Warm Mix Asphalt Manufacturing Processes*., Ventura et al. TRB Paper #09-1274
3 - *Laboratory Study on CO2 Emission Reductions Through Use of Warm-Mix Asphalt*., Mallick et al. TRB Paper #09-1951
4 – *Environmental/Structural Evaluation of Warm Asphalt in the Canadian Climate*. Tighe et al. ISAP 2008
5 – *Road Rehabilitation Energy Reduction Guide for Canadian Roads*. Natural Resource Canada

The percentages in the conclusion column are the suggested reduction by using warm asphalt. For the sake of comparison, a re-work example for warm asphalt will be derived from the Mill and Overlay PaLATE.

The PaLATE input for WMA Mill and Overlay will be done on the **Env Result** worksheet. Hence the inputs are

Energy → **Cell C18 =0.7*S43**
CO_2 → **Cell E18 = 0.55*U43/1000**
NO_x → **Cell F18 = 0.4*V43/1000**
SO_2 → **Cell H18 = 0.7*X43/1000**

Appendix E

PaLATE Numerical Output for Rehabilitation and Construction

Table 41: PaLATE Output Quantities

Technique	Abbreviation	Energy [MJ]	Water Consumption [kg]	CO2 [Mg] GWP	=NOx [kg]	PM10 [kg]	SO2 [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
CIR =50mm HMA + 100mm CIR	CIR	851409	254	45	391	196	9855	155	1	48	9837	119014	179485370
CIREAM = 50mm HMA + 100mm CIREAM	CIREAM	844974	251	44	388	196	9815	153	1	48	9735	160801	179493981
EAS = 50mm HMA + 150mm EAS	EAS	1264264	423	68	526	220	10455	251	2	82	17187	275823	179653485
FDR = 90mm HMA + 180mm FDR	FDR	1219783	329	63	562	333	17246	202	1	63	12644	214149	322979799
HIR = 50mm HMA + 50mm HIR	HIR	724088	184	36	333	186	9582	117	1	35	7024	118972	179433221
Mill & Overlay = 130mm HMA + 100mm M&O	M&O	1754805	476	90	798	480	24909	289	2	91	18263	309575	466830560
Mill & Overlay w 20% RAP = 130mm HMA + 100mm	M&O w RAP	1481675	382	74	723	389	24847	235	1	73	14680	254264	385137241
Rubblize 200 Conc + 100 HMA overlay	RUBB	1371305	366	71	652	372	19164	230	1	70	14049	237944	358866443
Concrete Overlay 125mm Concrete		982454	891	148	1884	757	1632	967	3	188	2741	27698	312291863
Mill & Overlay = 130mm HMA + 100mm M&O	0	1754805	476	90	798	480	24909	289	2	91	18263	309575	466830560
Mill & Overlay w 5% RAP = 130mm HMA + 100mm	0.05	1686522	452	86	780	457	24894	275	2	87	17368	295747	446407230
Mill & Overlay w 10% RAP = 130mm HMA + 100mm	0.1	1618240	429	82	761	434	24878	262	2	82	16472	281920	425983900
Mill & Overlay w 15% RAP = 130mm HMA + 100mm	0.15	1549958	405	78	742	412	24863	249	2	78	15576	268092	405560570
Mill & Overlay w 20% RAP = 130mm HMA + 100mm	0.2	1481675	382	74	723	389	24847	235	1	73	14680	254264	385137241
WMA Mill & Overlay	WMA M&O	1242338	476	51	418	480	17440	289	2	91	18263	309575	466830560
Concrete Expressway 260mm Conc+100mm OGDL+300mm Gran A		5826078	2011	388	4643	2506	21737	2169	7	428	12676	295078	1808029169
Concrete New 200mm Conc+100mm OGDL+150mm GranA		4528488	1566	297	3616	1852	21100	1676	5	333	10876	238121	1299105428
Asphalt Expressway 300mm HMA+200mm GranA+200mm GranB		5896147	1402	319	2503	2382	76581	878	5	263	49521	919354	2541725249
Asphalt New 150mm HMA+100mm OGDL+150GranA+300 GranB		3931992	864	219	1661	1891	47847	554	3	159	28605	522852	1545623913
Pervious Concrete 240mm Conc+200mm GranA		3983377	1409	279	3495	1748	2180	1696	5	323	5648	147392	1134972538
RCA Mix = 250mm Conc + 100mm OGDL+150mm Gran A		4939587	1700	332	4135	2022	21296	1952	6	376	12004	262717	1387481967
Porous Asphalt 100mmHMA+100mm OGDL+400mm GranA		3027075	648	168	1310	1474	38250	421	2	119	21219	425433	1605456041

Appendix F

PaLATE Bar Charts for Construction and Rehabilitation

.

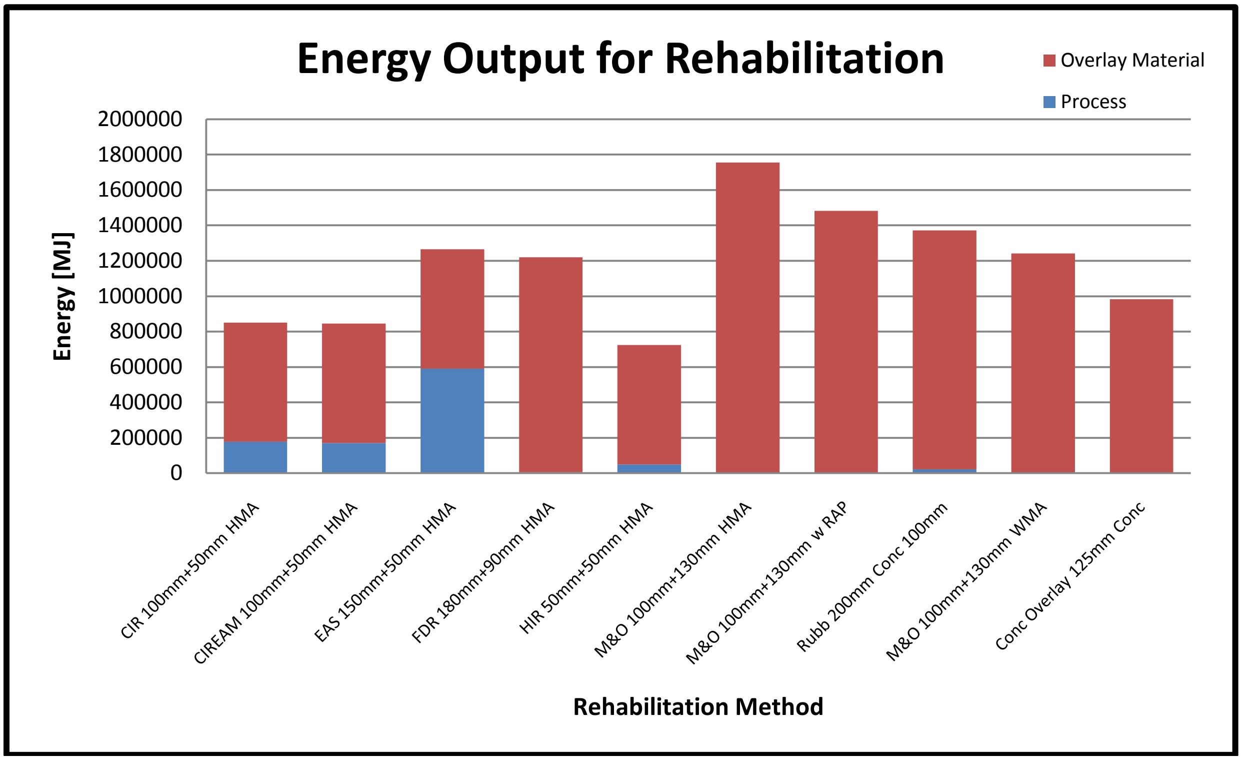


Figure 30: Energy Output for Rehabilitation

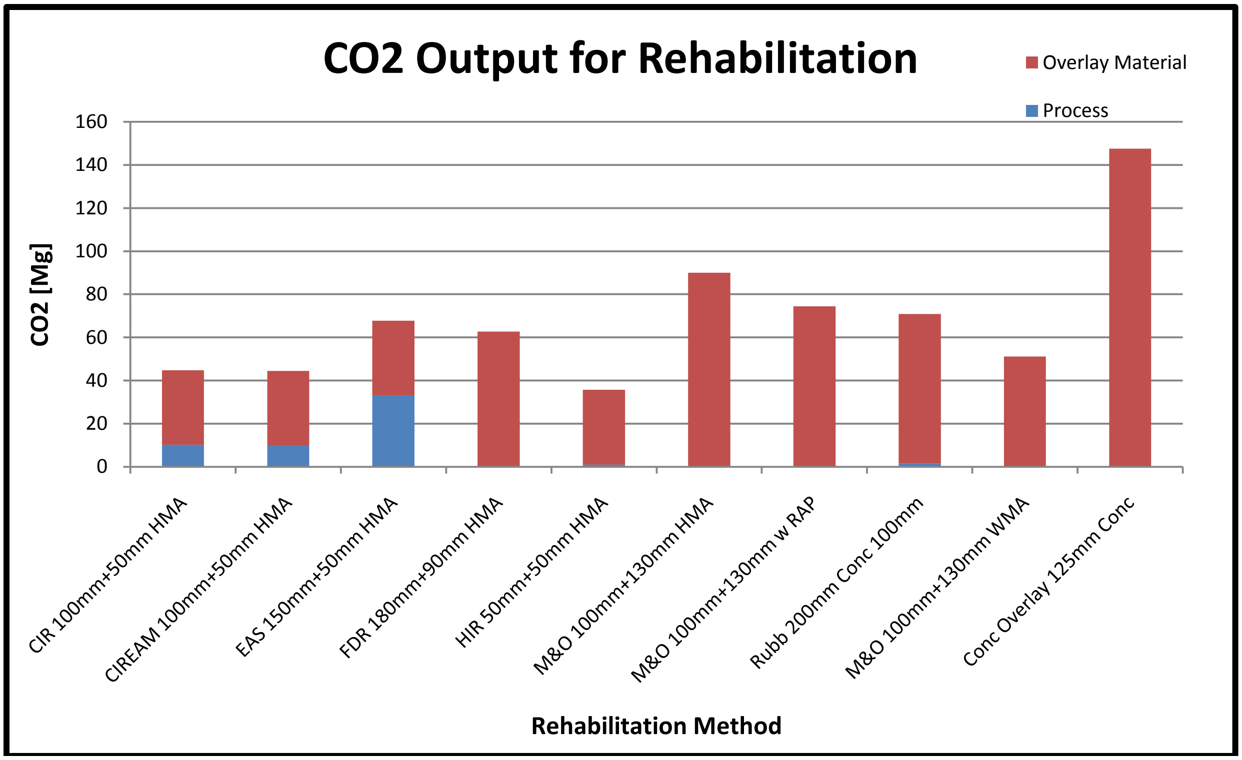


Figure 31: CO_2 Output for Rehabilitation

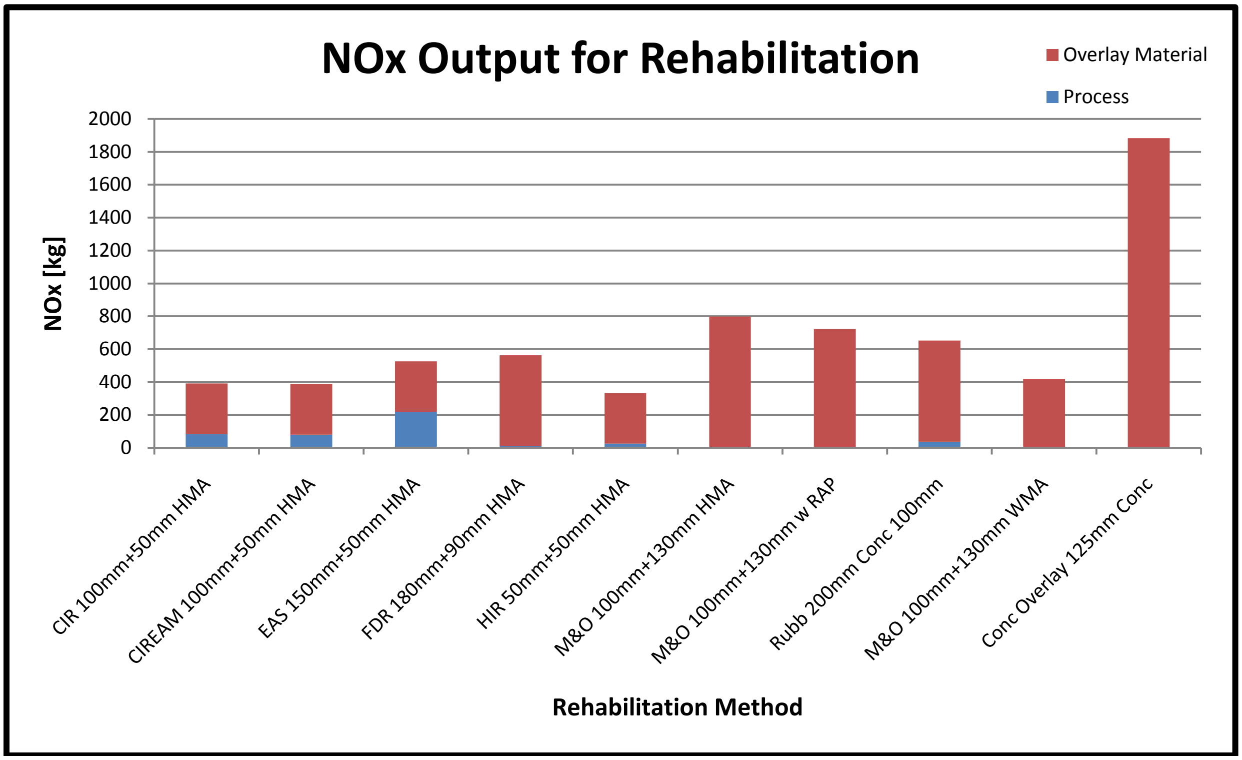


Figure 32: NO_x Output for Rehabilitation

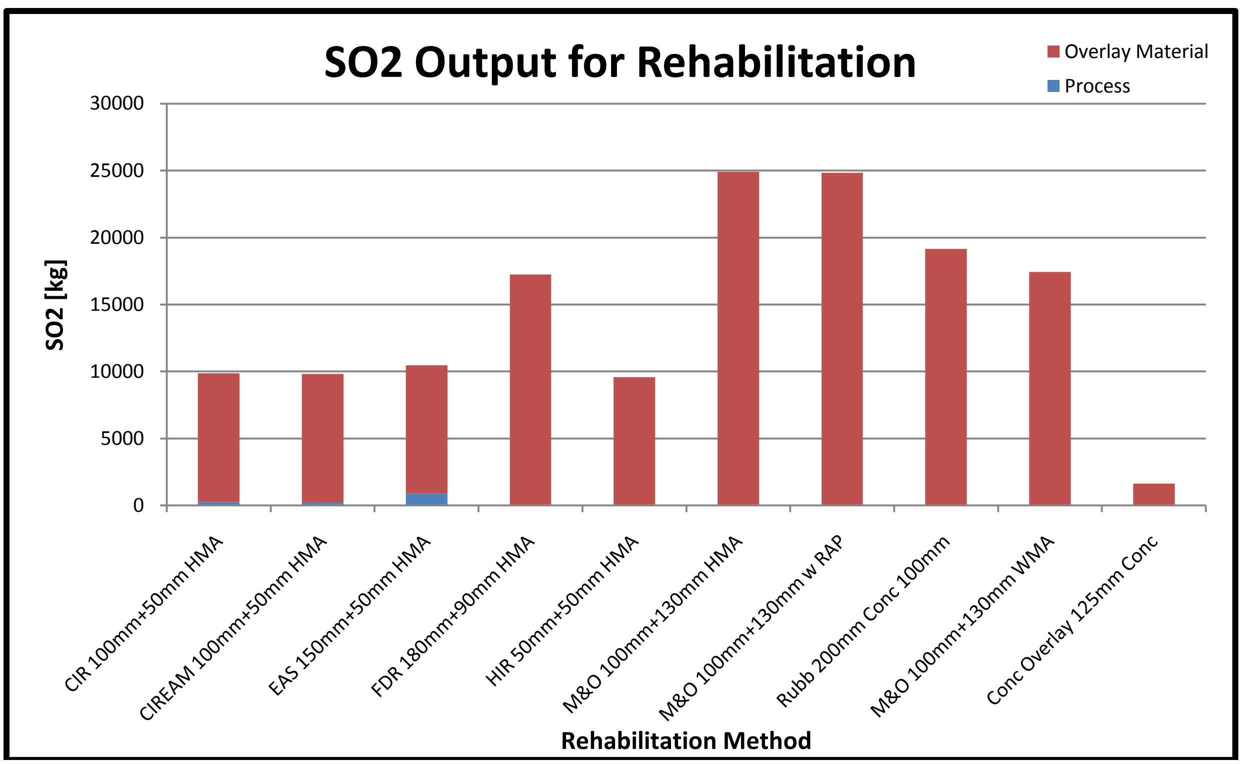


Figure 33: SO_2 Output for Rehabilitation

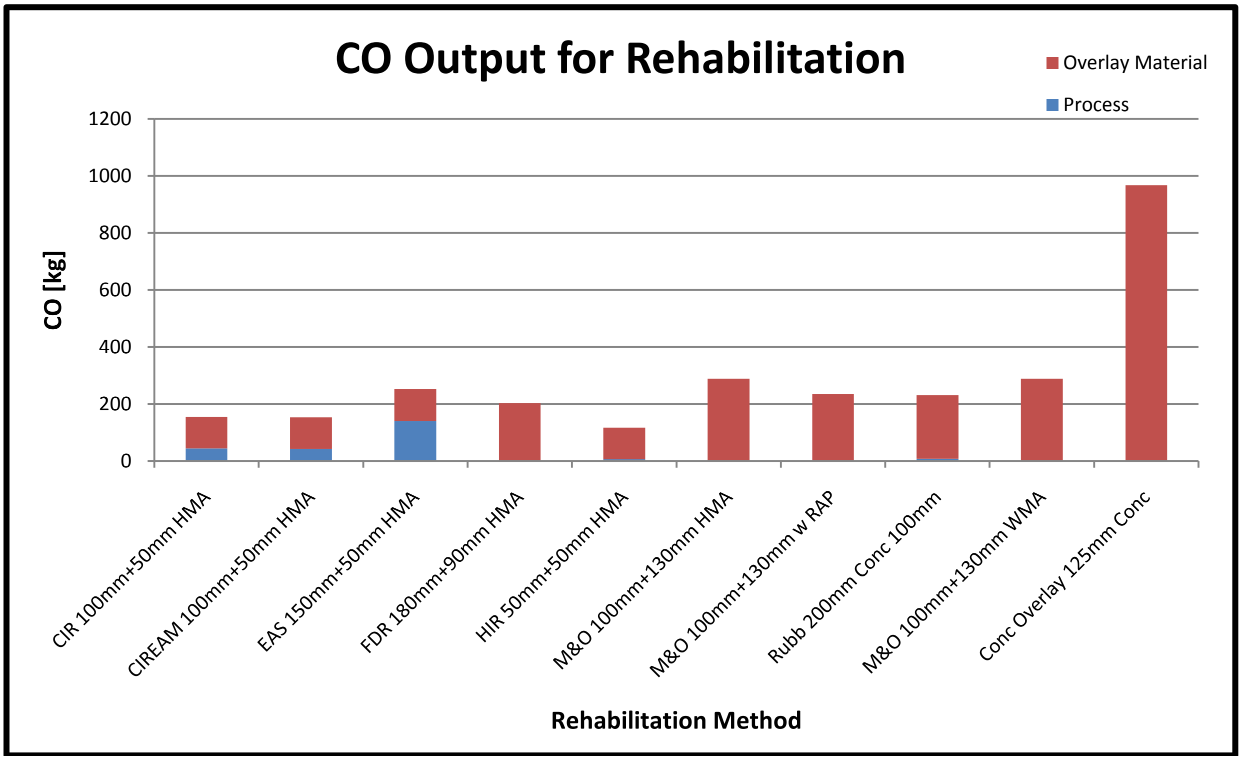


Figure 34: CO Output for Rehabilitation

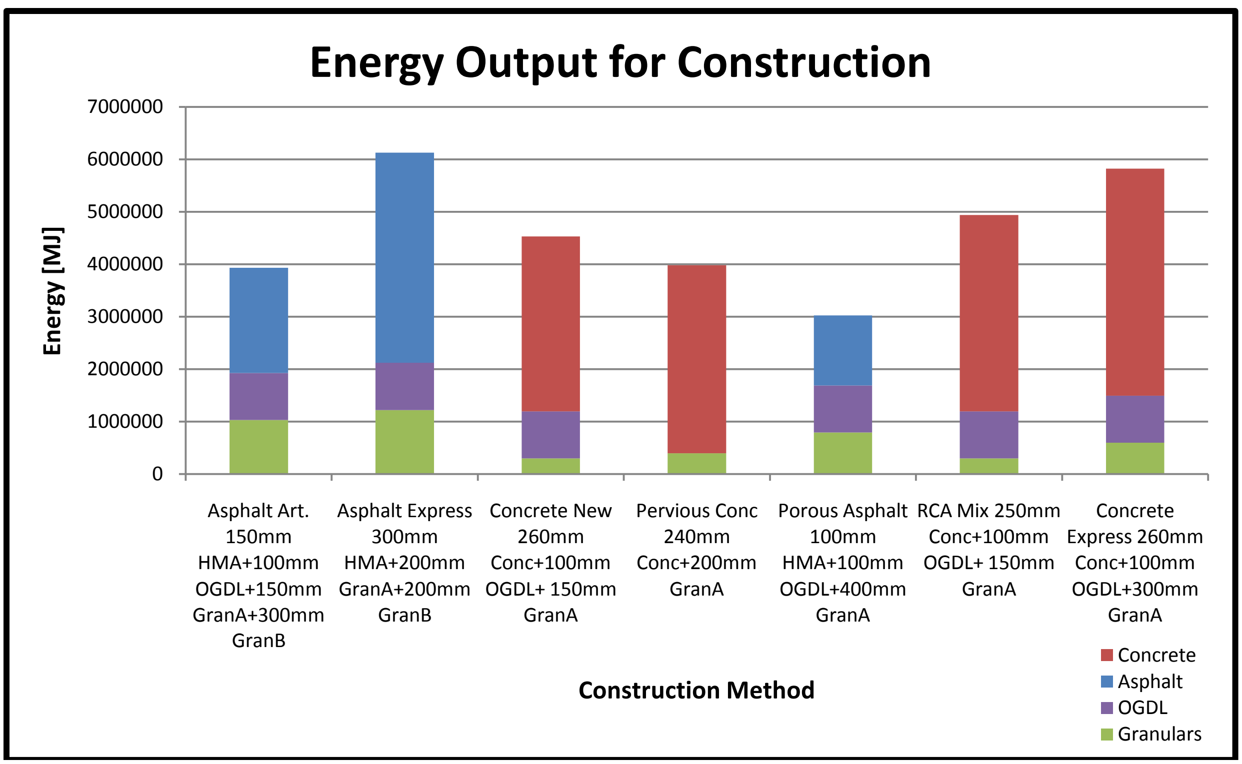


Figure 35: Energy Output for Construction

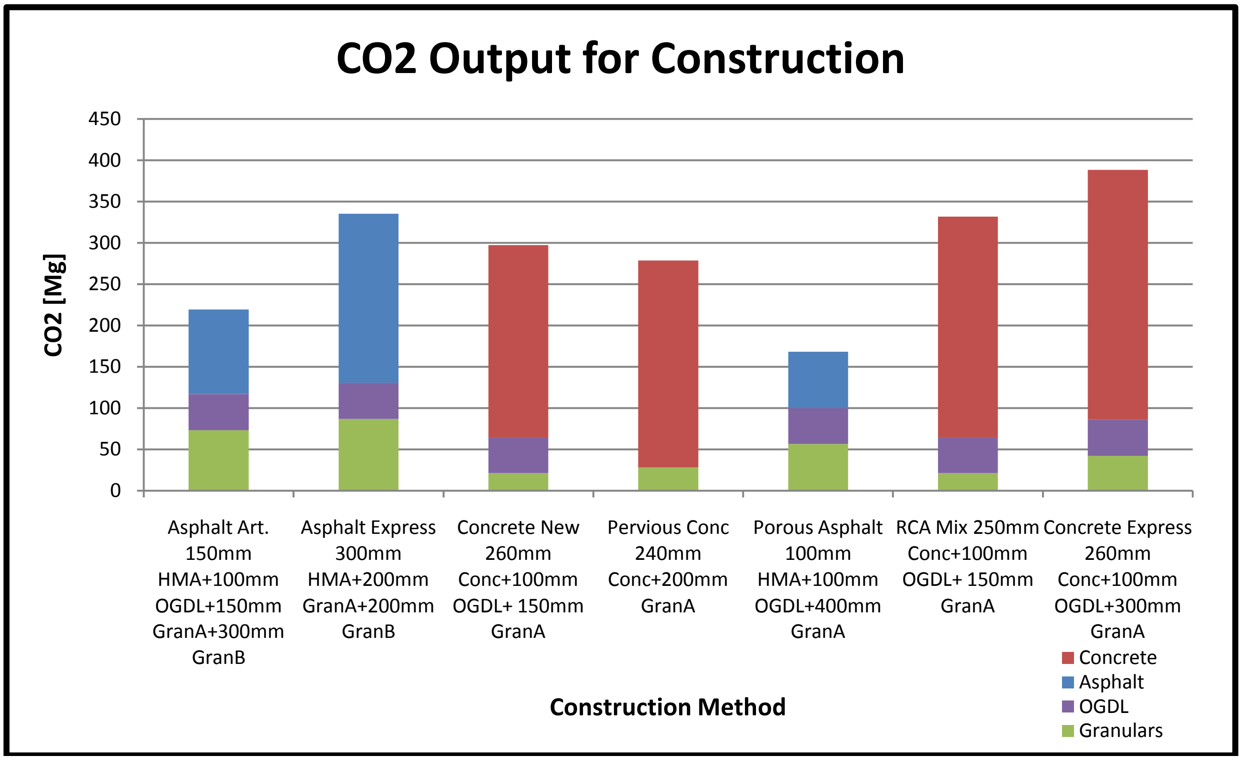


Figure 36: CO_2 Output for Construction

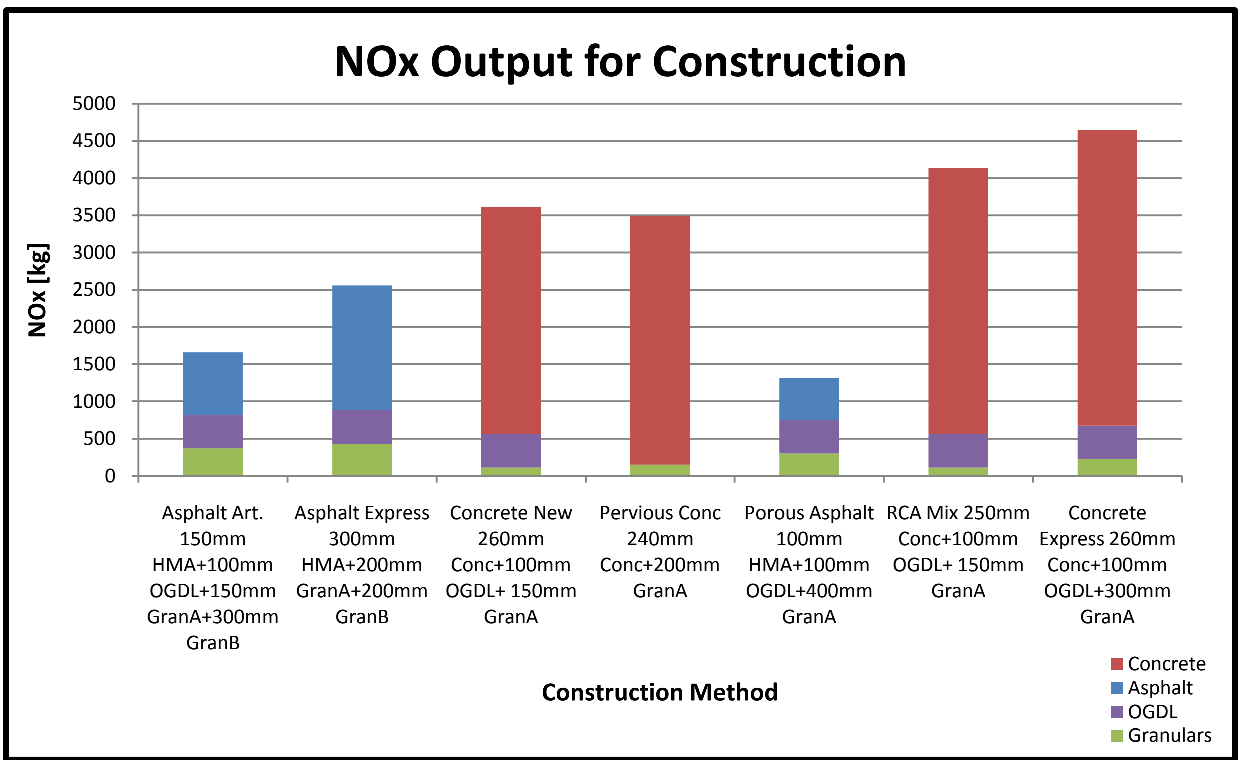


Figure 37: NO_x Output for Construction

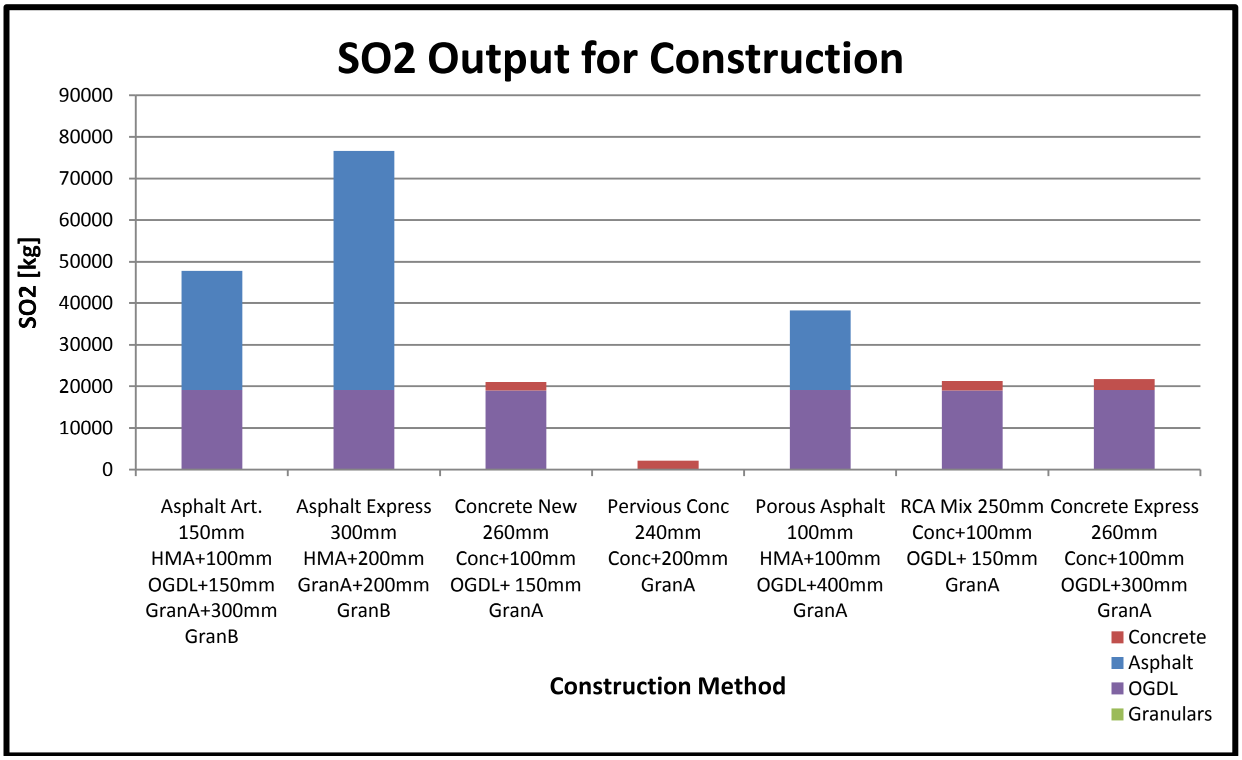


Figure 38: SO_2 Output for Construction

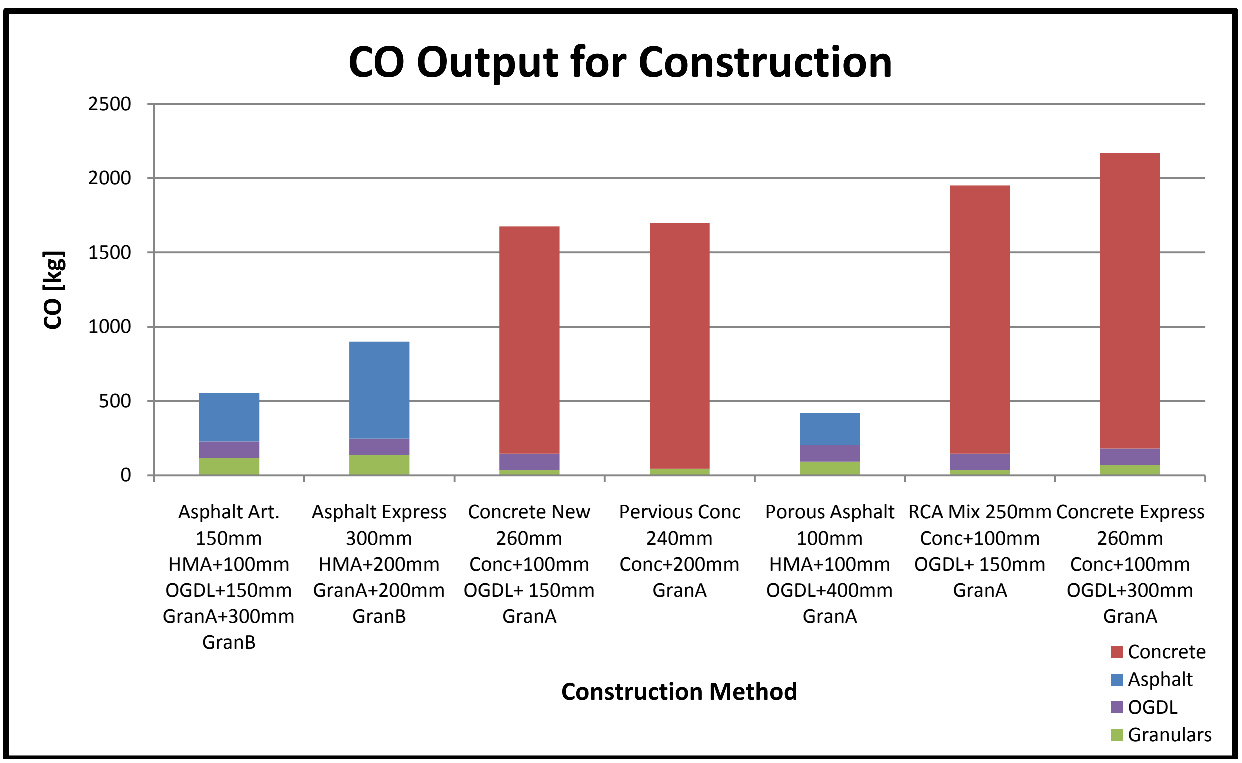


Figure 39: CO Output for Construction

Appendix G

Life Cycle Analysis for Emission and Energy

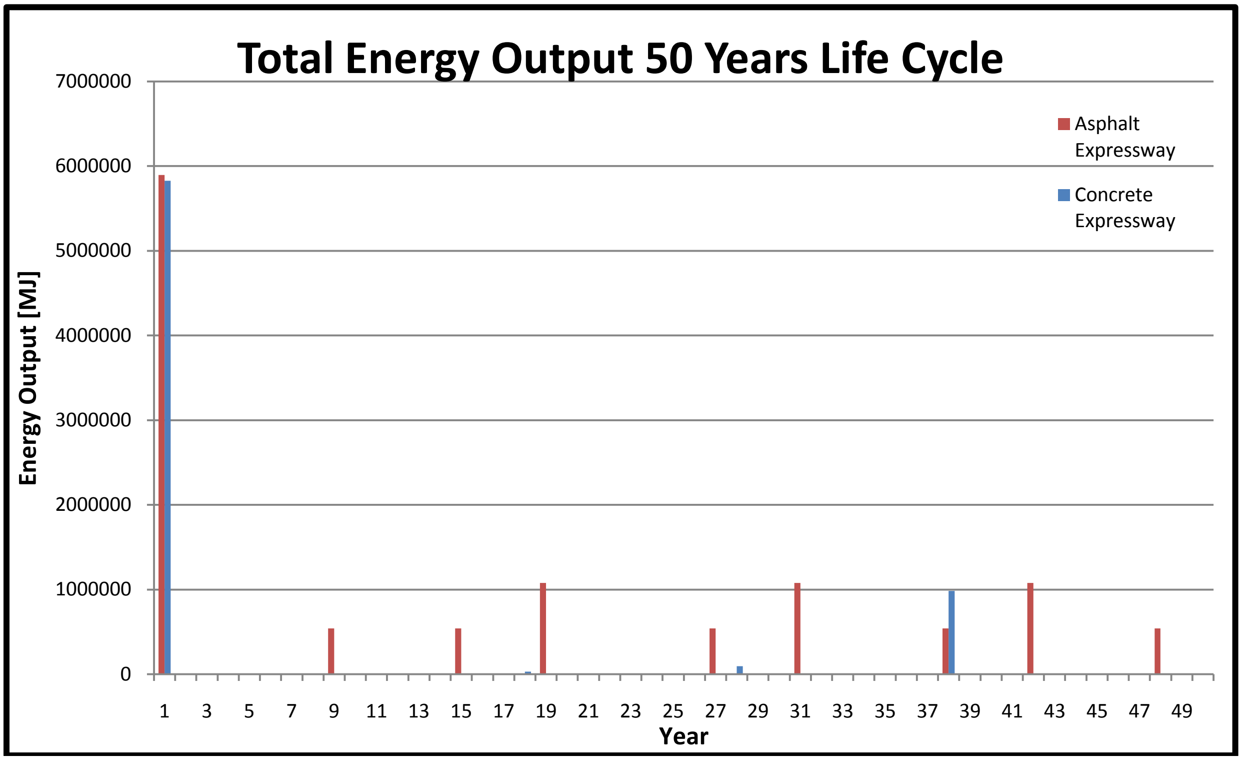


Figure 40: Energy Output Asphalt Pavement 50 Years Life Cycle

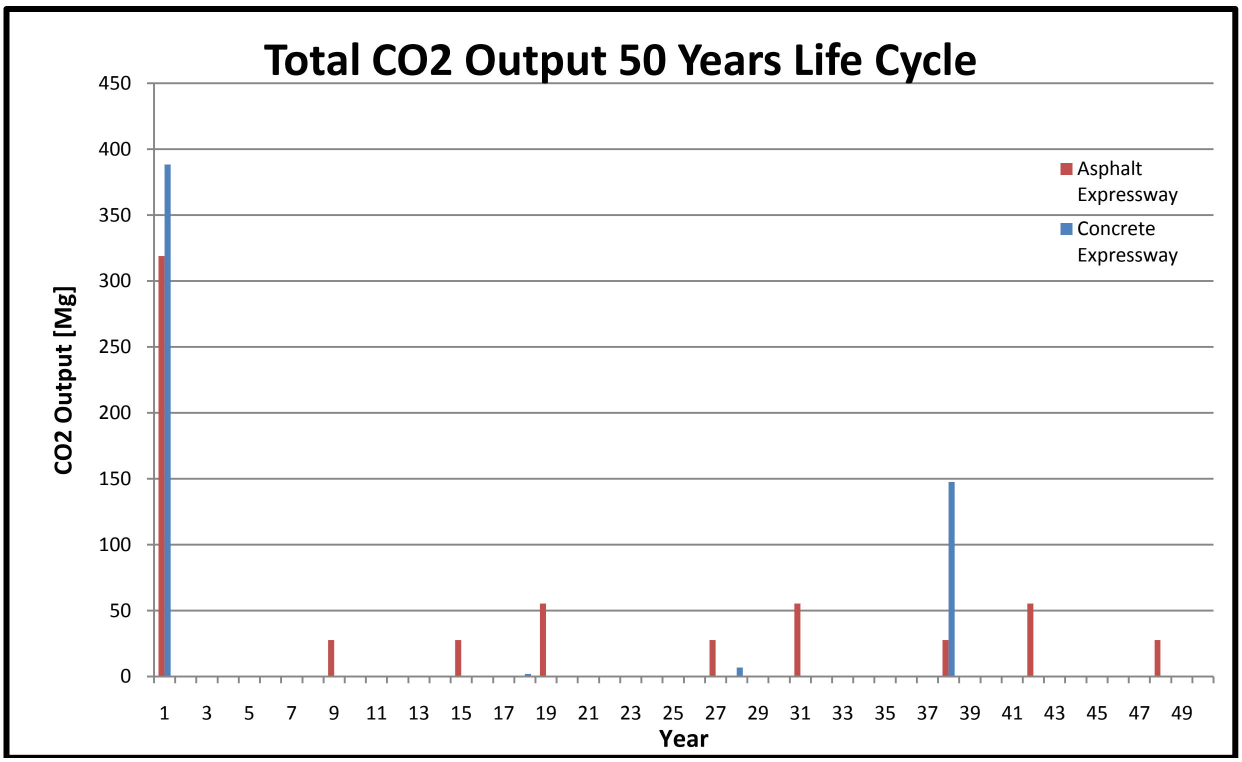


Figure 41: CO_2 Output Asphalt Pavement 50 Years Life Cycle

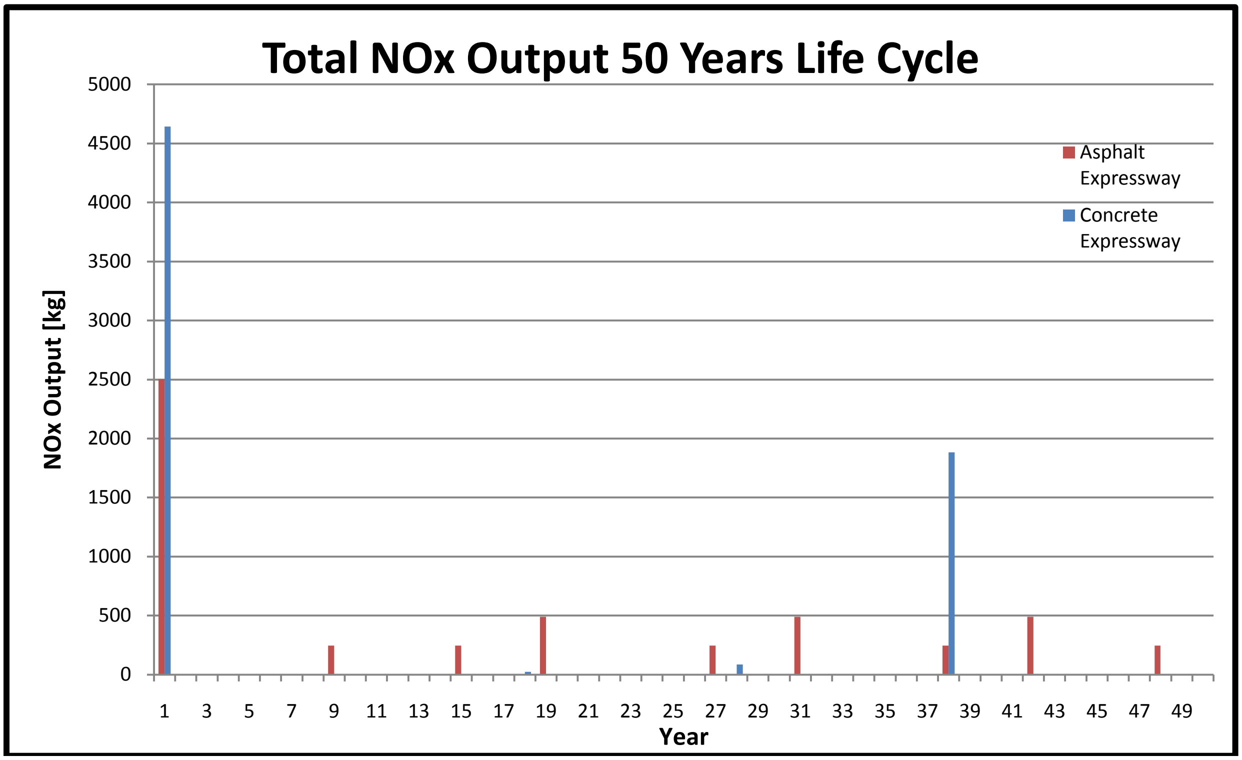


Figure 42: NO_x Output Asphalt Pavement 50 Years Life Cycle

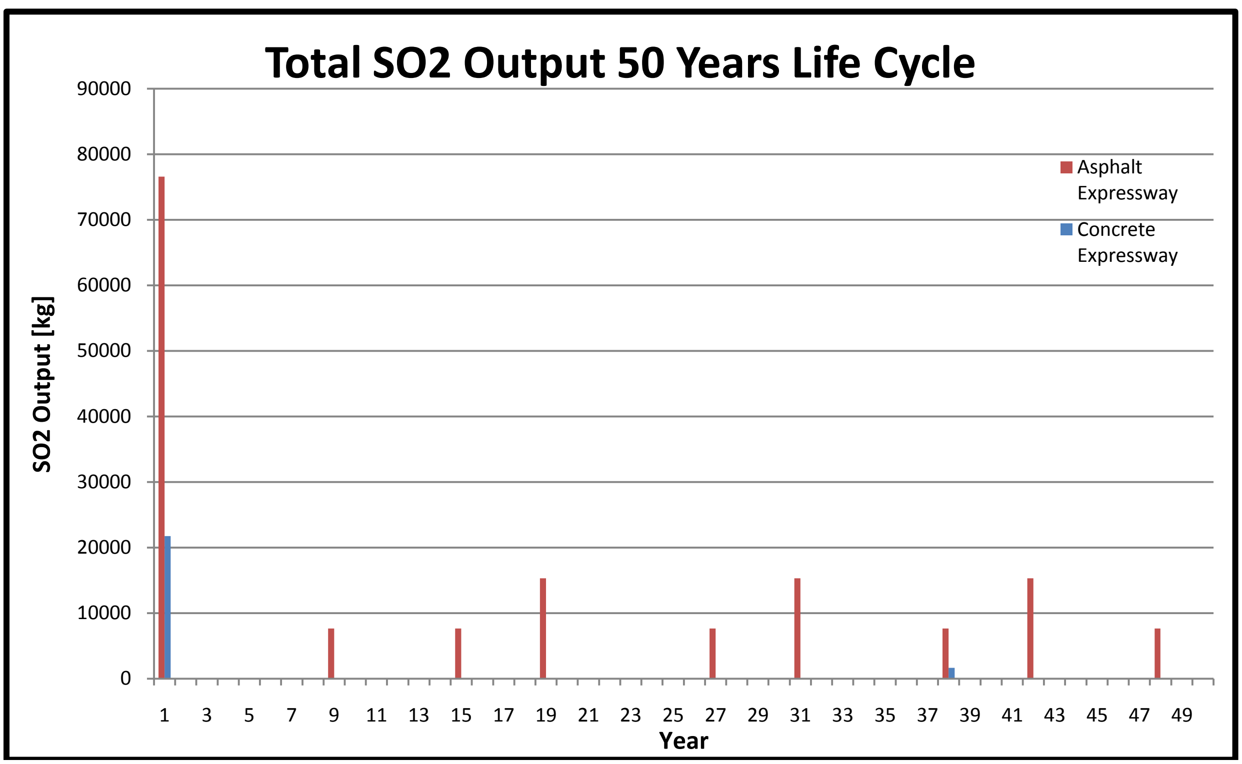


Figure 43: SO_2 Output Asphalt Pavement 50 Years Life Cycle

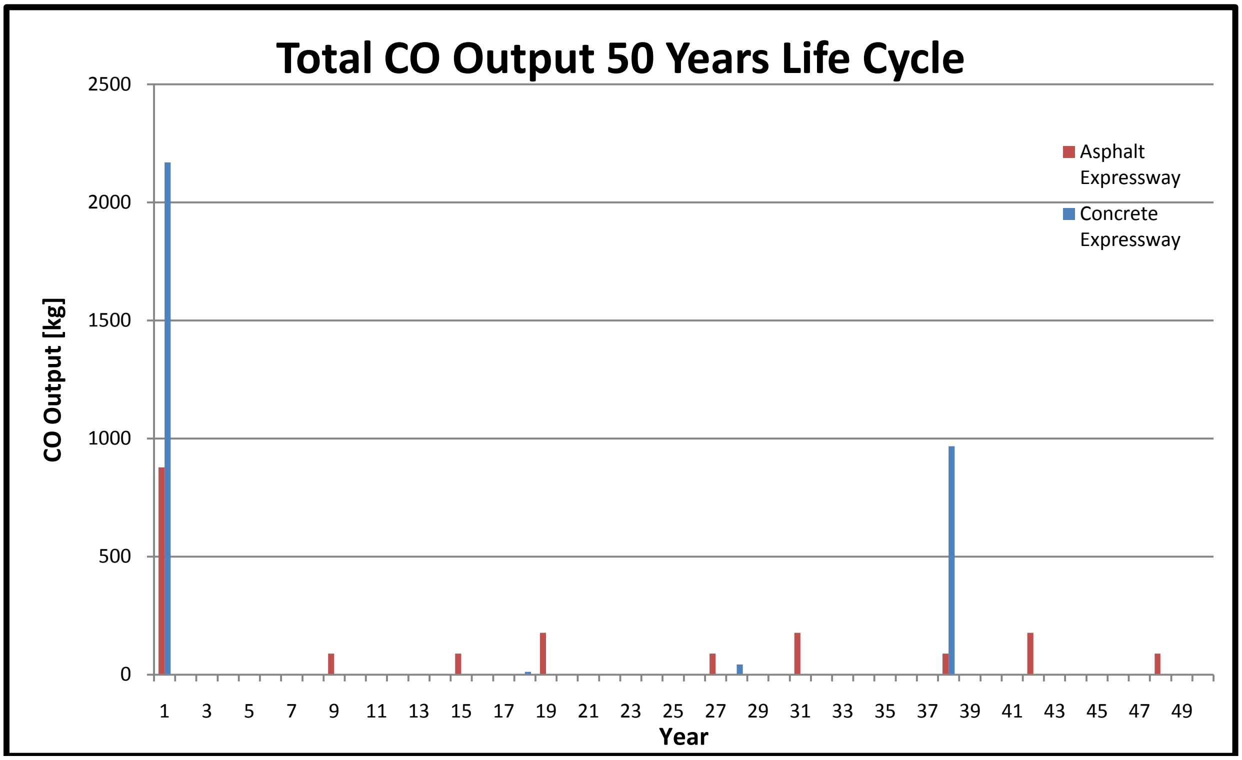


Figure 44: CO Output Asphalt Pavement 50 Years Life Cycle

Appendix H

Life Cycle Cost Analysis

Table 42: Control LCC Schedules

Type	Environmental, Material, and Construction Related Distresses	Load Related Distress	Reconstruction FDR	Reconstruction EAS
Schedule ID	A	B	C	D
Year 0	M2&O2	CIR+O1	FDR+O2	EAS+O1
1				
2				
3	R&S	R&S	R&S	R&S
4				
5				
6				
7				
8		M&P+R&S		
9	M&P+R&S		M&P+R&S	M&P+R&S
10				
11				
12				
13				
14	M2&O2		M1&O2	O2
15		M1&O2		
16				
17	R&S		R&S	R&S
18		R&S		
19				
20				
21				
22				M&P+R&S
23	M&P+R&S		M&P+R&S	
24		M&P+R&S		
25				M2&O2
26				
27	M2&O2		M2&O2	
28		M2&O2		R&S
29				
30	R&S		R&S	
End @ Year	39	40	40	37

Abbreviations

M2&O2	Mill 2 + Overlay 2
R&S	Rout & Seal
M&P+R&S	Mill & Patch + Route & Seal

CIR+O1	Cold In-place Recycling + Overlay 1
O2	Overlay 2 (Resurfacing)
M1&O2	Mill 1 + Overlay 2
FDR+O2	Full Depth Reclamation + Overlay 2
EAS+O1	Expanded Asphalt Stabilization + Overlay 1

Table 43: Modified LCC Schedule

Type	**Environmental, Material Related Distresses**	**Construction Related Distress**	**Concrete Overlay Option**	**Load Related Distress**	**Reconstruction FDR**	**Reconstruction EAS**
Schedule ID	A1	A2	A3	B1	C1	D1
Year 0	M2&O2	M2&O2	M2&O2	CIR+O1	FDR+O2	EAS+O1
1						
2						
3	R&S	R&S		R&S	R&S	R&S
4						
5						
6						
7						
8						
9	M&P+R&S	M&P+R&S			M&P+R&S	M&P+R&S
10						
11						
12						
13						
14	CIR+O1	O2	Concrete Overlay		CIR+O1	CIR+O1
15				CIR+O1		
16						
17	R&S	R&S			R&S	R&S
18				R&S		
19						
20						
21						
22						
23	M&P+R&S				M&P+R&S	M&P+R&S
24				M&P+R&S		
25		O2				
26						
27						
28	CIR+O1				CIR+O1	CIR+O1
29		R&S	Concrete Overlay	CIR+O1		
30					R&S	R&S
End @ Year	41	35	44	41	41	41

Table 44: LCCA in Present Worth Terms for Rehabilitations

Discount Rate 5.30%

Schedule ID	A	B	C	D	A1	A2	A3	B1	C1	D1
Year 0	$308,798.11	$170,353.12	$195,685.62	$177,983.12	$308,798.11	$308,798.11	$308,798.11	$170,353.12	$195,685.62	$177,983.12
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14	$149,857.14		$140,005.72	$130,154.30	$82,670.94	$130,154.30	$66,921.77		$82,670.94	$82,670.94
15		$132,958.90						$78,509.92		
16										
17										
18										
19										
20										
21										
22										
23										
24										
25				$84,911.27		$73,747.35				
26										
27	$76,578.81		$76,578.81							
28		$72,724.42			$40,119.52			$40,119.52	$40,119.52	$40,119.52

29							$30,841.89			
30										
Total PW	$535,234.06	$376,036.43	$412,270.14	$393,048.69	$431,588.57	$512,699.76	$406,561.66	$288,982.56	$318,476.08	$300,773.58
SV	$(49,190.90)	$(54,656.55)	$(50,452.20)	$(38,259.59)	$(30,615.99)	$(28,482.27)	$27,337	$(33,167.32)	$(30,615.99)	$(30,615.99)
Total W SV	$486,043.16	$321,379.88	$361,817.94	$354,789.10	$400,972.58	$484,217.49	$379,224.72	$255,815.23	$287,860.09	$270,157.59
Total Saved to Control					$(85,070.58)	$(1,825.67)	$(106,818.28)	$(65,564.64)	$(73,957.85)	$(84,631.51)
% Saved to control					-18%	0%	-22%	-20%	-20%	-24%

Table 45: Unit Pricing for Expressway Construction

Material	Unit Cost	Measurement Unit	Quantities	Total Components	Total as an item
Concrete JPCP	39.4	m^2	7000	$ 275,800.00	$ 617,344.00
OGDL	35.4	m^2	7000	$ 247,800.00	
Granular A	18.6	T	5040	$ 93,744.00	
SMA	172.04	T	694.4	$ 119,464.58	$ 1,032,204.66
Superpave 19	114.31	T	1736	$ 198,442.16	
Superpave 25	111.7	T	2777.6	$ 310,257.92	
OGDL	35.4	m^2	7000	$ 247,800.00	
Granular A	18.6	T	8400	$ 156,240.00	
Mill 80mm	14.3	m^2	7000	$ 100,100.00	$ 339,029.15
Patch 80mm	172.04	T	1388.8	$ 238,929.15	
Mill &Patch 40mm	6.9	m2	7000	$ 48,300.00	$ 48,300.00
Partial CPR Year 18	226.05	m^2	20.37	$ 4,604.64	$ 11,394.06
Full CPR Year 18	188.7	m^2	35.98	$ 6,789.43	
Partial CPR Year 28	226.05	m^2	73.5	$ 16,614.68	$ 39,202.07
Full CPR Year 28	188.7	m^2	119.7	$ 22,587.39	
Concrete Overlay	39.4	m^2	3500	$ 137,900.00	$ 137,900.00

Table 46: LCCA of Asphalt and Concrete Expressway

I=5.3%	Asphalt Expressway			Concrete Expressway			
Year	Activity	Price	Present Worth	Activity	Price	Present Worth	Present Worth Factor
0	Asphalt Expressway Construction	$1,032,204.66	$1,032,204.66	Concrete Expressway Construction	$617,344.00	$617,344.00	1
1							0.949668
2							0.901869
3							0.856475
4							0.813367
5							0.772428
6							0.73355
7							0.696629
8							0.661566
9	M&P 40	$ 48,300.00	$30,345.32				0.628268
10							0.596645
11							0.566615
12							0.538096
13							0.511012
14							0.485292
15	M&P 40	$48,300.00	$22,259.82				0.460866
16							0.437669
17							0.41564
18				Partial and Full CPR	$11,394.06	$4,497.47	0.39472
19	M&P 80	$339,029.15	$127,086.08				0.374853
20							0.355986
21							0.338068
22							0.321052
23							0.304893
24							0.289547
25							0.274973

26							0.261133
27	M&P 40	$48,300.00	$11,977.91				0.24799
28				Partial and Full CPR	$39,202.07	$9,232.40	0.235508
29							0.223654
30							0.212397
31	M&P 80	$339,029.15	$68,384.48				0.201707
32							0.191554
33							0.181913
34							0.172757
35							0.164062
36							0.155804
37							0.147962
38	M&P 40	$48,300.00	$6,786.86	Concrete Overlay	$137,900.00	$19,376.98	0.140515
39							0.133442
40							0.126726
41							0.120347
42	M&P 80	$339,029.15	$38,747.66				0.11429
43							0.108538
44							0.103075
45							0.097887
46							0.09296
47							0.088281
48	M&P 40	$48,300.00	$4,049.35				0.083837
49							0.079618
50							0.07561
Total Present Worth			$1,341,842.14			$650,450.85	
Expected Service Life for Last Rehab. (L_{EXP})	11			15			
Remaining life (L_{REM})	3			3			
Salvage Value			$995.99			$2,085.33	
Net Present Worth			$1,340,846.14			$648,365.51	

Appendix I

Comprehensive GreenPave Results

Table 47: GreenPave Ratings for 2008/2009 Fiscal Year

# Of Projects	WP #	Region	Option #	Cost	GreenPave Score	MR Score	GreenPave Rating
1	5-98-00	CR	Alternative 1 (New AC) HM 250, Gran A 150, Gran B 850	$496,055	3	2.00	Not Certified
			Alternative 2 (New PCC) PCC 280, OGDL 150, Gran A 250	$583,497	10	2.00	Bronze
			Alternative 3 (M&O) Mill 90, HM 100mm	$487,085	5	4.00	Not Certified
2	128-85-00	CR	Alternative 1 (M&O) Remove HM, CPR as req'd, 90mm HM	N/A	6	4.00	Not Certified
3	167-99-00	CR	Alternative 1 (M&O) Mill 40mm, 180mm HM	$508,500	5	4.00	Not Certified
			Alternative 2 (FDR) Mill 70mm, Pulverize to 300mm, 200mm HM	$598,500	9	7.60	Bronze
			Alternative 3 (EAS) Mill 70mm, Pulverize to 150mm with EA, 170mm HM	$643,000	13	6.80	Silver
4	2478-04-00	CR	Alternative 1 (O1) 140mm HM	$497,288	5	4.00	Not Certified
			Alternative 2 (M&O) Mill 50mm, 140mm HM	$484,264	5	4.00	Not Certified
			Alternative 3 (???) Scarify, 150mm A, 140mm HM	$543,552	14	7.60	Silver

5	2381.02.01	CR	Alternative 1 (New AC) 290mm HM, 150mm A, 600mm B	N/A	3	2.00	Not Certified
6	2-99-00	ER	Alternative 1 (New AC) 100mm HM, 200mm A, 250mm B	N/A	3	2.00	Not Certified
7	185-99-00	ER	Alternative 1 (FDR) FDR 250mm, 90mm HM	$163,679	13	6.50	Silver
			Alternative 2 (EAS) Pulverize 250mm, Foam 125mm, 50mm HM	$151,337	14	7.50	Silver
			Alternative 3 (CIR) CIP 80mm, 50mm HM	$154,814	13	6.80	Silver
8	194-99-00	ER	Alternative 1 (CIR) CIP 80mm, 60mm HM	$1,674,900	12	6.20	Silver
			Alternative 2 (FDR) IPP 200mm, 90mm HM	$1,604,800	13	6.90	Silver
			Alternative 3 (FDR) IPP 200mm, 50mm Gran A, 90mm HM	$1,677,400	13	6.80	Silver
9	196-99-00	ER	Alternative 1 (New AC) Widening 230mm HM, 260mm A, 650mm B	$1,674,900	3	2.00	Not Certified
10	452-98-00	ER	Alternative 1 (Rubb) Mill 147mm HM, Rubblize Conc, 100mm A (40% RAP), 130mm	$292,010	9	5.60	Bronze

			HM				
			Alternative 2 (M&O)	$320,034	8	4.50	Bronze
			Mill 147mm HM, 225mm A (40% RAP), 130mm HM				
11	146-98-00	NR	Alternative 1 (FDR)	$362,607	11	6.60	Silver
			FDR, 150mm Gran A, 130mm AC				
			Alternative 2 (FDR)	$329,486	15	8.50	Gold
			IPP to 300mmm, 100mm Gran A, 130mm AC				
			Alternative 3 (FDR)	$307,989	14	8.20	Silver
			IPP to 300mm, 130mm AC				
			Alternative 5 (CIR)	$347,796	17	11.00	Gold
			CIR (100mm), 60mm overlay				
12	324-97-00	NR	Alternative 1 (FDR)	$155,850	12	9.40	Silver
			Pulverize to 140mm, 50mm HM				
			Alternative 2 (FDR)	N/A	12	8.20	Silver
			Pulverize to 140mm, 50mm A, 50mm HM				
			Alternative 3 (FDR)	N/A	8	5.70	Bronze
			Pulverize to 140mm, 100mm A, 50mm HM				
			Alternative 4 (EAS)	N/A	15	9.00	Gold
			RDR with EA to 100mm, 50mm HM				
13	403-98-00	NR	Alternative 1 (O1)	$169,000	6	5.00	Not Certified
			50mm HM				
			Alternative 2 (M&O)	$186,700	6	5.00	Not Certified
			Mill 50mm, 90mm HM				
			Alternative 3 (FDR)	$189,300	16	9.80	Gold

			FDR, 60mm HM				
			Alternative 4 (EAS)	$156,900	16	9.50	Gold
			150mm EA, 50mm HM				
			Alternative 5 (FDR)	$226,800	5	4.00	Not Certified
			Remove HM, 50mm A, 100mm HM				
14	476-98-00	NR	Alternative 1 (FDR)	$2,346,894	14	7.80	Silver
			IPP to 160mm, 90mm HM				
			Alternative 2 (FDR)	$2,574,281	9	3.00	Certified
			FDR HM, 100mm A, 90mm HM				
			Alternative 3 (EAS)	$2,565,735	16	9.50	Gold
			IPP to 150mm using EA, 50mm HM				
15	5118-03-00	NR	Alternative 1 (M&O)	$135,000	6	5.00	Not Certified
			Mill 50mm, Pave 50mm HM				
			Alternative 2 (FDR)	$470,000	5	4.00	Not Certified
			Remove HM, 90mm HM				
16	5283-01-00	NR	Alternative 1 (M&O)	N/A	5	4.00	Not Certified
			Mill 100mm, Pave 100mm HM				
			Alternative 2 (New AC)	N/A	3	2.00	Not Certified
			750mm B, 150mm A, 200mm HM				
17	57-97-00	NWR	Alternative 1 (FDR)	N/A	11	4.90	Silver

			Mill, Pulverize to 300mm, 50mm A, 130mm HM				
18	407-00-00	NWR	Alternative 1 (FDR)	N/A	13	7.00	Silver
			IPP, 50mm Gran A, 90mm HM				
19	559-01-00	NWR	Alternative 1 (FDR)	N/A	13	6.90	Silver
			IPP (86.4mm), 75mm A, 60mm HM				
20	6016-03-00	NWR	Alternative 1 (FDR)	N/A	12	8.30	Silver
			Pulverize (284mm), 50mm A, 60mm HM				
21	71-00-00	SWR	Alternative 1 (M&O)	N/A	9	5.20	Bronze
			Mill HM, remove 50mm A, 300mm HM, 200mm A				
			Alternative 2 (New PCC)	N/A	4	3.00	Not Certified
			Remove HM, 280mm Conc, 100mm OGDL				

Appendix J

GDLCC Plots and Regression Comparison

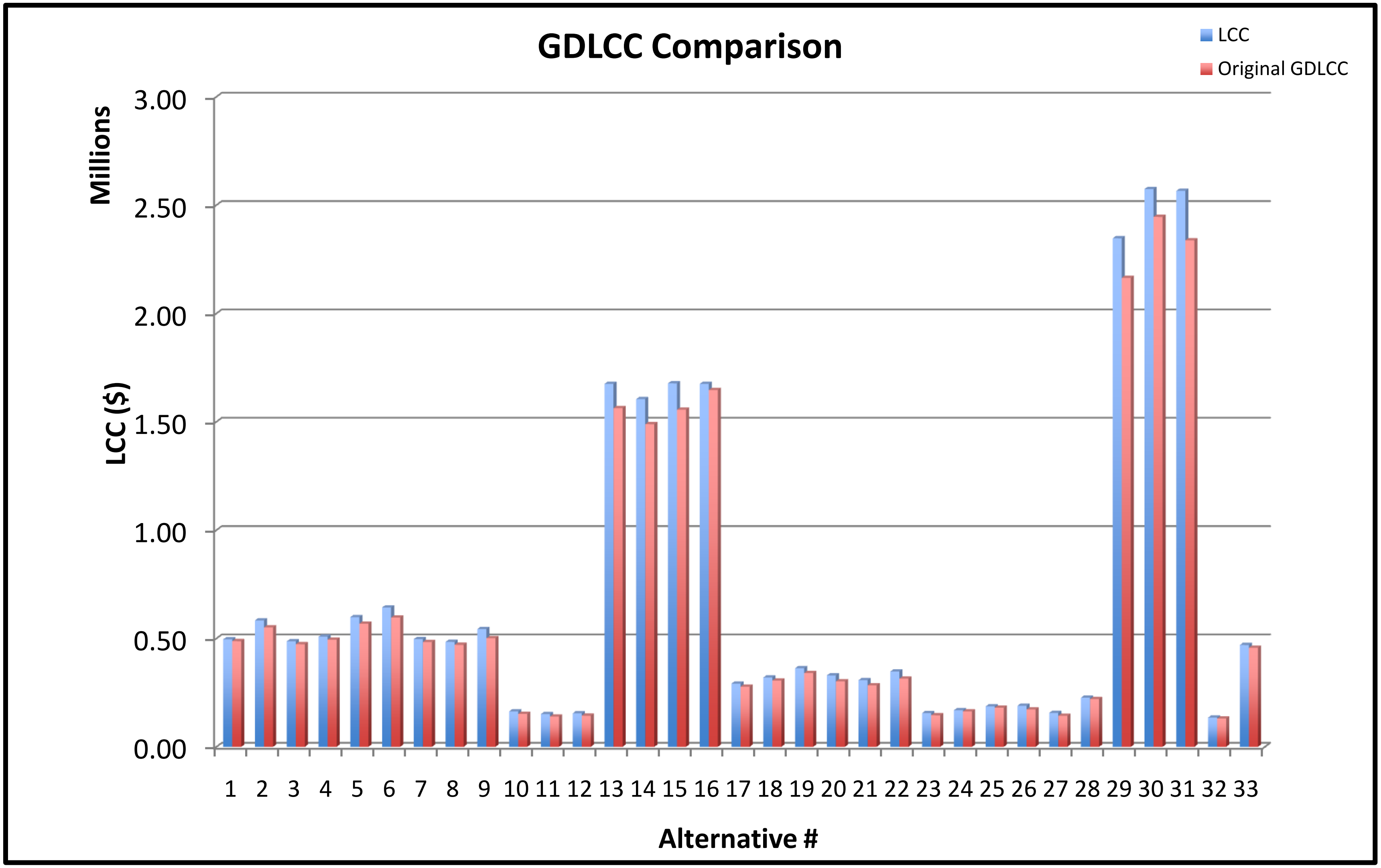


Figure 45: LCC Versus Original GDLCC Plot

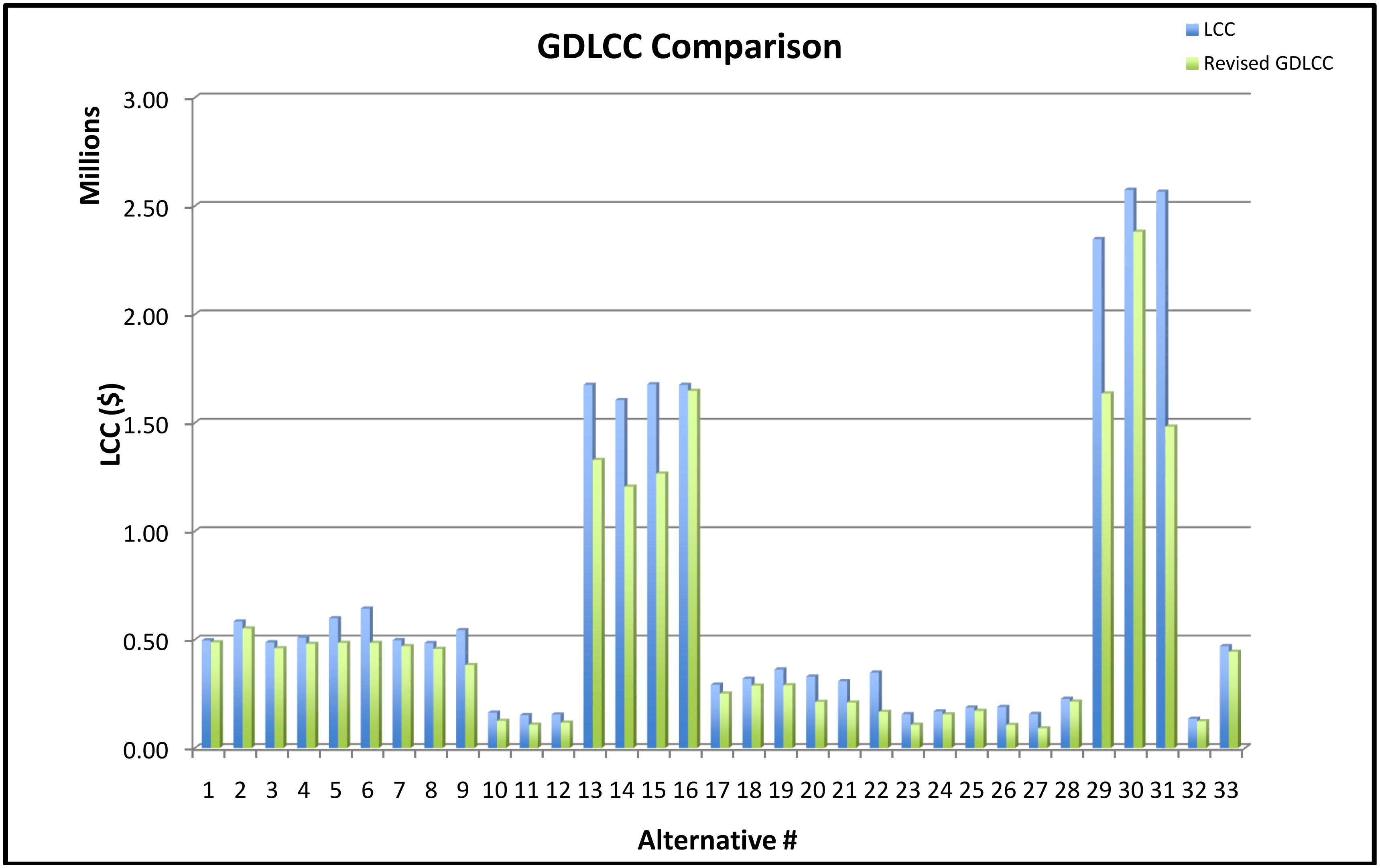


Figure 46: LCC Versus GDLCC Type P Plot

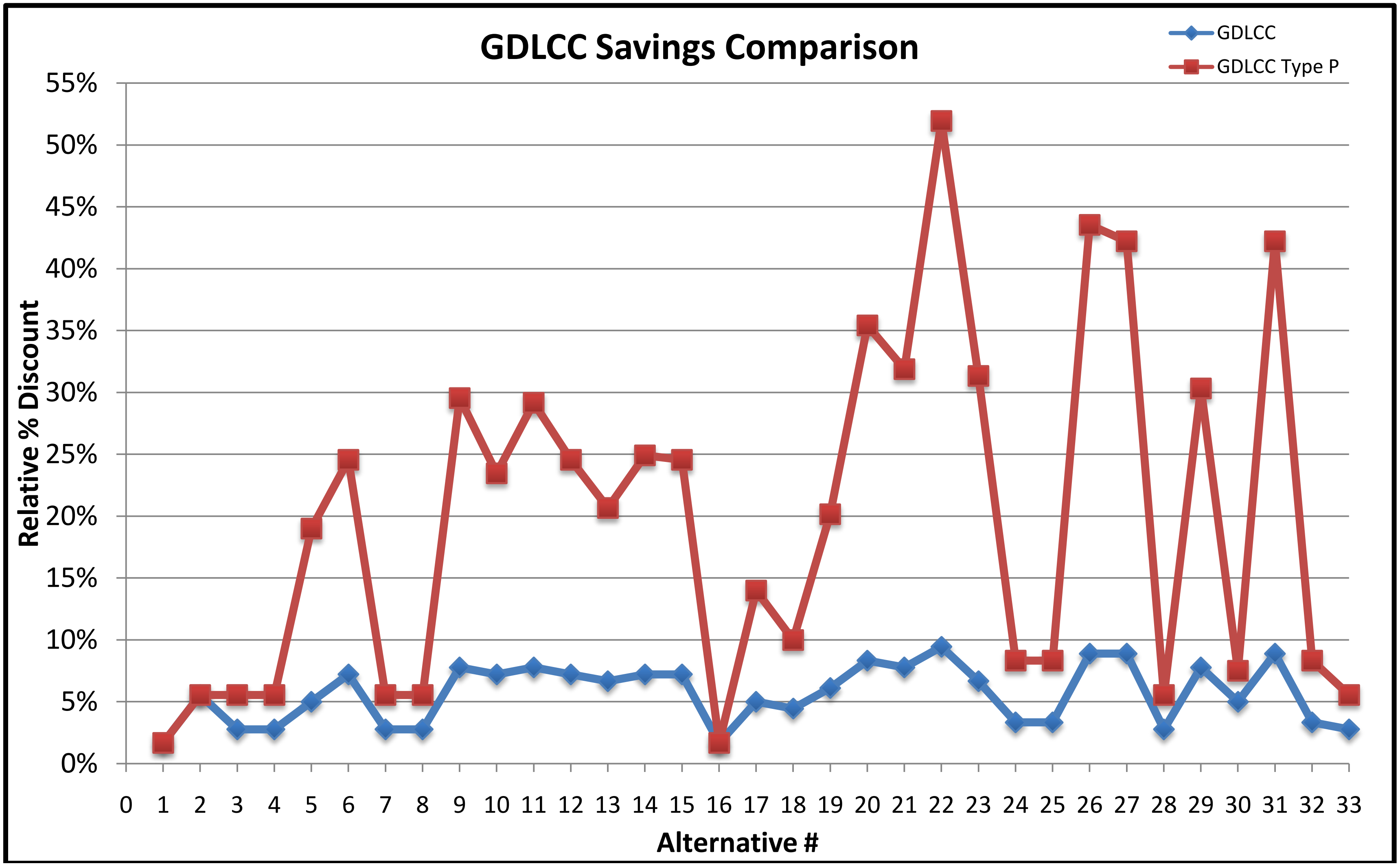


Figure 47: GDLCC Savings Comparison

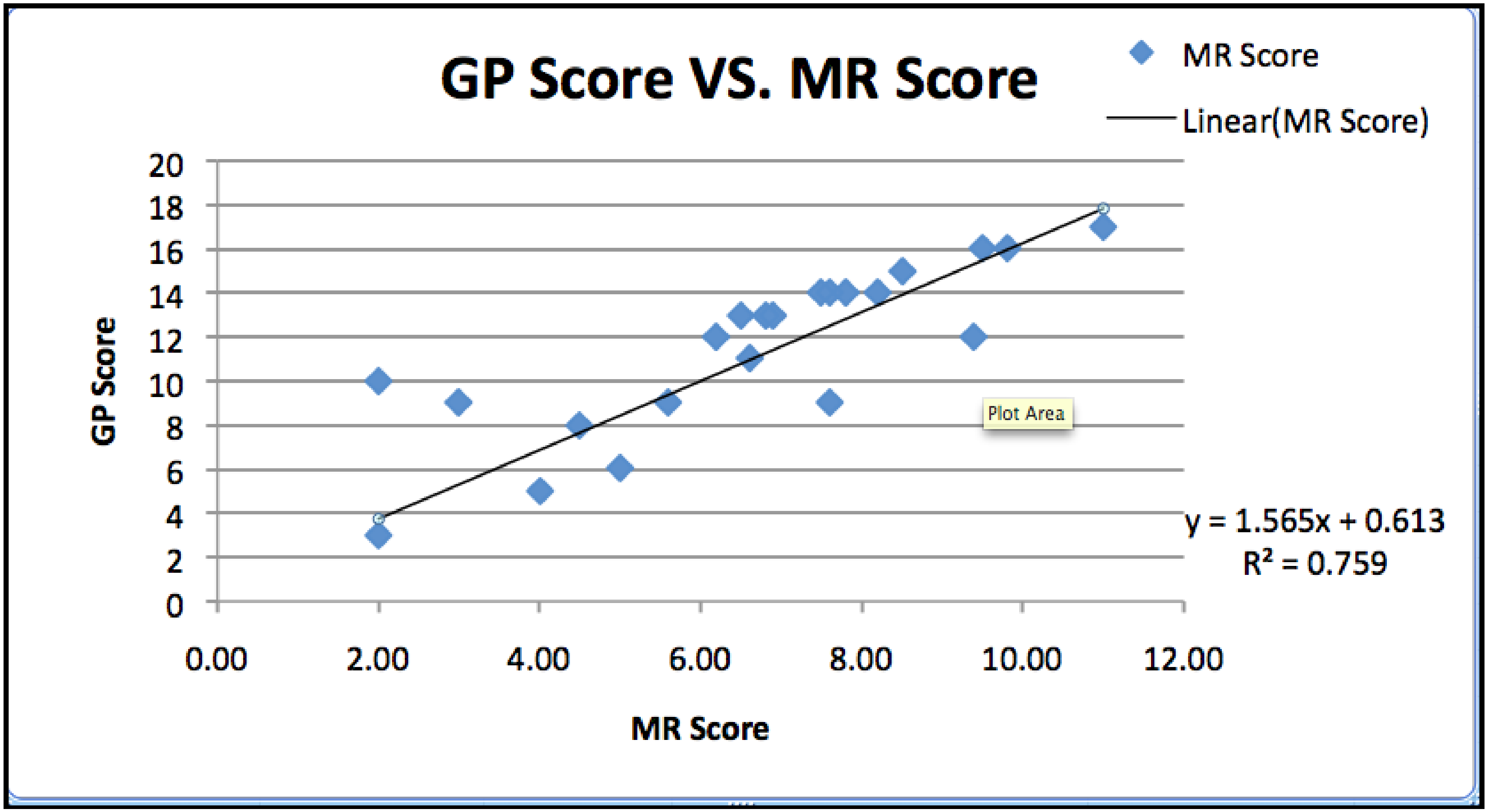


Figure 48: Linear Regression Model for GDLCC Type P

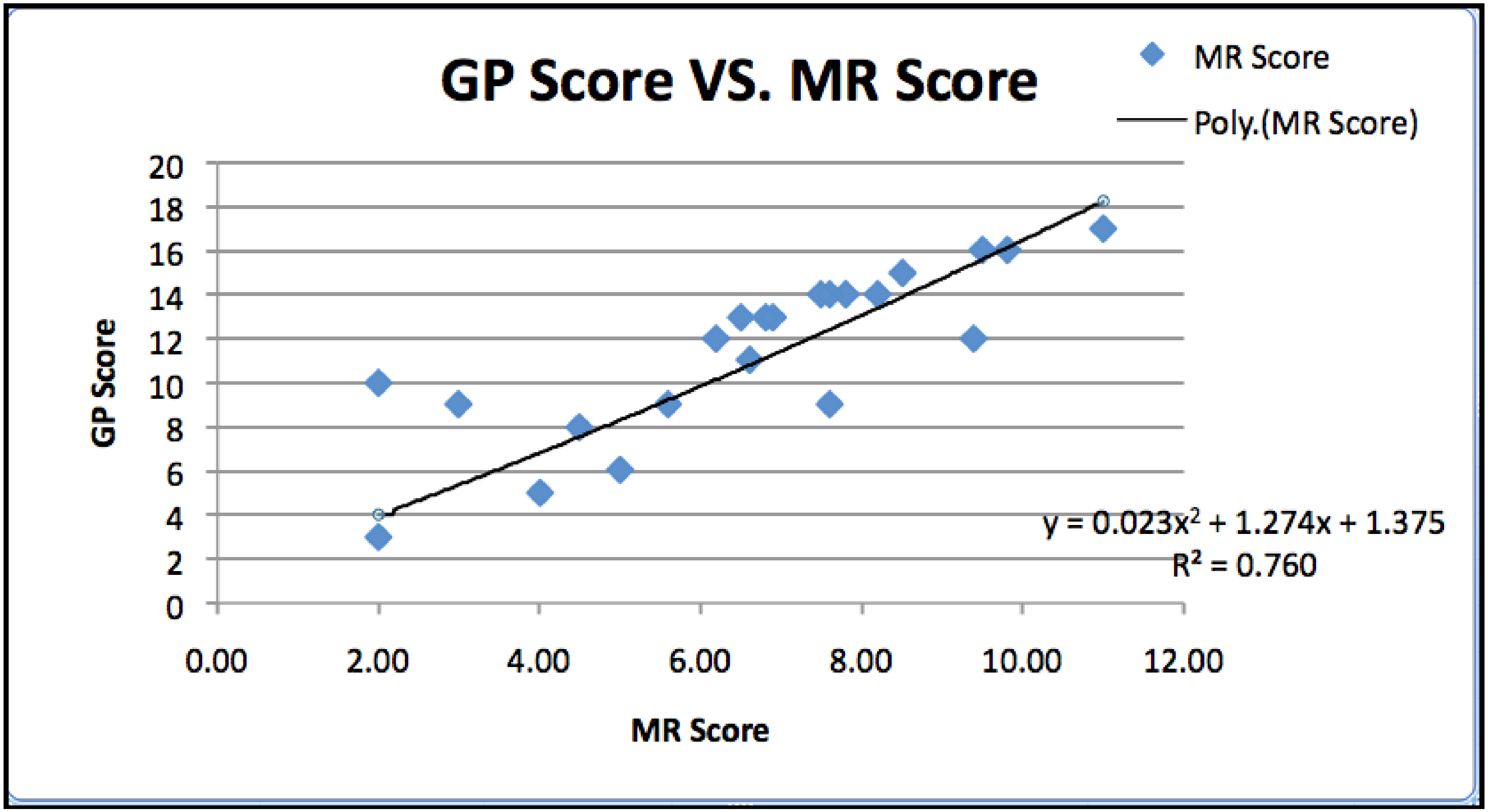


Figure 49: Quadratic Regression Model for GDLCC Type P

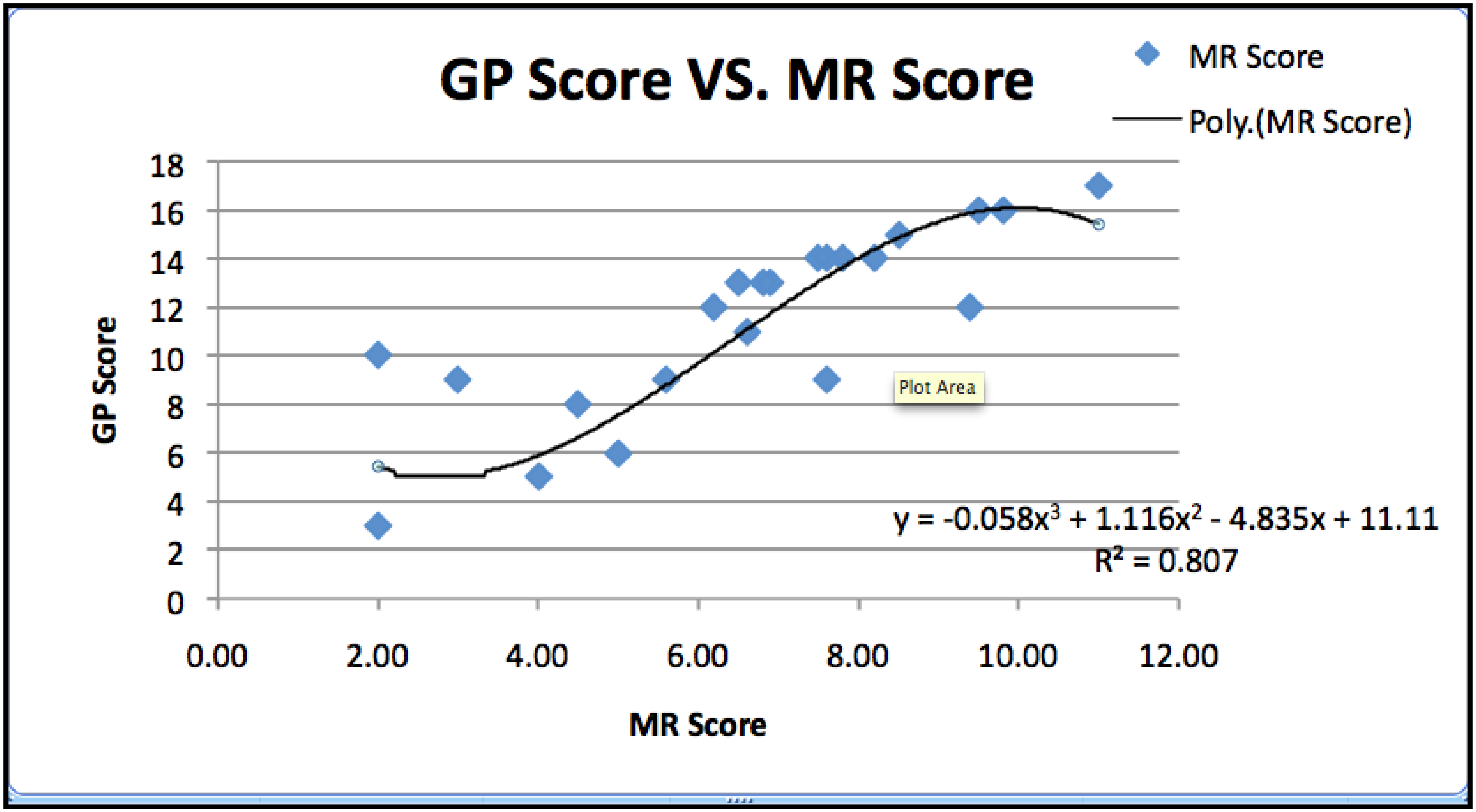


Figure 50: Cubic Regression Model for GDLCC Type P

Appendix K

Sustainable Decision Trees Set for PMS2

Table 48: Decision Tree Acronyms

Pavement Type	Acronym from PMS2 Figure 19	Acronym from Decision Trees in this Report (Figure 20, Figure 21, Appendix K)	Meaning
Asphalt	Recl+Ovly#	FDR with # Lift Overlay	Full Depth Reclamation # Lift Overlay
	Recon_AC		Reconstruction with Asphalt
	Recon_PCC		Reconstruction with Concrete
	Mil+Ovly#		Mill and Overlay with # lifts of asphalt
	CIR+Ovly#	CIR with # Lift Overlay	Cold In-Place Recycling with # lifts of asphalt
	EAS_Ovly#	EAS with # Lift Overlay	Expanded Asphalt Stabilization with # lifts of asphalt
Concrete	Rec_AC		Reconstruction with Asphalt
	Recon_PC_F		Reconstruction with Concrete Freeway
	Reh+DG		Concrete Rehabilitation and diamond grinding
	CPR+HM	CPR + # Lift Overlay	Concrete Pavement Restoration with # lifts asphalt overlay
	Reh+Ovly#		Concrete Rehabilitation with # lifts asphalt overlay
Miscellaneous	PCI	PCI	Pavement Condition Index
	AADT	AADT	Annual Average Daily Traffic
	ESAL	ESAL	Equivalent Standard Axle Load

- the symbol “ #” denotes number of asphalt overlay required for the treatment
- the treatment ends with “F” denotes treatment used on Freeway only

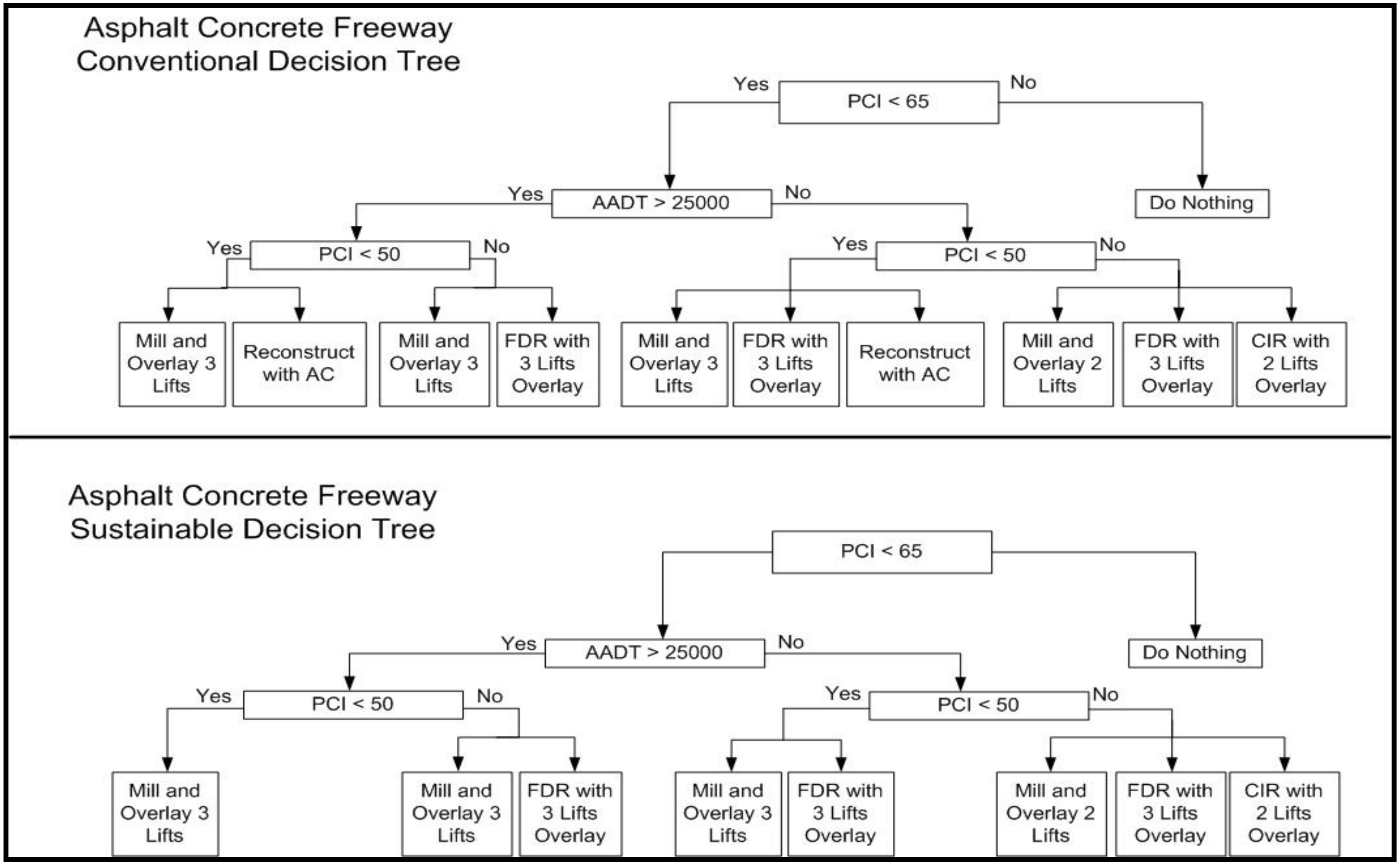


Figure 51: Asphalt Freeway Conventional VS. Sustainable Decision Tree

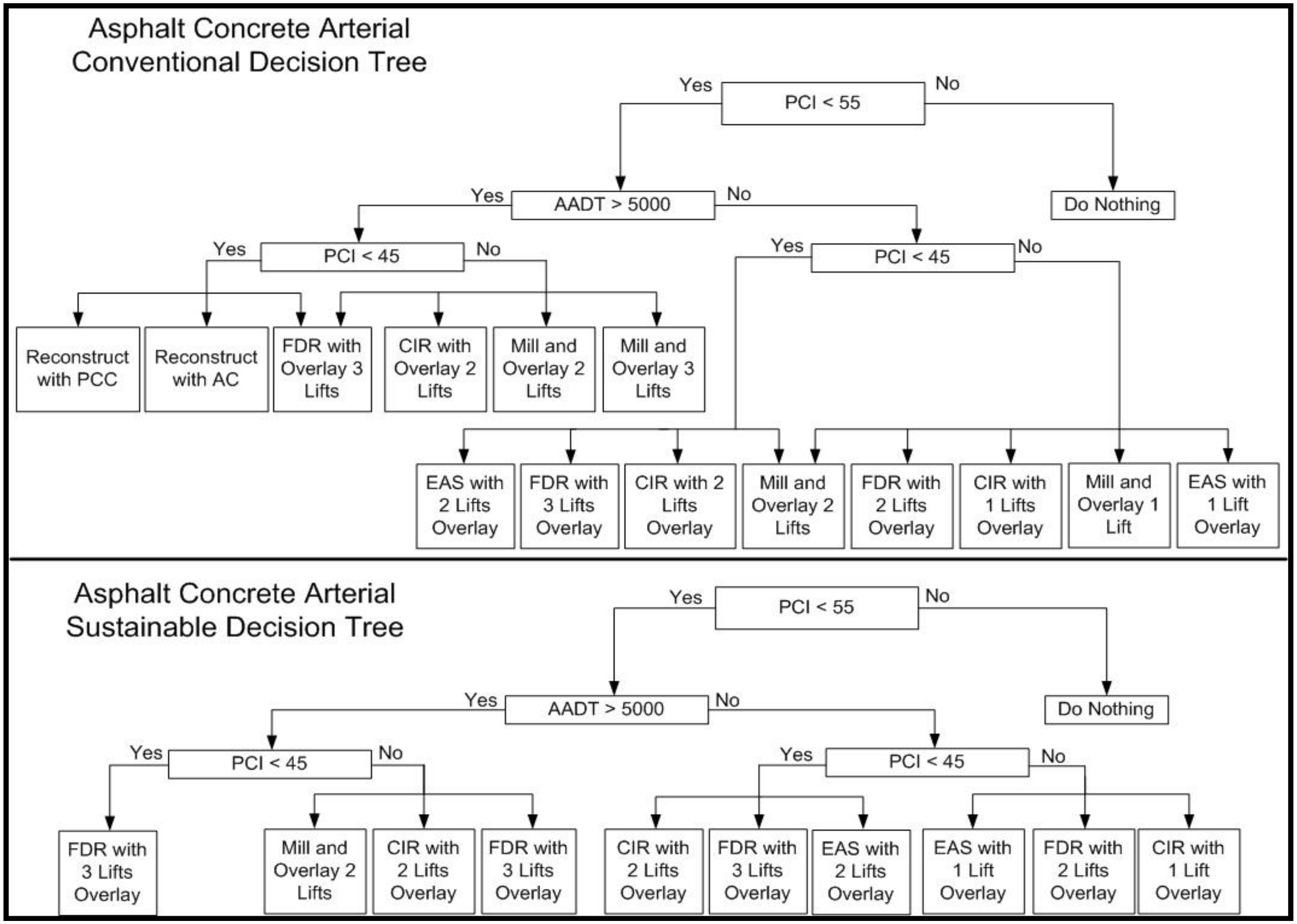


Figure 52: Asphalt Arterial Conventional VS. Sustainable Decision Tree

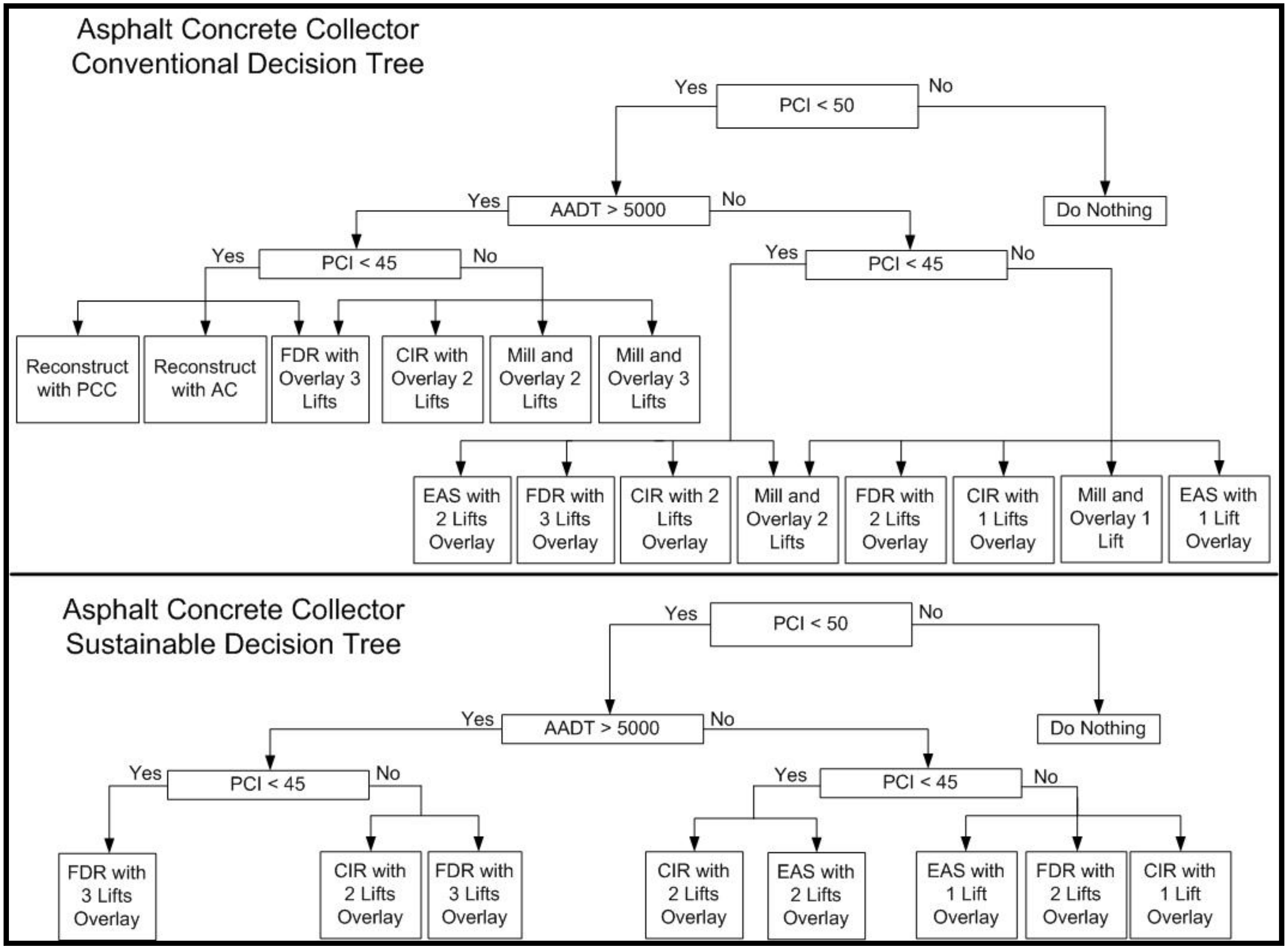


Figure 53: Asphalt Collector Conventional VS. Sustainable Decision Tree

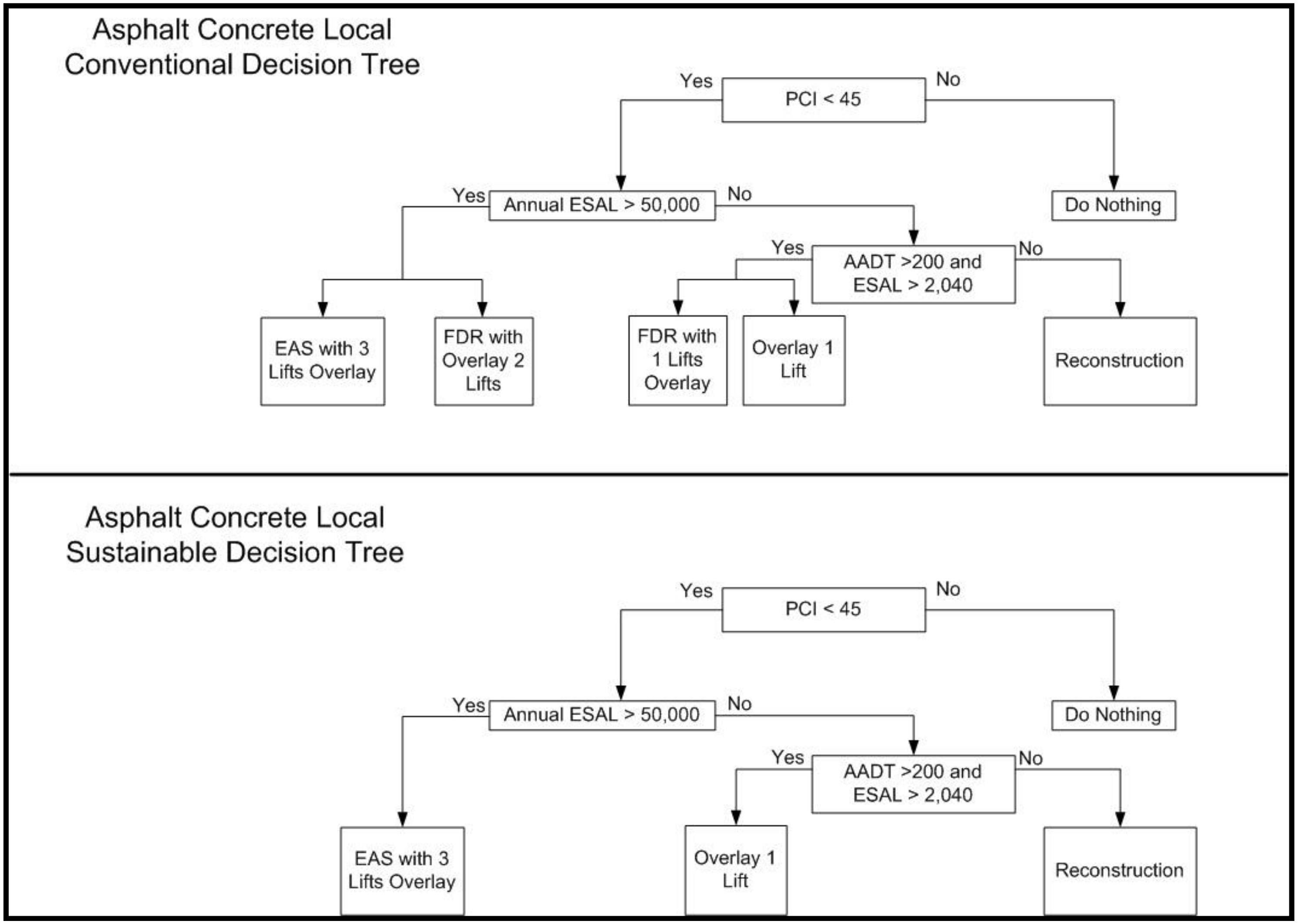


Figure 54: Asphalt Local Conventional VS. Sustainable Decision Tree

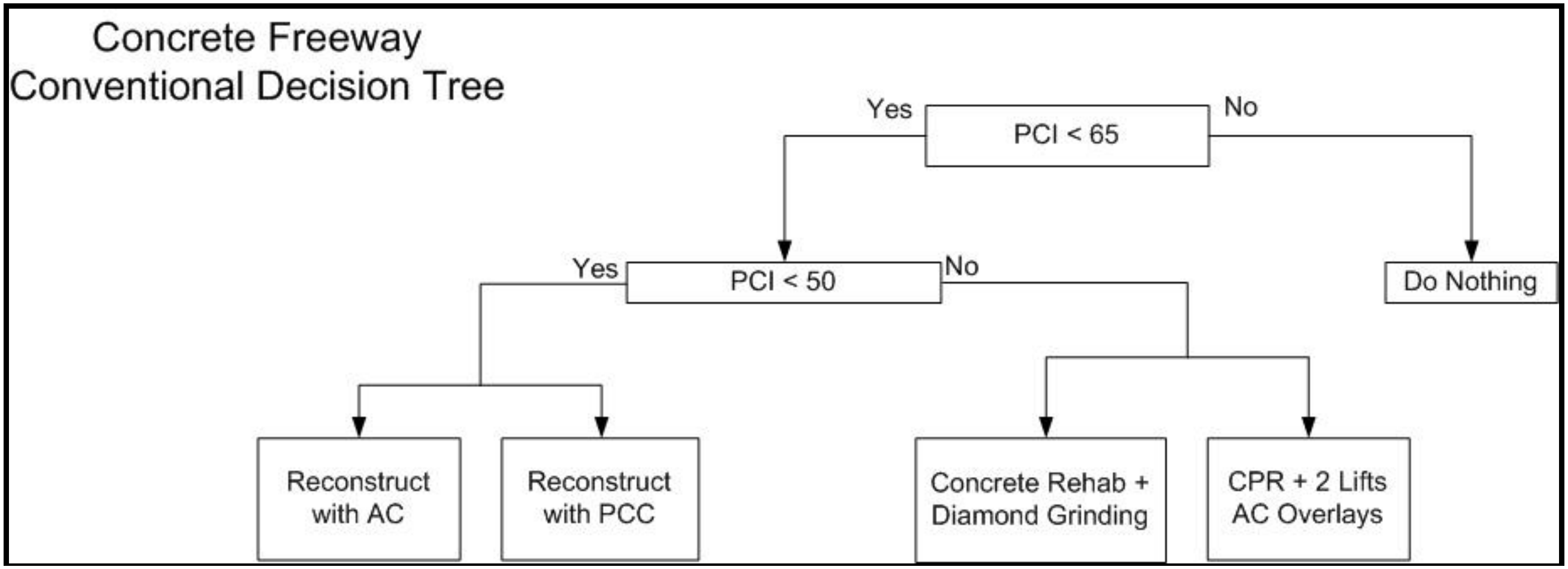


Figure 55: Concrete Freeway Decision Tree

- Note there is lack of treatment that has model in PMS2 for concrete freeway. Therefore, at this stage of the project, no sustainable decision tree can be proposed.

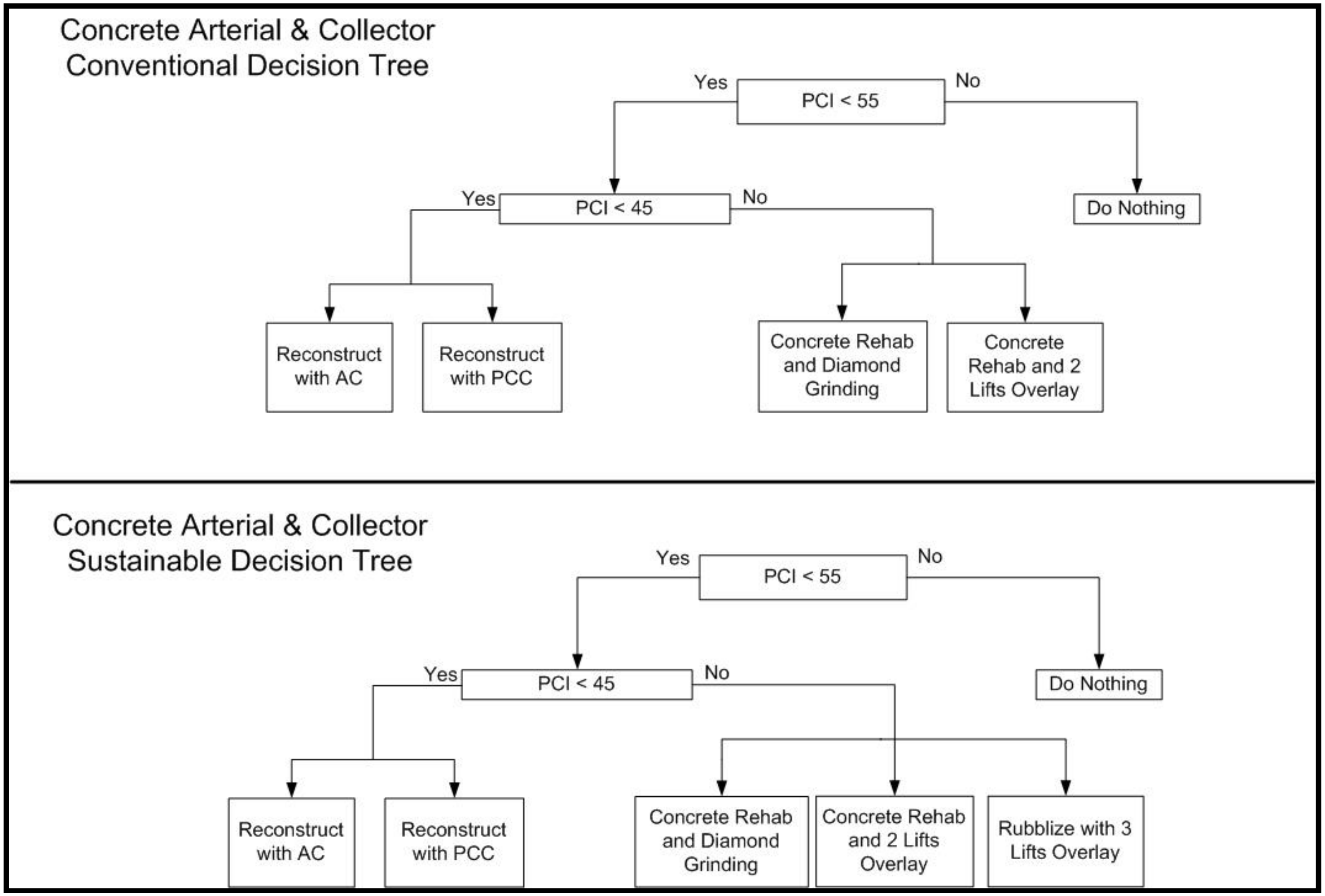


Figure 56: Concrete Arterial and Collector Conventional VS. Sustainable Decision Tree

- Note PMS2 has the same decision tree for arterials and collectors with concrete pavement. There is no decision tree defined for locals with concrete pavement

Appendix L

Minimum PCI Service Life for Network Level Analysis

Table 49: Minimum Service Lives in PMS2

Pavement Type	PMS2 Model CODE	Name	PCI Min
Asphalt	101	HM Overlay1	6
	102	Mill+HM Overlay1	7
	102F	Mill+HM Overlay1 Fwy	7
	104	Mill+HM Overlay2	10
	104F	Mill+HM Overlay2 Fwy	10
	105	Mill+HM Overlay3	12
	105F	Mill+HM Overlay3 Fwy	12
	106	FDR+HM Overlay1	9
	107	FDR+HM Overlay2	12
	108	FDR+HM Overlay3	14
	108F	FDR+HM Overlay3 Fwy	13
	110	Recon to AC3	14
	110F	Recon to AC5 Fwy	14
	111F	Recon to PCCFWY	24
	153	CIR + HM Overlay 1	10
	153	CIR + HM Overlay 2	13
	153F	CIR + HM Overlay 2 Fwy	12
	155	EAS 1Lft	9
	156	EAS 2Lft	11
	156F	EAS 2Lft Fwy	7
Concrete	201	CPR + Diamond Grinding	8
	202F	CPR +HM Overlay2 Fwy	12
	203	Recon to PCCFWY	25
	203 F	Reconstruction To AC Fwy	14
		CPR + HM Overlay2 NonFwy	12
	252	Rubble+HM Overlay 3	14
	253	Rubble+HM Overlay 4	15
Composite	302	Mil2Conc+HM Overlay2	11
	302F	Mil2Conc+HM Overlay2FWY	11
	303	Mil2Conc +CPR+Overlay2	13
	303F	Mil2Conc +CPR+Overlay2FWY	13
	304F	Reconstruction To PCCFWY	23
	305	Reconstruction To AC	14
	305F	Reconstruction To ACFWY	14
	354	Mil+Rubl+HM Overlay3	14

- Note, if a model code ends with the letter “F”, it denotes a freeway option

Appendix M

Treatment Average GP and MR Credits

Table 50: Mill and Overlay Typical Credits

Project ID	GP	MR
5-98-00	5	4
128-85-00	6	4
167-99-00	5	4
2478-04-00	5	4
452-98-00	8	4.5
403-98-00	6	5
5118-03-00	6	5
5283-01-00	5	4
71-00-00	9	5.2
Average	6.11	4.41

Table 51: Full Depth Reclamation Typical Credits

Project ID	GP	MR
167-99-00	9	7.6
185-99-00	13	6.5
194-99-00	13	6.9
194-99-00	13	6.8
146-98-00	11	6.6
146-98-00	15	8.5
146-98-00	14	8.2
324-97-00	12	9.4
324-97-00	12	8.2
324-97-00	8	5.7
403-98-00	16	9.8
476-98-00	14	7.8
57-97-00	11	4.9
407-00-00	13	7
559-01-00	13	6.9
6016-03-00	12	8.2
Average	12.44	7.44

Table 52: Expanded Asphalt Stabilization Typical Credits

Project ID	GP	MR
167-99-00	13	6.8
185-99-00	14	7.5
324-97-00	15	9
403-98-00	16	9.5
476-98-00	16	9.5
Average	14.8	8.46

Table 53: Cold In-place Recycling Typical Credits

Project ID	GP	MR
185-99-00	13	6.8
194-99-00	12	6.2
146-98-00	17	11
Average	14	8

Table 54: New Asphalt Construction Typical Credits

Project ID	GP	MR
5-98-00	3	2
2381-02-01	3	2
2-99-00	3	2
5283-01-00	3	2
Average	3	2

Table 55: New Concrete Construction Typical Credits

Project ID	GP	MR
71-00-00	4	3
5-98-00	10	2
Average	7	2.5

Table 56: Overlay Typical Credits

Project ID	GP	MR
2478-04-00	5	4
403-98-00	6	5
Average	5.5	4.5

Table 57: Rubblization with Overlay Typical Credits

Project ID	GP	MR
452-98-00	9	5.6