Quantifying Pavement Sustainability

Final Report Tasks 1 - 7

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Abstract	This report presents all the findings of the project "Quantifying Pavement Sustainability" which was carried out from 2008 to 2010. The ultimate goal of this project is to develop a framework for formally incorporating sustainability into pavement engineering for the MTO. In order to achieve this goal, this project began with a comprehensive literature review of state-of-practice sustainable pavement material and technologies. 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 program evaluations and life cycle cost of pavements. Lastly, network level pavement sustainability is examined. Ideas are proposed for more sustainable maintenance and rehabilitation programming at the network level work are proposed in this project.
Key Words	Sustainability, Sustainable Pavement, GreenPave, Design, Network Level, Project Level, Maintenance and Rehabilitation, Framework for Sustainable Practice

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Ministry of Transportation
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Quantifying Pavement Sustainability

Final Report – Task 1 to 7
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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 operation. In general, sustainability is about maintaining the current infrastructure without compromising the need or resources of the future generation. The basis of sustainability consists of three elements: economy, society, and environment. Sustainable pavement is about integrating these three basic elements into pavement engineering best practices. The challenge of this project lies in how to move sustainable practices forward in a progressive and balanced manner.

With the concept of sustainability wide spreading in the general public, the need of quantifying sustainable practices is highly regarded. The initiatives by LEED^{TM}, 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 is currently working on a 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. In general, this project contains four primary research activities:

1. Assess the current pavement technologies available in economic, social, and environmental perspectives through the literature review and PaLATE software.
2. Aid in the development of Green Pavement Rating System to use in MTO pavement project evaluation.
3. Develop indicators to measure pavement sustainability at project and network level pavement management for MTO.
4. Propose a framework for sustainable pavement practice for MTO.

This report covers the outcome of the Quantifying Pavement Sustainability project. This project is intended to provide a simple yet practical solution for MTO to incorporate sustainability objectively into pavement engineering.

There are a total of seven primary tasks in this report. These are as shown in Figure 1:

Task 1	• Project Introduction Kick Off Meeting
Task 2	• Literature Review
Task 3	• Quantify Typical Savings
Task 4	• GreenPave Review and Project Level Indicators
Task 5	• Network Level Frameworks
Task 6	• Guidelines for Indicator Computation
Task 7	• Final Project Presentation
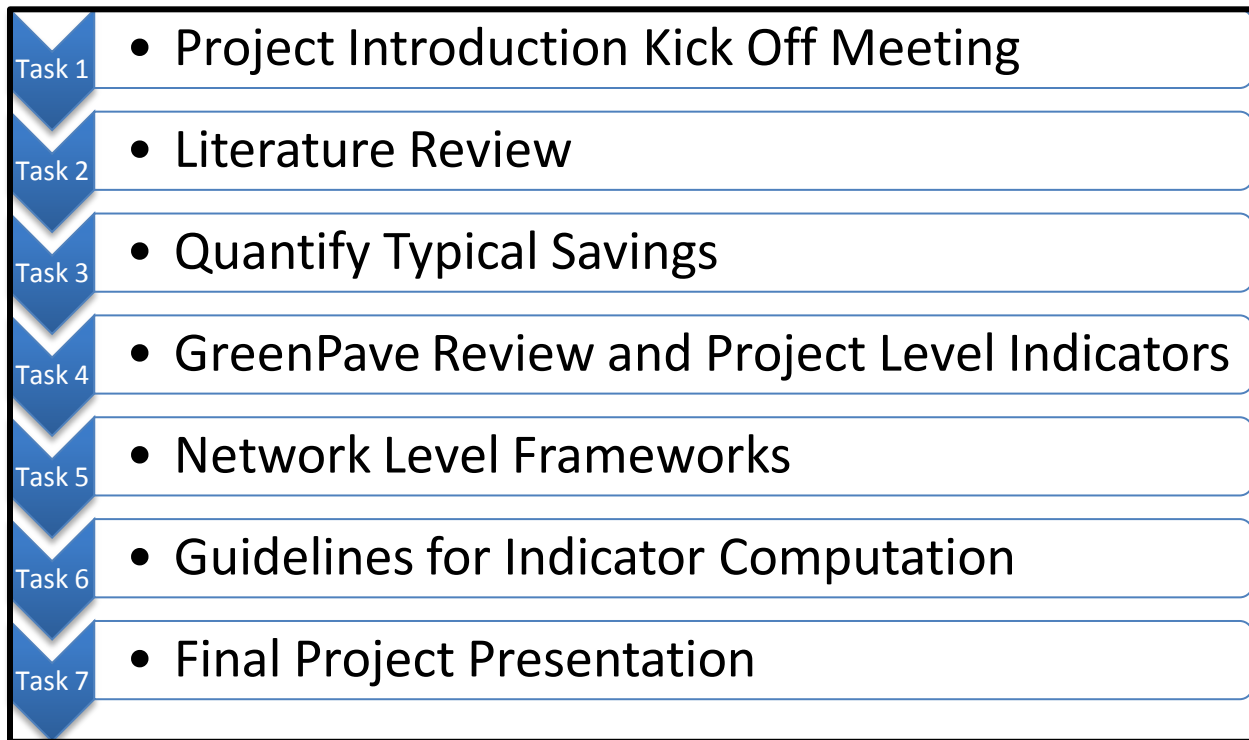
Figure 1: Summary of Task for This Project

Figure 22 in Appendix A shows a Gantt chart to demonstrate the individual tasks to complete this project. This final report discusses all the seven tasks outlined in the project proposal. Majority of the discussion of task 1 to 5 are covered in progress reports 1 to 3 previously. This final report revisits, updates all the previously discussed tasks and ensures full explanation of the work completed. The new items in this report include results of Task 6 and 7. Task 6 is primarily an extension of Task 4 and 5 regarding a more comprehensive examination on pavement sustainability indicators calculation for project and network level applications. Task 7 is completed by the submission of this final report and a presentation to MTO staff.

Although this report acts as the extension of progress report 3, this report is structured in chorological order by individual tasks suggested in the proposal.

2. Task 1

The kick-off meeting between CPATT and MTO for this project was held 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 2 shows the organization team of this project and their respective roles over the entire duration of the project.
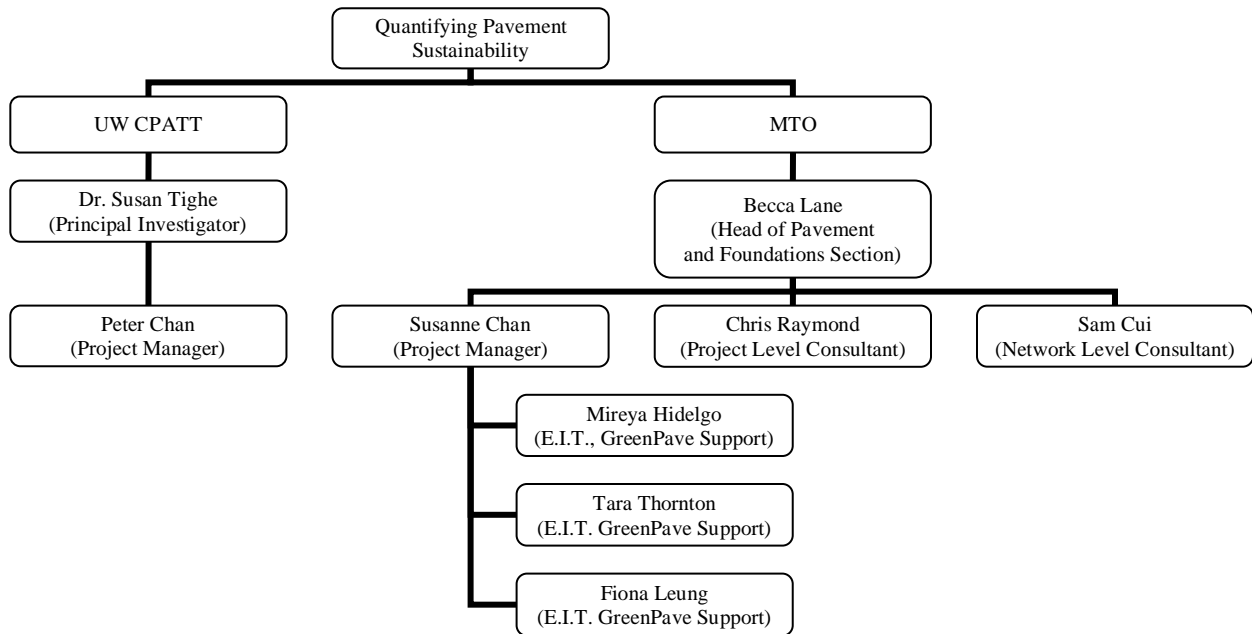
Figure 2: Project Organization Chart

3. Task 2

3.1. LITERATURE REVIEW

As the concept of sustainable living 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, different 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 environmentally friendly pavement.

Task 2 can be separated into three main sub reviews: review for pavement engineering, review for sustainability initiatives, and a workshop hosted by CPATT and MTO that included 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 for Ontario highways maintained by MTO. For green initiatives, the main emphasis will be targeted in rating systems that are currently available for different infrastructure projects. The CPATT/MTO sustainable pavement workshop involved a gathering several pavement professionals in Ontario to 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. The alternatives reviewed would lean toward application on Ontario highways managed by MTO. The literature review of this chapter revisits and updates the existing work over the duration of the project. Table 1 shows the items reviewed by CPATT in this chapter.

Table 1: Literature Review Items

Materials	Construction Techniques	Preservation Techniques	Green Initiative
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	Precast Concrete	
Interlocking Concrete		Rubblization	

3.2. MATERIALS

Recycling, reusing, and reclaiming of existing materials are crucial to advance sustainable development. Construction materials can be expensive and now 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 of virgin materials. Therefore, a first step to quantify pavement sustainability involves evaluating how materials are currently used and how their benefit can be maximized.

3.2.1. 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 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 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 of asphalt cement's gradation may not be economically justified in contractors' perspective.

3.2.2. Recycled Concrete Aggregates

Recycled concrete in pavement applications is most commonly in the form of Recycled Concrete Aggregate (RCA). The application consists of reusing concrete waste from demolished sidewalk, curb and gutter 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 test track with 0%,

15%, 30%, and 50% RCA mixes. 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].

3.2.3. 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 candidate as aggregate for pavement [Huang, 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 seem to be reported for incorporating glass in asphalt.

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; hence make it an unsuitable material as concrete aggregates. According to OPSS 1010, glass may be use as granular A, M, or S at 15% maximum of total aggregate [OPSS 1010, 2004].

3.2.4. Ceramic Whiteware

Ceramic whiteware typically include crushed toilets from the local area. Based on lab testing by MTO, these ceramic whiteware products are high strength aggregate for granulars [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.

3.2.5. 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 current specification has no plan to incorporate rubber in asphalt or granular [Senior et al, 1994]. The availability and cost of processing of crumb rubber are two major obstacles that limit its utilization in pavement applications.

3.2.6. 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 wore 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. Manufactured asphalt shingles tabs 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 recycled asphalt shingles (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.

Despite RAS saves waste disposal costs, researchers believes 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% is allowed to replace 1% RAP in hot mix [OPSS 1151, 2007].

3.2.7. Interlocking Concrete

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 at 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 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 of 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.

3.3. DESIGN AND CONSTRUCTION TECHNIQUES

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

3.3.1. 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, 2008]. Perpetual pavement is designed to eliminate repair on top surface during the life of the pavement [El-Hakim, 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, 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, 2009]. A life cycle cost analysis shows that the price differential for perpetual pavement and conventional pavement are insignificant [El-Hakim, 2008].

3.3.2. 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 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].

3.3.3. 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 effort 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].

3.3.4. 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 no different from 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 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]. Damaged PICP can be individually repaired. PICP 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 a popular alternative used in MTO highways.

3.3.5. Warm Mix Asphalt

Significant research effort has been put into warm mix asphalt (WMA) pavement. The idea of warm asphalt is to allow the placement of asphalt pavement at lower temperatures. A variety of warm asphalt additives is available in the market. 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].

3.3.6. Quiet Pavement

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 shows that 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 of 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 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 thru the pavement, hence reduce the surface temperature.

Despite the above environmental benefits in the OGFC, due to a short observed life span and higher winter maintenance cost is 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 (NGOFGC) has been adopted by various transportation agencies in the U.S. It is believed that NGOFGC will inherit the benefit of OFGC 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 NGOFGC are more open graded, have increase air void to 18%, more asphalt cement by 20%, enhanced by rubber polymer asphalt, and use fibre addictives to achieve high permeability in the mix [Yildirim, 2007].

3.4. 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 technique that are deemed to have sustainable elements in it.

3.4.1. 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 the 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 about 14 days prior to open for traffic [Chan, 2010].

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

3.4.2. 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 the 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 testings and statistical modelling for CIREAM versus CIR mix to further understand the behaviour of CIREAM and CIR [Lane, 2010]. The test results shows 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.

3.4.3.   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 is because of its short curing duration similar to CIREAM [Infraguide, 2005]. The pulverized material from the FDR process is compacted and reused as granulars on the existing ground.

FDR utilizes high reused content because existing pavement does not recollect as RAP. Other 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].

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 shows minimal thermal cracking appears on the FDR section with nearly no rutting after four years of surface [Miller, 2010].

3.4.4.   Microsurfacing

Microsurfacing is a common pavement maintenance treatment for flexible pavement. It is often applied on the 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 shows 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].

3.4.5. Diamond Grinding

Diamond grinding is a rehabilitation treatment used for rigid pavement to restore ride quality and frictional properties given the pavement are still structurally adequate [Haas, 1997]. It is an effective treatment to reduce 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, and an expected service life of 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 sign of joint problems [Hein, 2006].

The major benefit of diamond grinding is that it can be completed quickly given traffic is off peak hours [MTAG, 2006]. Diamond grinding is a cost effective rehabilitation treatment.

There is no construction specification in the OPS for diamond grinding. However, OPSS 350 does describe the machinery requirement for diamond grinding operations.

3.4.6. 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 available, 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, curing during installation. Precast concrete does not require on site curing, which means the damaged area can be opened to traffic quickly.

However, there are drawbacks with precast concrete panels, which limit the use of precast concrete for pavement rehabilitation. First, the full depth dimension of the slab for the damage area is difficult to measure accurately. Secondly, the base layer and subgrade layer must be properly compacted to mitigate slab cracking. The construction cost of using precast concrete is higher than conventional cast-in-place concrete, but it is compensated with the short construction duration [Hein, 2006].

3.4.7. Rubblization

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 significant amount of granulars 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 exhibit structural distresses or material related distresses such as freeze thaw damage in concrete and alkali-silica reactivity [ACPA, 1998]. Although rubblizing the concrete pavement and overlay mitigate reflective cracking, the drawback of rubblization is the subgrade condition of the pavement after rubblization is unknown at the design stage of the project [ACPA, 1998].

3.5. SUSTAINABILITY INITIATIVES

As the concept of sustainable infrastructure becomes more prevalent, different agencies will develop various rating systems to quantify the sustainability or environmental benefit associated with 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 a green pavement rating system for MTO projects. This project reviews four sustainability initiatives: LEED™, Greenroads, GreenLITES, and Green Guide for Road Task Force.

3.5.1. LEED™

In Canada, Leadership in Energy and Environmental Design (LEED) Green Building Rating System^{TM} 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 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 system for six different building applications [CaGBC, 2008]:

- New Construction
- Existing Building
- Commercial Interior
- Cores and Shells
- Homes
- Neighbourhood Development

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

- Sustainable Site
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources

- Indoor Environmental Quality
- Innovation and Design

For any LEED™ certification building application, each criterion above requires specific prerequisite 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.

3.5.2.   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 3 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 3: Pavement Related Credits in Greenroads Version 1.0

The credits shown in Figure 3 are specific sustainable pavement engineering practices considered in Greenroads. Greenroads has a custom credits categories allow innovative or unlisted sustainable practices that should be awarded for credits [Muench, 2010]. In general, Greenroads does not considers 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 project evaluation for certification. Greenroads should not be interpreted as standards, nor it is legislated that transportation projects must achieve Greenroads certification.

3.5.3. GreenLITES

In September 2008, the New York State Department of Transportation (NYSDOT) released the GreenLITES. GreenLITES is a certification program for NYSDOT designs meeting criteria for

sustainable transportation infrastructure as a whole [NYSDOT, 2009].

GreenLITES is a "self certification program" that evaluates the extent 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 project. 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 4 demonstrates the broad nature of credits available in GreenLITES [GreenLITES, 2009].

Figure 4: GreenLITES Excel Scorecard

As seen in Figure 4, a GreenLITES credit is awarded base whether the project satisfy 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.

In the 2009 revision of GreenLITES, it 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].

3.5.4.   Green Guide for Road Task Force

The Transportation Association of Canada (TAC) is currently undertaking a project to develop the "Green Guide for Road Task Force". According to TAC, this Green Guide is meant to

"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 both urban and rural settings." [TAC, 2010]

The Green Guide considers thirteen application areas in relation for sustainable transportation practices [TAC, 2010]. The numbered list below demonstrates these application areas [TAC, 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. As of February 2010, the layout for this Green Guide is unknown. The expected completion date for the Green Guide is September 2010 [TAC, 2009].

3.6. 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. Participants for the workshops consist of members from the industries, consultant, contractor, material suppliers, MTO and University of Waterloo. 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 introductory presentation of all participants by Dr. Susan Tighe and Ms. Becca Lane. Mr. Finlay Buchanan, coordinator technology innovation of 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 following questions in the breakout session.

- Identify sustainable technologies (concrete materials, asphalt materials, pavement design tools and asset management, new construction and reconstruction processes, preservation strategies, and rehabilitation.)
- Why are these technologies sustainable?
- What are the benefits of using the technologies? How well are these technologies currently utilized? Can we better utilize the technologies?
- Are there barriers to implementation?
- How can we address pavement sustainability in 5, 10, and 50 years?
- What are the costs to develop sustainable technologies?
- What are the benefits of implementing pavement sustainability?
- How should we achieve a balanced quantification of a sustainable pavement technology?

- Are there other technologies that should be explored?

A workshop summary is shown in Appendix B of the report. The summary is a gathering of the responses for the above questions at the workshop. Below is a bullet points list of some common sustainable ideas that were gathered out from the work group discussion, the number in the brackets indicate which group(s) has indicated the specific idea in the breakout session. The bullet point list is ascending sorted based on its frequency brought up at the workshop. Please note the sequence of the bullet point list does not suggest that one idea is more important than others.

- Research, Development, Education, and Training (1, 2, 4, 5, 6)
- Long Life Pavement Performance (1, 2, 4, 5, 6)
- Greenhouse Gas (GHG) emission (1, 3, 4, 6)
- Risk Associated with Innovation/Resistance to Change (1, 3, 4, 6)
- Life Cycle Costing (1, 2, 3, 5)
- Fuel/Energy savings (1, 4, 6)
- Testing and Monitoring of materials and performance (1, 5, 6)
- Specification Handcuff (1, 2, 6)
- In-place Recycling (4, 5, 6)
- Recycled Material (2, 5, 6)
- Performance Specification (1, 6)
- Use of By Products (1, 2)
- Different Perspective at Provincial and Municipal Level (2, 5)
- Future Recyclability (2, 6)
- Cost Reduction As Technology Gain Practices (2, 6)
- Non-Renewable Resource Savings (3, 4)
- Budget Restriction (3, 5)
- Proactive Planning (5, 6)
- Improve Safety (5, 6)
- Emission Measurement (2)
- Noise Reduction (3)
- Development of New Tools and Mandate Them into Specification (3)
- Surplus Material Plan and Material Storage (4)
- Lack of Incentive and Rewards (6)

As seen above, it is evident that there is a great overlapping in some sustainable ideas. 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 Task 3 in relation to identify social aspect of sustainable pavement.

4. Task 3

4.1. QUANTIFYING TYPICAL SAVINGS

The focus on Task 3 is quantifying typical savings associated with different pavement engineering practices. In general, the quantification is broken down into three components: Environmental Savings, Economic Savings, and Social Cost. The goal of Task 3 is to distinguish the performance differences between various pavement engineering practices.

4.2. ENVIRONMENTAL SAVINGS BY PALATE

The environmental quantification is to complete with PaLATE. PaLATE stands for "Pavement 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 only serves as the life cycle analysis (LCA) tool to quantify environmental impacts of road construction or rehabilitation projects. PaLATE is not used to calculate life cycle cost (LCC) for this project. The current version of PaLATE (as of 2009) can only compute LCC up to 40 years analysis period; whereas MTO recommends a 50 years analysis period for major freeway projects [Lane, 2005]. 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 are summarized in Table 4.

Table 4: Pavement Technologies Being Quantified

New Construction	Rehabilitation/Reconstruction	
Asphalt Pavement	Cold In-place Recycling	Mill & Overlay (M&O)
Concrete Pavement	Cold In-place Recycling with Expanded Asphalt Material	Rubblization with Asphalt Overlay
Concrete Pavement with 30% (RCA)	Hot In-Place Recycling	Mill & Overlay with 20% RAP
Pervious Concrete Pavement	Full Depth Reclamation	Mill & Overlay with Warm Mix Asphalt
Porous Asphalt Pavement	Expanded Asphalt Stabilization (EAS)	

For each of the pavement technologies identified in Table 4, 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. The user must convert the quantities to imperial units for design inputs into the current version of PaLATE.

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 C for more details regarding WMA discounting with PaLATE.
- Open Graded Drainage Layer (OGDL) is assumed to have the same material composition as HMA.
- 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].

For the third component, material transport distance, PaLATE requires the material transportation distances from the contractor's plant to the construction site. The assumptions for transportation distances are summarized in Table 5.

Table 5: Assumed Material Transport Distance

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

Table 5 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 would diminish the benefit of this material.

Appendix C provides a detailed PaLATE documentation for compiling the PaLATE workbooks using the pavement technologies suggested in Table 4. 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 user to get familiar with PaLATE to perform environmental quantification on pavement design alternatives.

4.2.1.   PaLATE Results for Rehabilitation and Construction

The numerical results from PaLATE are attached in Appendix D as Table 39.

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 analysed are energy, carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide

(SO_2), and nitrous oxide (NO_x). Appendix E shows these environmental impacts in the form of bar charts for different rehabilitations. The PaLATE analysis results for rehabilitation treatment are shown Figure 27 to Figure 31. For the rehabilitations shown in Figure 27 to Figure 31, the output is divided into two parts: Process, and Overlay. The PaLATE output for 'overlay' considers the addition of asphalt to the existing pavement surface. The PaLATE output for 'process' 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 asphalt overlay. From the PaLATE analysis, the process output in the rehabilitation contributes minimal energy or emission. Furthermore, process output is contributed by the material production and material transportation to prepare for asphalt overlay in rehabilitation.

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

- Appendix E suggested Hot In-place Recycling (HIR) consumes less energy than CIR and CIREAM. This finding does not seem to be consistent with the literature because HIR involves heating the asphalt, which likely would 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 E. The difference in the input for the asphalt emulsion 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 rehabilitation techniques are adequate to provide rehabilitation on pavement exhibit structural distresses.
- Overlay material contribute significant energy use and emission in the analysis

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.

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

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 how much relative savings percentages. Table 6 shows the results of Equation 1, note that HIR was excluded as the PaLATE output for HIR seems incorrect.

Table 6: 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%
WMA M&O	29%	43%	48%	30%	N/A	38%

- 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 N/A in Table 6.

As shown in Table 6, 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. FDR and EAS yield 30% less environmental impact than M&O. WMA saves an average of 38% in environmental impact. However, it should be noted that the rehabilitation processes presented in Table 6 have different performance service lives. Therefore, the PaLATE results only account for environmental impact during pavement construction or rehabilitation. Hence, the results from Table 6 should be interpreted as one-dimensional parameters that estimate the environmental impact produced during construction or rehabilitation for a typical one kilometre, 2 lanes highway.

For new pavement construction, it is difficult to establish a control option for a comparison because asphalt and concrete are two distinct materials that have unique performance characteristics and associated service lives. The environmental evaluation of new construction compares asphalt pavement and concrete pavement. Emission and energy output for construction are shown in Figure 32 to Figure 36. The PaLATE results for construction are categorized by material type: concrete, asphalt, 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 and the conventional asphalt or concrete pavement. Appendix D shows the results from the PaLATE evaluation for pavement new construction.

These results in Appendix C 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
- 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, LCC 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. Based on the analysis assumption that the transportation distance for all materials is equal, it is concluded that 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. Previously, emissions and energy are considered on individual construction or rehabilitation at project level basis. Appendix E 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 7 shows the life cycle schedule that listed the rehabilitations necessary for asphalt and concrete pavement construction over the course of 50 years. Table 8 shows the total energy and emission estimations from PaLATE for a typical 1-kilometre two-lane highway.

Table 7: 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 CPR Concrete
15	Mill 40mm, Patch 40mm Asphalt	28	Full and Partial CPR Concrete
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 8: Total Energy and Emission Estimates for 50 Years

Quantities	Asphalt	Concrete
Energy (MJ)	8,967,988	5,871,140
CO_2 (Mg)	480	376
SO_2 (kg)	113,097	29,175
NO_x (kg)	3,907	4,288
CO (kg)	1,421	1,996

The result from Table 8 is the summation of energy and emission quantities from Figure 37 to Figure 46. The estimation in Table 8 shows concrete consumes less energy, produces less CO_2 and SO_2 over 50 year life cycle. Asphalt emits less NO_x and CO over the 50 years life cycle. From Figure 37 to Figure 46, it is observed the energy use and emissions generated in rehabilitation are insignificant compared to construction energy and emission output.

4.3. ECONOMIC SAVINGS

For the economic quantification of pavement rehabilitation, it can be broken down into two sub-quantifications: hot mix asphalt (HMA) savings, and life cycle cost analysis (LCCA). On the other hand, the economic quantification for new pavement construction involves an assessment of total material utilized during construction.

4.3.1. 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 a crucial step toward more sustainable pavement. 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.

All treatments in the rehabilitation analysis 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 9 summarizes the overlay thickness in millimetres requires for each rehabilitation method.

Table 9: Overlay Thickness for Rehabilitation

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 9, 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.

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

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 10 shows the result of HMA materials savings.

Table 10: HMA Material Savings

Technique	Tonnes Used	Tonnes Saved	% Saved
HIPR: 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%
100% V.A. Overlay 130mm	2256.8	0	0
80% V.A. Overlay 130mm	1805.44	451.36	20%
WMA Overlay 130mm	2256.8	0	0

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

$$\left(1 - \frac{\mathrm{Re}\,hab\_HMA}{M\&O\_HMA}\right) \times 100\% \qquad (3)$$

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

Table 11 converts the results from Table 10 into actual economic savings of HMA material. The economic cost of rehabilitation typically consists of two major components: process, and overlay. For the economic quantification, cost data are extracted from MTO HiCO Database [HiCO, 2008]. HiCO stores the bidding cost breakdown for MTO projects. The unit costs in Table 11 are averages calculated from HiCO cost data. HiCO measures rehabilitation processes in m^2 and overlay in tonnes.

Table 11: Typical Economic Savings between Pavement Rehabilitation

Technique	Unit Price	Unit	Quantity	Price	Total	Total Savings	% Savings
HIR Process	$8.86	m²	7000	$62,020	$165,173	$(143,624)	-47%
HIR: Overlay 50mm	$118.84	T	868	$103,153			
CIR Process	$9.60	m²	7000	$67,200	$170,353	$(138,444)	-45%
CIR: Overlay 50mm	$118.84	T	868	$103,153			
CIREAM Process	$14.11	m²	7000	$98,770	$201,923	$(106,874)	-35%
CIREAM: Overlay 50mm	$118.84	T	868	$103,153			
FDR Process	$1.43	m²	7000	$10,010	$195,685	$(113,112)	-37%
FDR: Overlay 90mm	$118.84	T	1562.4	$185,675			
EAS Process	$4.36	m²	7000	$74,830	$177,983	$(130,814)	-42%
EAS Overlay 50mm	$118.84	T	868	$103,153			
Rubblization	$4.36	m²	7000	$30,520	$236,826	$(71,971)	-23%
Overlay 100mm	$118.84	T	1736	$206,306			
Mill Process 2	$5.80	m²	7000	$40,600	$308,798	$ -	0%
100% V.A. Overlay 130mm	$118.84	T	2256.8	$268,198			
Mill Process 2	$5.80	m²	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	m²	7000	$40,600	$316,133	$7,334	2%
WMA 100% V.A. Overlay 130mm	$122.09	T	2256.8	$275,533			

Table 11 shows the comprehensive cost differences of the pavement rehabilitation alternatives. From Table 11, 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 shows a 47% cheaper 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 11 also shows adding RAP in the pavement is cheaper 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 in task 2.

4.3.2. Life Cycle Cost Analysis for Pavement Rehabilitation and Reconstruction

Life Cycle Cost Analysis (LCCA) is important in the decision-making process for both project and network level pavement management. MTO typically choose the project alternative that has the lowest LCC. Sustainable pavement also considers optimizing economic benefit for transportation agency. For the LCCA in this section typical pavement dimensions from PaLATE analysis is 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.

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

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

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 12
L_{REM}	= Remaining Service Life = L_{EXP} – (m – n)
C	= Cost of Rehabilitation/Construction
i	= Discount Rate 5.3%

Table 12 summarizes the typical service life of the pavement rehabilitations listed in Table 11 [Chan, 2009].

Table 12: Typical Service Life for Pavement Rehabilitation/Reconstruction

Technique	Service Life (Years) (L_{Exp})
HIR → Hot In-place Recycling + 1 lift Overlay	12
CIR → Cold In-place Recycling + 1 lift Overlay	15
CIREAM → Cold In-place Recycling with Expanded Asphalt + 1 lift	15
M&O → Mill 2 lifts & Overlay 2 lifts	14
Resurfacing →Overlay 2 lift	12
FDR → Full Depth Reclamation + 2 lifts Overlay	10
EAS → Expanded Asphalt Stabilization + 2 lifts 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 40 in Appendix G [Chan, 2009]. However, these LCC schedules can be modified for a lower LCC. Prior to the discussion of LCC schedule modification, one must understand the relationship of rehabilitation technique and pavement distresses. Table 13 shows a matrix of different rehabilitations applicability against different distresses.

Table 13: 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

* Note FDR and EAS were not considered in Table 13 because it is referred as reconstruction
* Resurfacing is also referred as overlay

The costs of rehabilitation used in LCCA computation are shown in Table 11. 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 13, the control LCC schedules are shown in Table 40.
2. Modify the LCC schedule from Table 40 by substituting cheaper rehabilitation alternatives after year zero. The modified LCC schedules are shown in Table 41.
3. Compute the LCC based on the schedules from Table 40 and Table 41.
4. Compare the cost difference from step 3 computation as shown in Table 42

Table 14: Summary of Net Present Worth Calculation

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%	

CIR is clearly a more economical alternative than M&O. Table 14 clearly shows using CIR can provide a 20% saving over the pavement service life than using M&O. Based on the 30 years life cycle cost analysis, 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 savings. Although CIR is a very sustainable rehabilitation technique, it should be noted that other constraints such as design, availability, and site conditions could affect the agency's selection of the proposed treatment.

4.3.3. Material Savings in New Construction

For new construction, flexible and rigid pavements are the two primary types of pavement structures managed by MTO. It should be noted surface treatments are also a major type of pavement. However, only flexible and rigid were considered in this evaluation. Due to performance and costing methodology difference in flexible and rigid pavements, it is appropriate to compare total aggregates used in each of these pavements. 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 the coarse and fine aggregate used in surface course, granular base, and granular subbase. The aggregate quantities are taken from the PaLATE analysis. Table 15 summarized the aggregates used for each new construction technique. Note that each technique suggested in Table 15 has a different service life. Table 15 is another one-dimensional way to demonstrate the amount of material exhausted for different pavement construction techniques.

Table 15: Total Aggregates for Different Construction Technique

Construction	Layer	Material	Yd^3	Total Yd^3	Total m^3	Rounded
New Asphalt	WC1	HMA	1304.56	5218.21	3989.61	4000
	SB1	GRAN. A	1304.56			
	SB2	GRAN. B	2609.09			
New Concrete	WC1	CONC	1192	3366.26	2573.69	2600
	WC2	OGDL	869.7			
	SB1	GRAN. A	1304.56			
Pervious Concrete	WC1	CONC	1393	4002.11	3059.83	3100
	WC2	OGDL	869.7			
	SB1	GRAN. A	1739.41			
Concrete with 30% RCA	WC1	CONC	1242.5	6025.86	4607.1	4600
	WC2	OGDL	869.7			
	SB1	GRAN. A	1304.56			
	SB2	GRAN. B	2609.1			
Porous Asphalt	WC1	HMA	862.381	4524.3	3459.07	3500
	SB1	GRAN. A	3661.92			

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, Table 15 suggested that conventional concrete pavement construction uses the least amount of aggregates. On the other hand, asphalt pavement uses approximately 35% more aggregate to build a roadway than concrete pavement. Flexible pavement design tends to have a thicker granular base, hence it increases the virgin aggregate content as shown in Table 15. The difference in aggregate required for pervious concrete and porous asphalt pavements is approximately 10%.

4.4. SOCIAL COST IDENTIFICATION

Social cost is also an important sustainability component. Unfortunately social cost 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 in December 2008. The workshop was a gathering of stakeholders from MTO, CPATT, consultants, contractors, and material suppliers to brainstorm pavement sustainability. This list of social cost does not specifically target any pavement construction or rehabilitation technique. Instead it acts as a baseline to develop a sustainable pavement rating system for Task 4. In order to achieve socially sustainable pavement 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 service life design).
4. Illustrate material conservation.
5. Illustrate fuel conservation.
6. Material management (better stockpile, storage).
7. Material availability and accessibility awareness.
8. Labour availability and accessibility awareness.
9. Innovation (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 (proper lane closure, detour, staging design, proper construction access, reduce traffic interruptions).
15. Improve safety for travellers and workers.
16. Noise reduction.

5. Task 4

5.1. Green Pavement Rating System and Indicator Development

The results from Task 3 are used to develop the MTO's green pavement rating system. Task 4 focuses on project level pavement sustainability. The first component of Task 4 is to understand and review MTO's project level green pavement rating system, unofficially named "GreenPave". After the review of GreenPave, the work for Task 4 is summarized in three steps:

1. Perform preliminary GreenPave trial evaluations on MTO pavement projects for different regions.
2. Assess GreenPave evaluation results to identify potential trends and patterns.
3. Develop indicators that correlate GreenPave result and LCC of a design alternative at project level.

In general, this project focuses on innovation, framework development for implementing sustainability into current practice, incorporates stakeholder input, and provides quantification to typical savings. GreenPave is solely a rating system used by MTO. This project emphasizes the inclusion of GreenPave into both network and project level management. It is expected GreenPave will compliment this project and assist in implementing sustainable pavement practices in Ontario.

5.2. 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. GreenPave resembles GreenLITES, but with a sole emphasis on Ontario pavement experience and current practice. GreenPave does not operate like LEED™ or Greenroads because it is not a third party rating system that acts as a separate project component. 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, CPATT uses GreenPave 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. The bullet list below summarized the major changes to GreenPave in June 2009. Table 16 shows the credits breakdown for GreenPave [Chan, 2009a]. Table 17 shows the new certification levels breakdown for GreenPave [Chan, 2009a].

Table 16: 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 17: 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. Table 16 shows the different categories considered in GreenPave, as of March 2010. In general, GreenPave credits consist of three categories: design credits, construction credits, and innovation credits. Design credits are awarded based on pavement design assessment. 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.

In a GreenPave evaluation of a project, the credits from each category are totalled where Table 17 shows five certification levels allow 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.

5.2.1. GreenPave Evaluation Trial Results

From May 2009 to July 2009, CPATT has participated in the evaluations of various pavement

designs using GreenPave. GreenPave evaluations are generally completed by MTO staff using the excel template as shown in Figure 5. Individual project evaluations are not discussed in this report because GreenPave is only a tool that aids in developing indicators for this project. Figure 5 shows the GreenPave scorecard in the form of a sample project evaluation result. Each GreenPave point is shown on the scorecard. A summary of GreenPave project evaluations was compiled in October 2009 as attached in Appendix H [Thornton, 2009]. The information in Appendix H is used to develop indicators for Task 5. However, some alternatives shown in Appendix H do not contain LCC because they were not proposed in the pavement design. Figure 6 shows a sample GreenPave result from Appendix H [Thornton, 2009].

Figure 5: GreenPave Excel Template

D42	▼	⊙	_fx_	Alternative 1 (Rubb)			
	A	B	C	D	E	F	G
	**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 6: Sample GreenPave Results Summary

Figure 6 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.

5.3. Indicator Development at Project Level

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 the economic cost of the alternative. Therefore, economic indicators must be combined GreenPave credits to get an overall sustainability evaluation. The advantage of GreenPave credits is that they are simple to use and provide an environmental measure of the practice.

Two indicators are proposed to measure pavement sustainability at the project level in this project: Green Discounted Life Cycle Cost (GDLCC) Type P, and Parameter D. Both of these indicators use mathematics to derive a value that measures pavement sustainability using the information provided in Appendix H. 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.

5.3.1. Green Discounted Life Cycle Cost (GDLCC) Type P

The concept of GDLCC was originally suggested by MTO. GDLCC Type P is a project level indicator designed to measure pavement sustainability proposed by CPATT 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 considers 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% cheaper than alternative 2 in LCC, then the GreenPave score of 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. Hence, 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 the alternative.

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

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

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

In equation 7, the 0.2 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 16. A maximum of 14 credits can be achieved in the MR score as suggested in Table 16. In general, an environmental friendly pavement design alternative should achieve a high GreenPave score 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 I contains plots that use information from GreenPave trials in Appendix H 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. Different regressions models of linear, quadratic, and polynomial are tested to fine the best-fit correlation coefficient, R^2, value. Based on the assumption that GP score is dependent on the MR score of the design alternative, linear and polynomial regression models were tested using Excel. Table 18 shows the regression result using the data given from Appendix H. Appendix I shows the regression plots from Excel.

Table 18: 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 18 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 I. Nevertheless, the results in Table 18 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.

5.3.2. 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 scores of an alternative. The development of D is initiated by the weak sensitivity of GDLCC as shown in equation 6 in 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 compute 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 score 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
Max(alt_LCC)   = Alternative that has the highest life cycle cost in a project

Equation 8 and 9 convert GP score and LCC into fractions with arithmetic. Equation 8 suggests the smaller value of x is calculated from a higher GP score. 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 is simply the distance of x and y coordinates from the origin. 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 H, a series of D value can be plotted as shown in Figure 7. Note Figure 7 only shows four representative alternatives from Appendix H to illustrate the graphical representation of D. Table 19 shows the corresponding x, y, and D value for Figure 7.
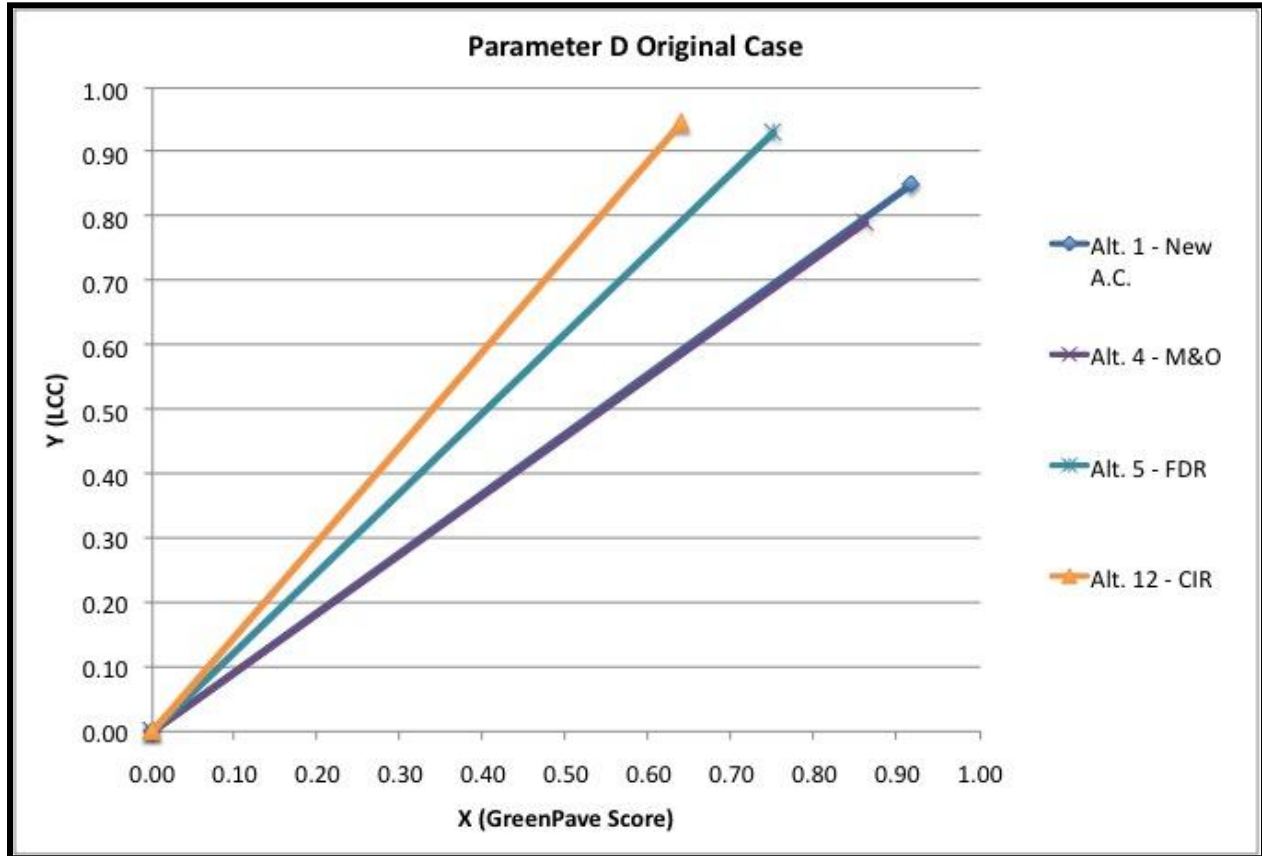
Figure 7: Graphical Representation of Parameter D

Table 19: Data Table for Figure 7

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 7 and Table 19, it is not evident which alternative is most sustainable. Overall, Figure 7 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 given in Table 17 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, Table 17 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 targets either construction or rehabilitation projects only [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 include 20 and 25 as shown in equation 11 and 12 respectively as a revised equation 8.

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

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

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 minimum 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 17. Table 20 shows results of x using equation 8, 11, and 12.

Table 20: 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 20 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 7 shows 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 7 come from a different project. 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.

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

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

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 21 shows y values using equation 9, 13, and 14.

Table 21: 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 21 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 21 is calculated using equation 9 with value of 0.946, it is irrelevant because the agencies rarely choose the alternative with highest LCC.

Figure 8 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 22 shows the corresponding numerical results for Figure 8.
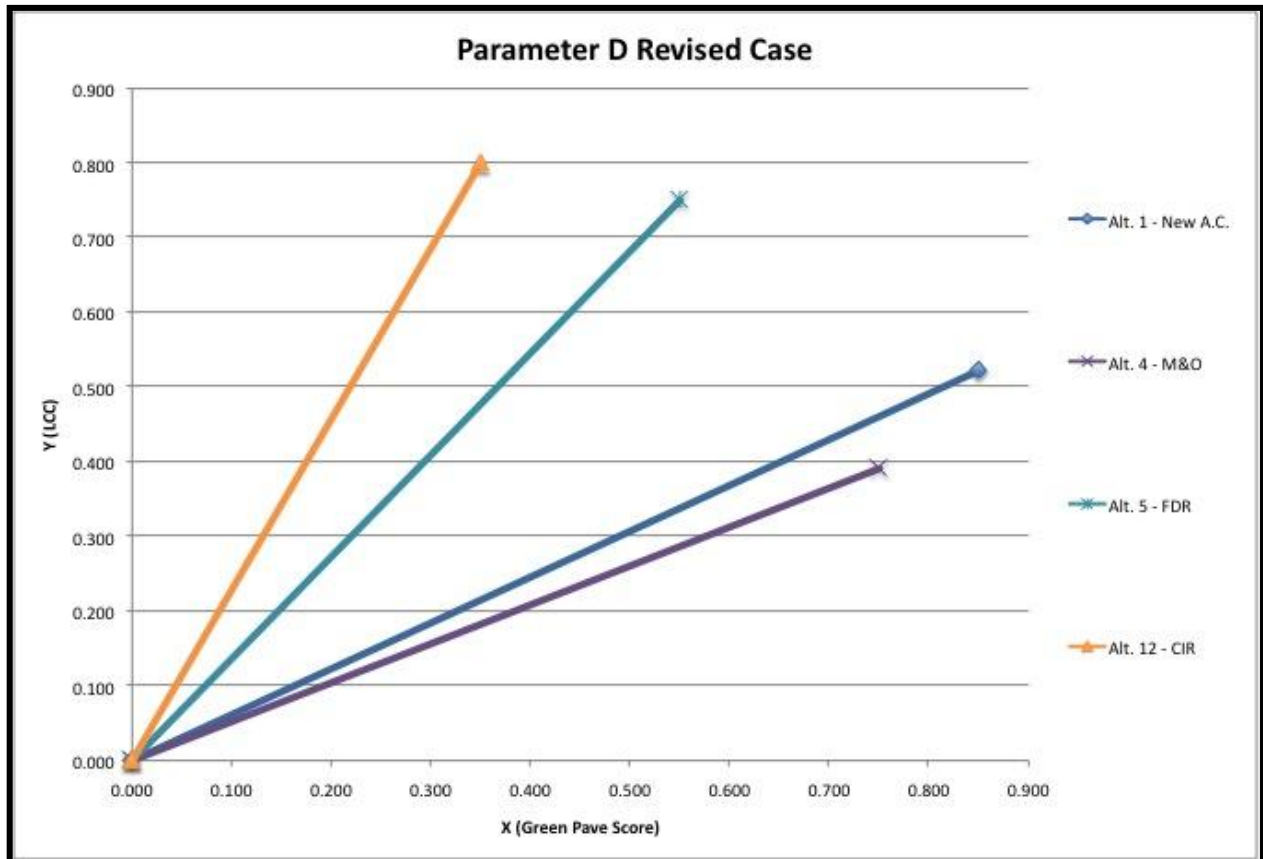
Figure 8: Revised D Results

Table 22: 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

5.4. Interpretation of Sustainable Pavement Indicators in the 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 every day project level decision making processes, social costs are very implicit and difficult to quantify numerically. Therefore, numerical social cost at project level would require additional research effort that is beyond the scope of this project.

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 scores 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 cost.
- 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 to assess design alternatives within different projects in a given highway network.

6. Task 5

6.1. Framework Development

The main goal of Task 5 is to develop framework for sustainable pavement at the project level and network level practices. Most of the work from Task 1 to 4 emphasizes on project level practices. Task 5 has included:

- Develop a project level framework.
- Evaluation of current network level practices by MTO.
- Protocols to promote more sustainable planning have been evaluated.
- Assessing pavement sustainability at network level using indicator.
- Develop a network level framework.

6.2. Project Level Framework

The framework for sustainable pavement practice at project level would revolve around GreenPave. Figure 9 provides a visual representation of the project level framework.
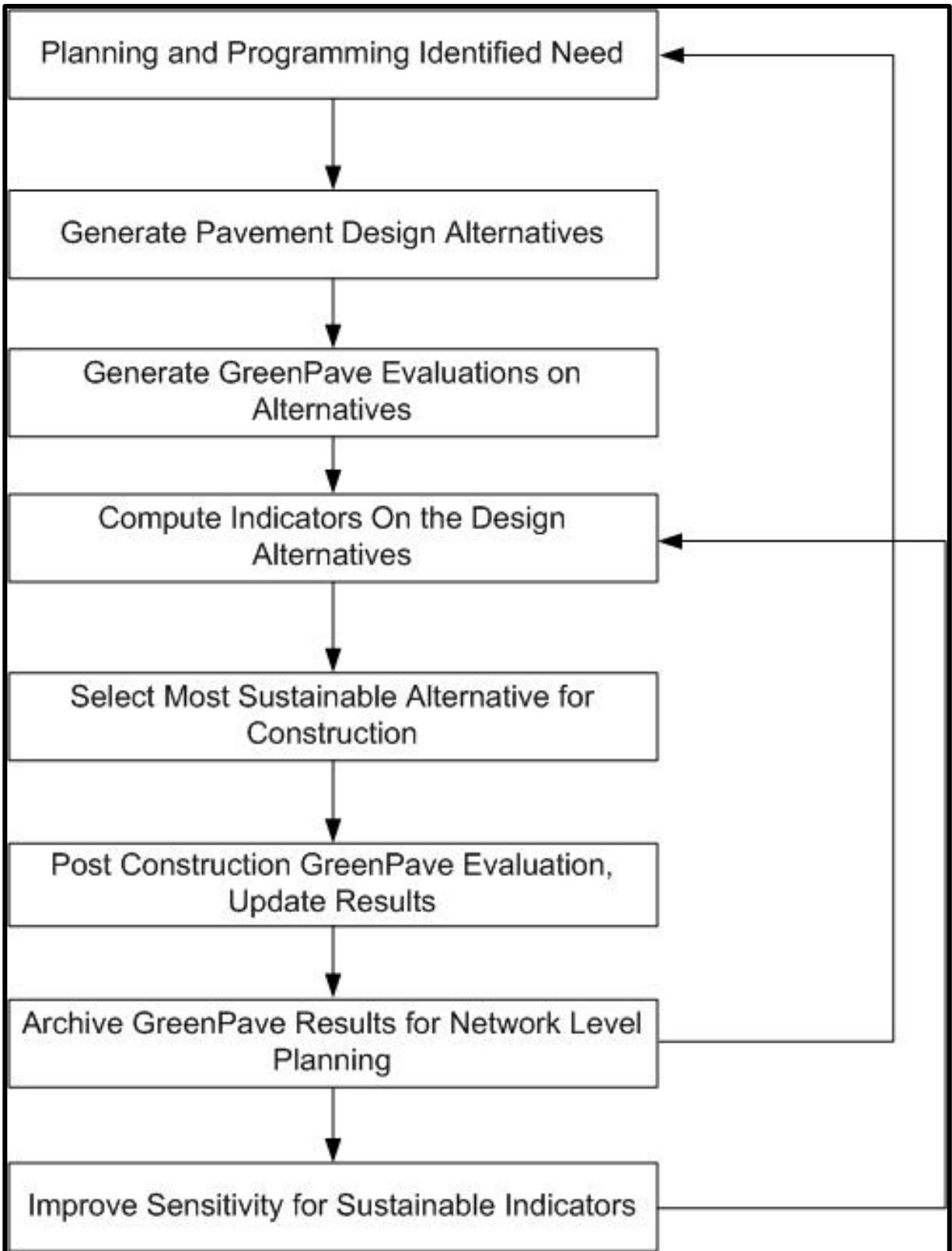
Figure 9: Sustainable Pavement Framework at Project Level

Figure 9 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 Pavement Condition Index (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.

6.3. Network Level

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 revolves around PMS2, MTO's pavement management system. 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)

The role of PMS2 in this project involves generating M&R analysis for sustainable practice at network level. The utilization of PMS2 in network level activities is divided into two main parts: Conventional M&R Analysis; and Sustainable M&R Analysis.

6.4. Conventional M&R Analysis

This section discusses M&R Analysis practiced by MTO at network level using PMS2. In general, the PMS2 operates in three main environments as shown in Figure 10. The next

subsections discuss the work in each environment.
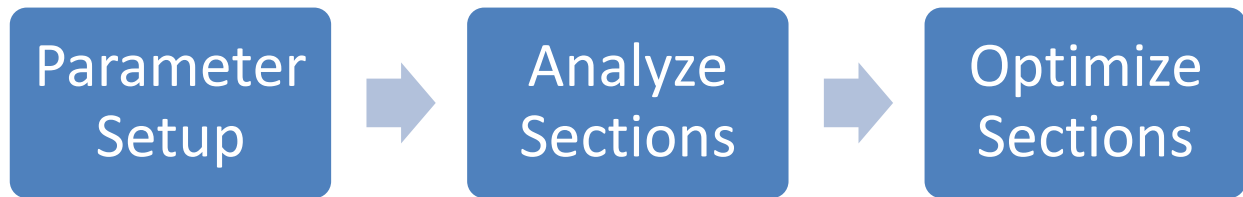
Figure 10: Work Environment in PMS2

6.4.1.   Parameter Setup

The first step in the M&R analysis is to establish the constraints required for the M&R analysis. Figure 11 shows a screen capture of the necessary constraints for PMS2 M&R analysis.

Figure 11: 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 the PMS2 can be considered in the analysis. A decision tree set is a group of individual decision trees that based on 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 a sustainable M&R analysis, the modified set of decision tree from the 2008 Decision Tree is used.

For the section analysis, Figure 11 shows two combo boxes that need to be selected: Based On, and Strategies. These combo boxes controls how the sections to be analyze. For the "Based On" combo box, typically choose the "always analyze" option, which would considers all the sections in the selected highway regardless of pavement condition. For the "Strategies", there are three options available [MERO, 2006]:

- Single Implementation – Considers rehabilitation only occurs once during the analysis period at a given section.
- 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.
- 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.

It is suggested "Multiple Tree Implementation" should always be used as it considers more rehabilitation possibilities in the analysis.

Several analysis parameters can be set in PMS2 prior to analyse 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.

Table 23 summarizes the initial constraints for a typical M&R analysis in PMS2.

Table 23: 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 place for few minutes to complete. User 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 Implementation
3. Number of distinct highway sections selected for analysis
4. Programming and analysis period
5. Computer processing power and computer network stability

6.4.2.　　　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 12.
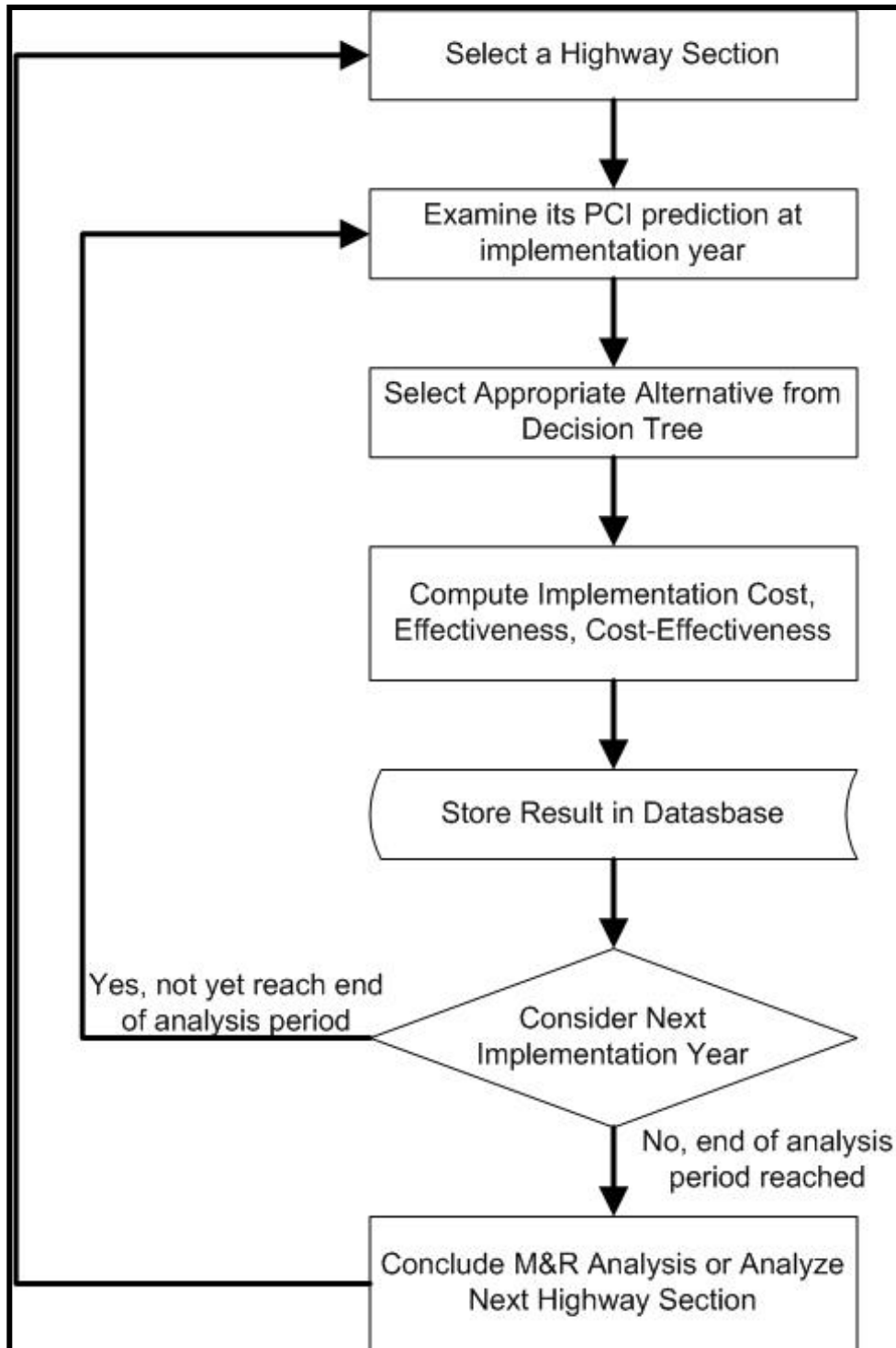
Figure 12: PMS2 Analysis Framework

PMS2 processes the sections using the protocol shown in Figure 12 internally and report 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.

6.4.3. Optimize Sections

In the conventional M&R analysis, PMS2 can optimize the analysis results. PMS2 have primarily two methods to optimize alternative: performance target, and budget constraints. Table 24 shows the comparison between the two optimization methods based on CPATT's experience working with PMS2.

Table 24: 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 requirement	• Attempt to use up all available budget • Select treatment based on largest marginal cost-effectiveness until budget is exhausted given the treatment satisfy PCI requirement
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 24 shows a comparison of the two optimization methods in PMS2. For this project, the budget constraint optimization will not be used because it is inappropriate for CPATT to propose budget constraint 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 10.

$$CE = \frac{Effectiveness}{Cost} \tag{15}$$

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 13 shows a sample graphical illustration of effectiveness from PCI vs. Time plot for a given pavement treatment.
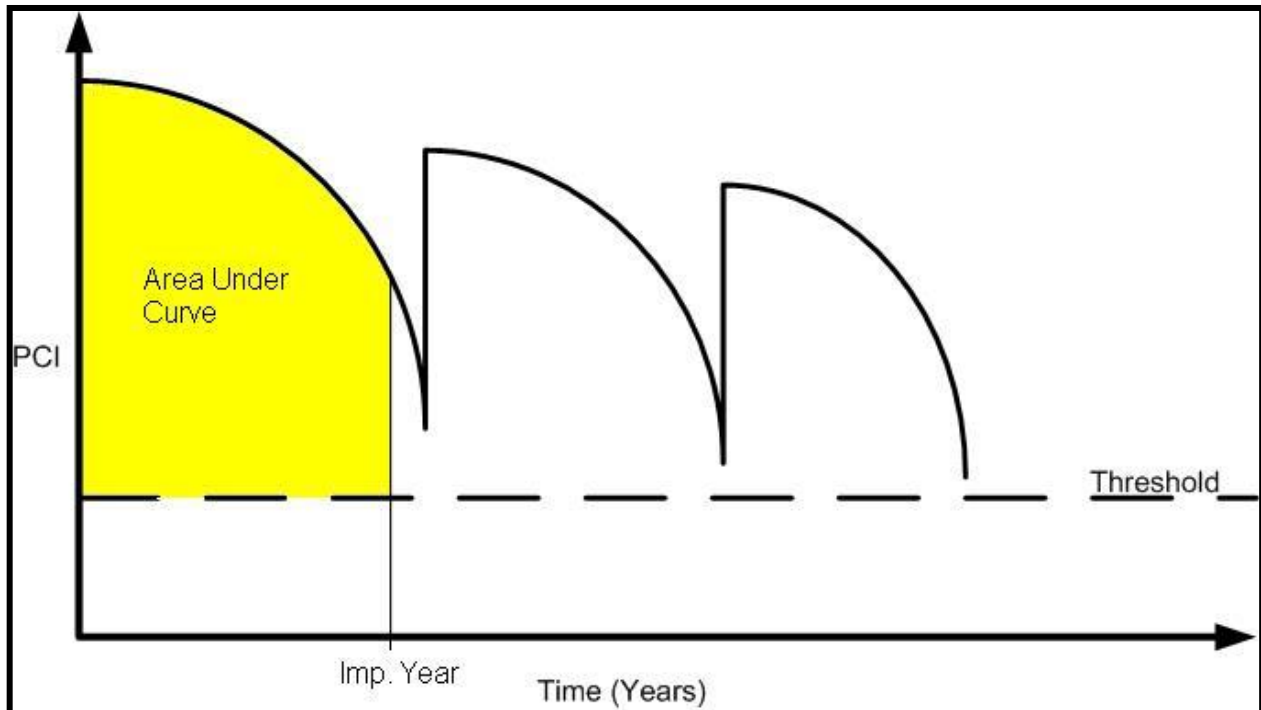
Figure 13: Sample Pavement Deterioration Model and Effectiveness

The area under curve from Figure 13 is multiplied by an effectiveness factor to arrive 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 13 but Highway A has more AADT than Highway B. Then it is more effective to rehabilitate Highway A first than Highway B.

The cost in equation 15 is the implementation cost suggested by PMS2. The interpretation of implementation cost from PMS2 shall 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 treatment is delayed due to poorer 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 14 shows the screen capture of optimization constraints in PMS2 [PMS2, 2009].

Network M&R Optimization

Related Tasks

- Learn more about M & R analysis and optimization
- Change the selected section data view
- Modify or create a new subset
- View or modify maintenance and rehab. treatments
- View or modify treatment decision trees
- View or modify optional cost models
- View or modify optimization constraint sets

Project Design Analysis...

Optimization Constraints 6-3-c

Temp

Description: Temp   ID: Temp

Budgets | **Performance** | Options

☑ Performance Constraints by Class: Freeway

Constraints: ○ Avg & %<T   ● Index Distribution   ○ RSL Distribution

Year	RCI %<=LV	RCI LowV	RCI %>=HV	RCI Hi-V	DMI %<=LV	DMI LowV	DMI %>=HV	DMI Hi-V	PCI %<=LV	PCI LowV	PCI %>=HV	PCI Hi-V
2009	100	0	0	0	100	0	0	0	3	65	67	70
2010	100	0	0	0	100	0	0	0	3	65	67	70
2011	100	0	0	0	100	0	0	0	3	65	67	70
2012	100	0	0	0	100	0	0	0	3	65	67	70
2013	100	0	0	0	100	0	0	0	3	65	67	70
2014	100	0	0	0	100	0	0	0	3	65	67	70
2015	100	0	0	0	100	0	0	0	3	65	67	70
2016	100	0	0	0	100	0	0	0	3	65	67	70
2017	100	0	0	0	100	0	0	0	3	65	67	70
2018	100	0	0	0	100	0	0	0	3	65	67	70
2019	100	0	0	0	100	0	0	0	3	65	67	70
2020	100	0	0	0	100	0	0	0	3	65	67	70
2021	100	0	0	0	100	0	0	0	3	65	67	70
2022	100	0	0	0	100	0	0	0	3	65	67	70
2023	100	0	0	0	100	0	0	0	3	65	67	70
2024	100	0	0	0	100	0	0	0	3	65	67	70
2025	100	0	0	0	100	0	0	0	3	65	67	70
2026	100	0	0	0	100	0	0	0	3	65	67	70
2027	100	0	0	0	100	0	0	0	3	65	67	70
2028	100	0	0	0	100	0	0	0	3	65	67	70
2029	100	0	0	0	100	0	0	0	3	65	67	70
2030	100	0	0	0	100	0	0	0	3	65	67	70
2031	100	0	0	0	100	0	0	0	3	65	67	70
2032	100	0	0	0	100	0	0	0	3	65	67	70
2033	100	0	0	0	100	0	0	0	3	65	67	70

OK

Figure 14: 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 that a small percent of the highway network can be below the target value. For roads and highways under provincial jurisdiction, Table 25 shows the typical target performance PCI value [Chan, 2009b].

Table 25: 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 25 shows a sample case regarding how the performance target should be set in PMS2 for different classes of road. For example, Table 25 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 is distributed into the 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 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.

6.5. 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 M&R treatment. 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

6.5.1. 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, 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 are made. Despite PMS2 has poor accessibility for user, PMS2 is a powerful pavement management system that MTO should utilize to achieve maximum benefit using the available funds.

6.5.2. Sustainable Decision Tree

In order to create a sustainable M&R analysis, CPATT reviewed and revised the current 2008 decision trees set in PMS2. For the 2008 decision trees 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 15 shows a screen capture of PMS2 decision tree for asphalt arterial [PMS2, 2009]. Figure 16 translates the decision tree in Figure 15 in terms of hierarchy. The acronyms shown in Figure 15 and Figure 16 are presented in more detail in Appendix E.
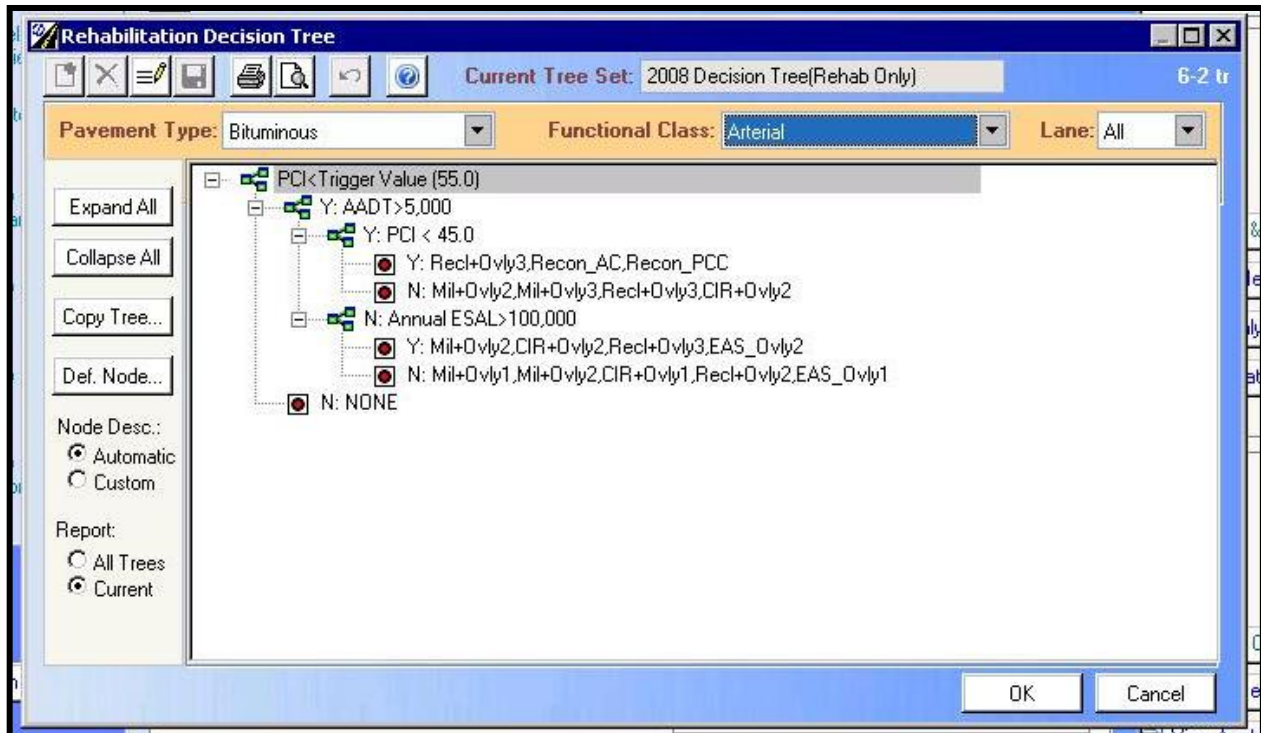
Figure 15: PMS2 2008 Decision Tree for Asphalt Arterial
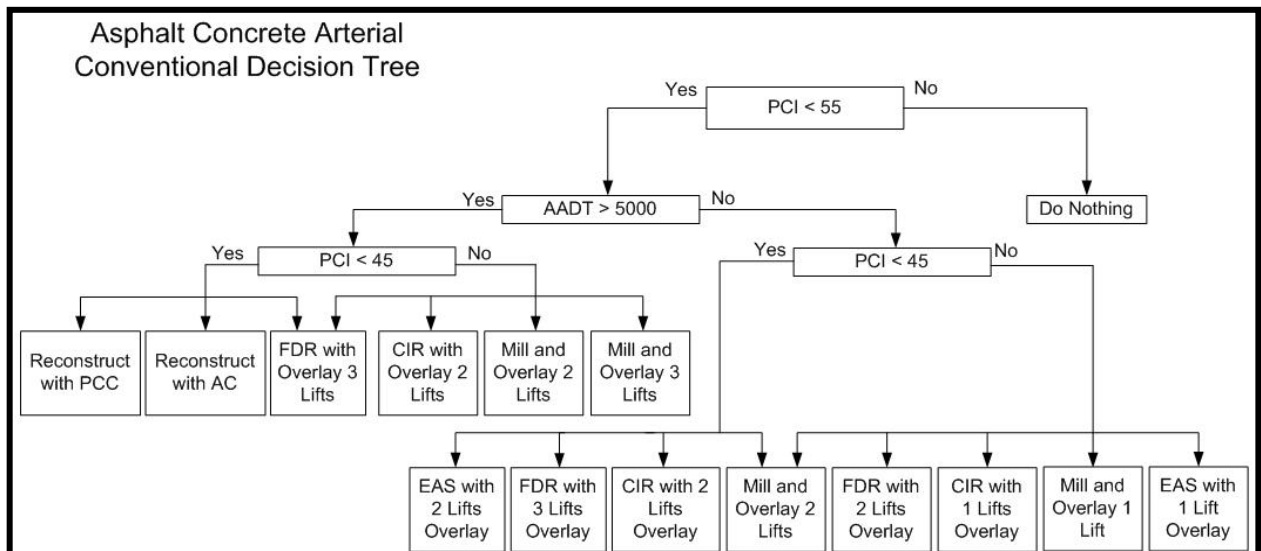
Figure 16: Decision Tree in Hierarchy Form

For this research, the identified treatments that were available in the decision trees were examined. Any treatments that felt 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 16, the treatment of "Reconstruct with portland cement concrete (PCC)" is not a very practical option because:

• Two other alternatives can be used to satisfy such pavement condition (reconstruct with

asphalt and full depth reclamation with overlay 3 lifts) as shown on the decision tree
- Construction duration with PCC may deem this treatment not social friendly
- Concrete reconstruction does not have significant initial cost advantage in MTO general practice

In terms of the environmental impact, the decision trees are modified to eliminate treatments that are not environmental friendly. In other words, users can restrict PMS2 to choose the more environmentally friendly alternative if desirable. Another example in Figure 15, 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 is also to reduce the number of alternatives available and that can be considered in a decision tree. As shown in Figure 16, PMS2 considers three to five alternatives based on the condition of the pavement and the section's AADT. At the end of the analysis, we want to select the most sustainable alternative available. For example from Figure 15, 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 17.
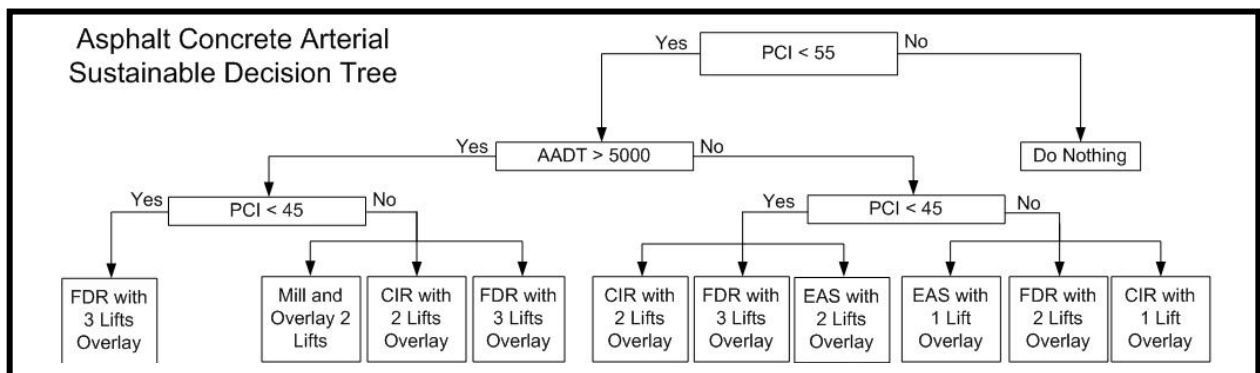
Figure 17: Sustainable Decision Tree for Asphalt Arterial

Appendix J 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 analysed 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.

6.5.3. 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, CPATT recommends to use "always analyze" and "multiple implementations" strategies together. 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 prepare budget at the needed year.

The "multiple 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 PCI.

6.5.4.   Discount rate suggestion and GDLCC Type N

In a sustainable M&R analysis, a 25 years programming period with a 5% discount rate has been selected for this project. A 25 years 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 use 5.3%. Although one may argue that 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 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.

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

Where:
LCC = Life Cycle 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)

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

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 reason for converting GDLCC into an equivalent annual worth presents up the social aspect of sustainability. 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 K. 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 score and MR score for the treatment are considered. Table 26 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 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 L shows data that are used to derive Table 26. As more GreenPave trials are completed and analyzed over time, the values in Table 26 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 L, no GreenPave evaluation was made on concrete pavement rehabilitation due to the small amount of concrete pavement available in Ontario. Therefore, Table 26 does not have any typical GP credits or MR credits suggestion for concrete rehabilitation treatment at this moment. However, GreenPave starts to be implemented in 2010, typical GP credits, material and resources credits can be computed with higher confidence.

Table 26: 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.

6.5.5.   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 conventional performance target optimization method is adequate and can be used as a basis to compare the conventional practice versus the sustainable practices. Unfortunately, the computations of effectiveness and effectiveness factor in PMS2 are not transparent to the user. Therefore, the reliability of the effectiveness value could present misleading results.

A potential 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. 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 outlined in Table 25. 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 25. In a sustainable M&R analysis, the user can also establish stricter performance targets.

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.

6.6. Sustainable Network Level Framework

The sustainable network level framework demonstrates the sequence of activities that MTO should do to promote pavement sustainability. The sustainable network level framework proposed by CPATT to MTO is shown in Figure 18.

Network Level M&R Programming

Field Performance Monitoring

↓

M&R Data from PMS2

↓

Analyze Sustainable Options Available Thru Decision Trees

↓

Calculate GDLCC Type N

↓

Select Option with Lowest GDLCC Type N Thru Optimization

↓

Propose Budget Allocation and Rehabilitation Schedule
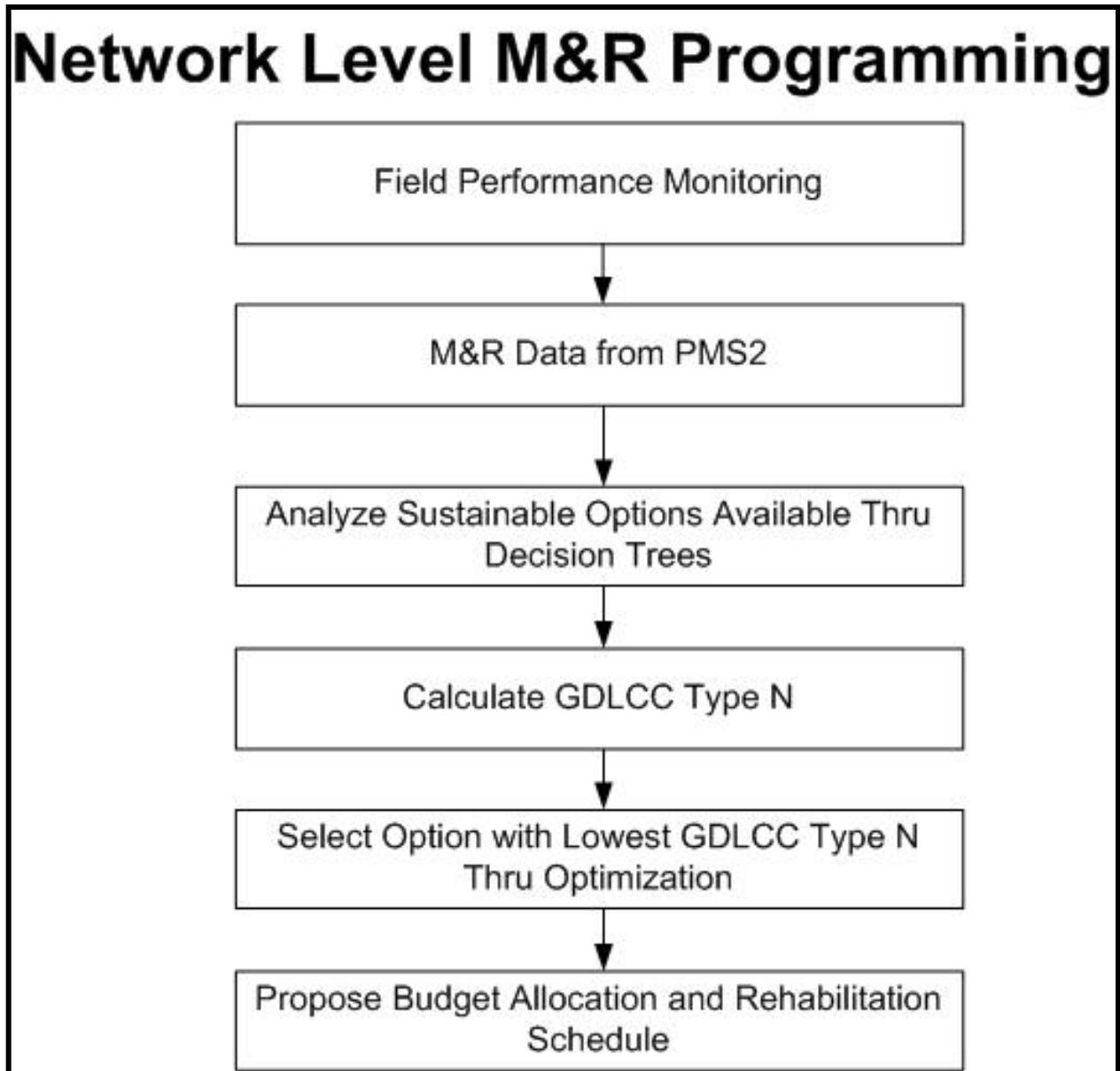
Figure 18: Sustainable Network Level Framework

From a sustainability perspective, the field performance monitoring and continuous update of pavement condition data are initial steps toward network level pavement sustainability. These data serve as the working platform of any network level M&R analysis. MTO can 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 18:
   • Analyze sustainable options available thru usage decision trees
   • Compute GDLCC Type N
   • Select the option with lowest GDLCC Type N thru optimization
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.

6.7. Connection between Project level 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 a sounded 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 19 shows the connection between project level and network level framework.
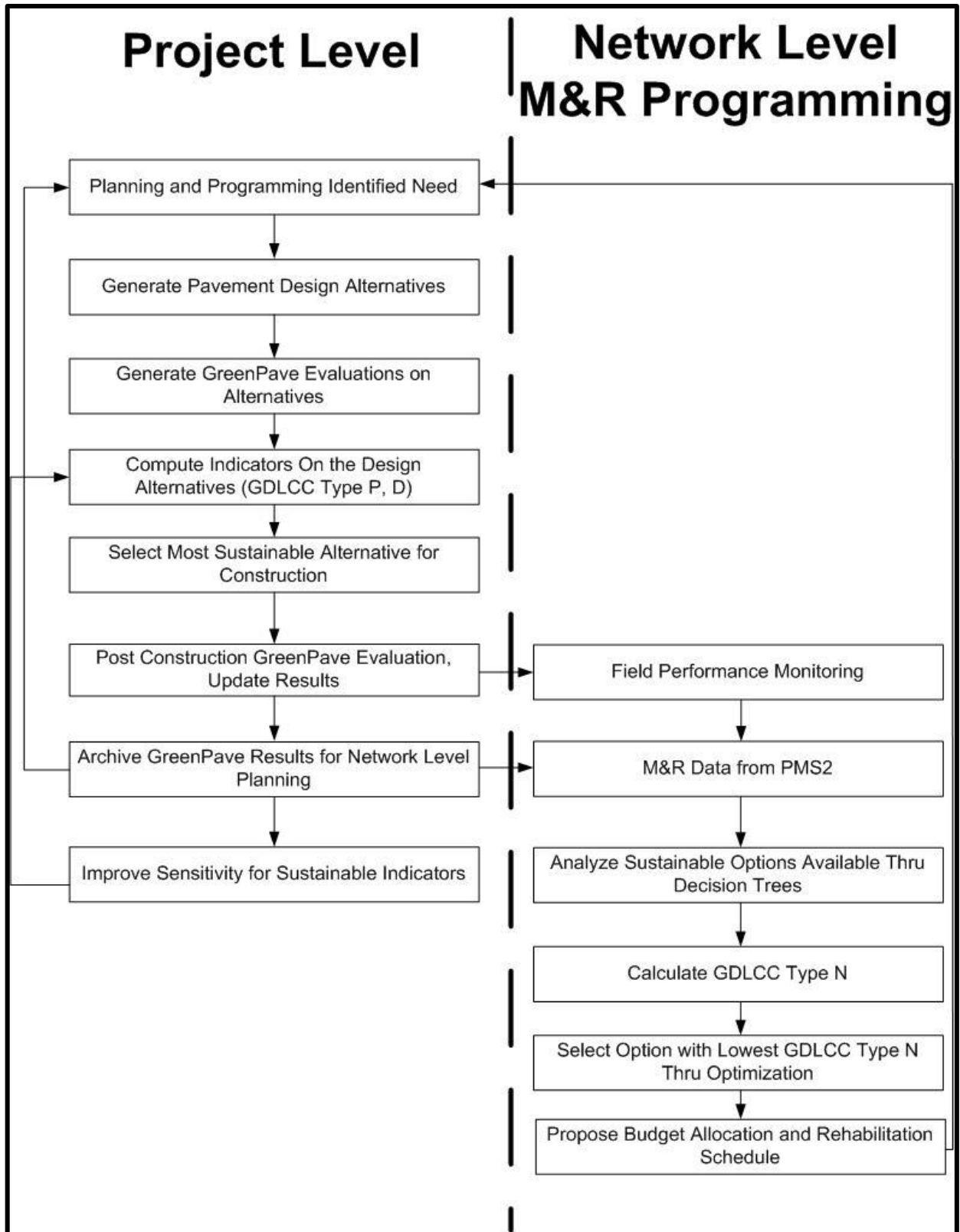
Figure 19: Combined Sustainable Pavement Framework

In terms of pavement sustainability, Figure 19 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 GDLCCs or D.

7. Task 6

7.1. Indicator Computation

In task 4 and task 5, three indicators are proposed to measure pavement sustainability at network level. Task 6 involves drafting guidelines and examples for indicator computation. As previously suggested, the indicators should be simple to compute by MTO staffs, so Excels templates for the indicators for the ease of calculation. The intent of Task 6 is for MTO to understand how to compute sustainable indicators through numerical examples. Observations from the calculation are also discussed in this task.

7.2. Calculation of GDLCC Type P

This section shows a numerical example for the computation of GDLCC Type P. Consider a project with the data given in Table 27 from project WP# 403-98-00 [Thornton, 2009]:

Table 27: GDLCC Type P Data

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 27, 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 cheapest 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

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

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

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

For Alternative 2

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

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

For Alternative 3

$$GDLCC\_Type\_P = \$156900 - \$156900 \times \left(\frac{Min(9.5,10)}{10}\right) \times \left(\frac{16}{36}\right)$$

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

For Alternative 4

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

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

Observations of the results:
- 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 27, 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 cheaper than alternative 2.

7.3.   Calculation of GDLCC Type N

The calculation of GDLCC Type N is completed using equation 16. Consider an example based on the data given below [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 28: 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   [1] – From Appendix K, Table 45
Imp. Cost   = Implementation Cost   [2] – From Table 26

From Table 28 it is observed that

- 3 treatment methods (FDR, M&O, 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 45, not Table 12. 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 28

For Alternative 1 (*and 4*)

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

For Alternative 2 (*and 5*)

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

For Alternative 3 (*and 6*)

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

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.

7.4.   Calculation 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 27. 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 29 summarizes the x and y components of the given project data. The data are substitute into equation 10 to calculate D.

Table 29: 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
$$D = \sqrt{0.75^2 + 1.00^2} = 1.25$$

From the calculation of D, alternative 3 is the most sustainable alternative with the lowest D value. Figure 20 shows the visual representation of D for the data from Table 27.
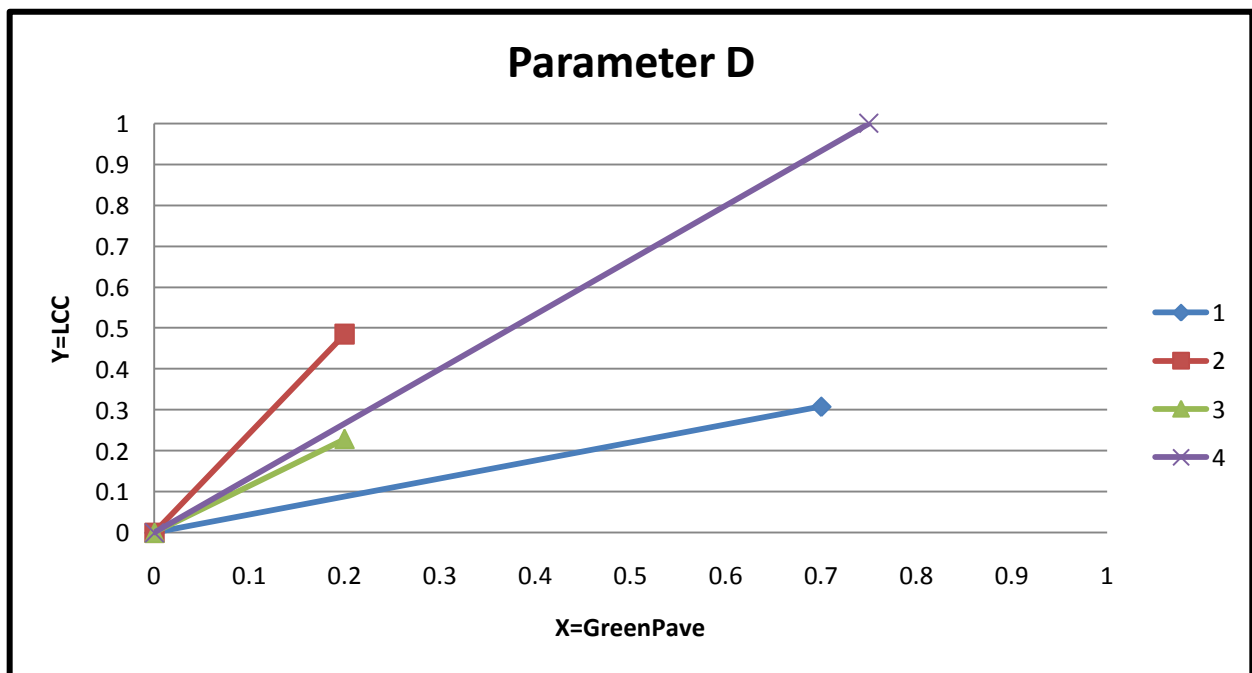
Figure 20: Parameter D plot for Project 403-98-00

Clearly, from Figure 20 above, alternative 4 has the longest vector and alternative 3 has the shortest vector. Numerical value of D is an 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. Consider the data in Table 30 for the fictitious example.

Table 30: 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

The corresponding x, y, and D values are shown in Table 31.

Table 31: 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 31 shows in the fictitious case is the same the original case. However, Figure 21 shows the graphical representation of the fictitious case, which demonstrates the difference between the alternatives.
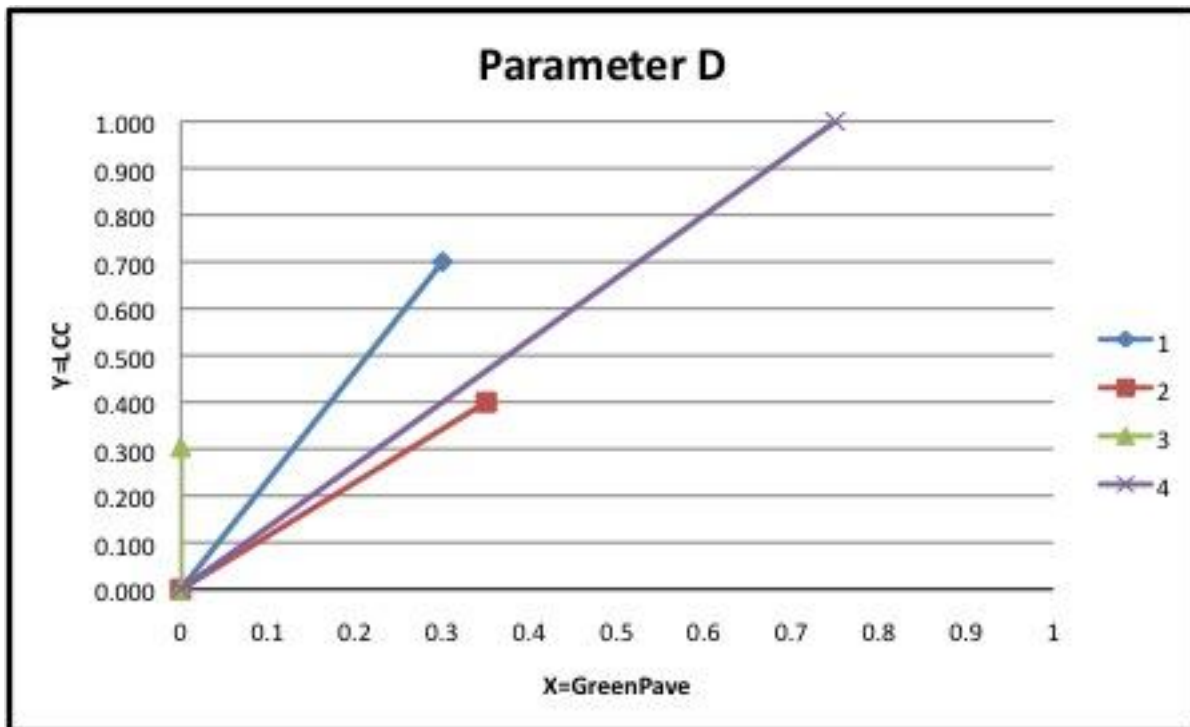
Figure 21: Fictitious Case of Parameter D

As shown in the plot above, alternative 4 was kept the same as a control alternative. All other alternatives lies in different region of the plot compared to Figure 20. Although alternative 3 is still the most sustainable option available as shown in Figure 21, user of parameter D should plot

the vectors for the alternatives to truly the sustainability performance of different alternatives.

8. Task 7

8.1. Final Project Presentation at MTO

The presentation for this project was scheduled on April 7, 2010, 2pm, at MTO Downsview Office. The purpose of the presentation is to provide a summary of findings for project Task 1 to 6. Dr. Susan Tighe P.Eng, and Mr. Peter Chan represented CPATT to present this presentation to MTO staffs. The presentation outline is shown in six steps:

1. Project background.
2. Review MTO sustainability Initiatives and other 'green' initiative available.
3. Discuss different treatments for sustainability.
4. MTO Green pavement rating system, GreenPave.
5. Implementation framework and network level.
6. Conclusions.

The presentation started with a discussion of sustainability. The general scope of sustainability, sustainable transportation, and sustainable pavement are introduced to the audiences. Task 2 of the presentation began by illustrating various MTO sustainable practice examples. These examples included CIR project on Highway 7 at Perth, EAS project at Highway 17 near Lake Superior, perpetual pavement project on Highway 401 and pervious concrete parking lot at Highway 401 Guelph Line interchange. Four green initiatives were presented: LEED™, Greenroads, GreenLITES, and Green Guide for Road Task Force. These initiatives served as the basis in developing a green pavement rating system for MTO that is used as a tool for environmental quantification of sustainability. The CPATT/MTO Sustainable Pavement Workshop and the workshop questions were presented as a starting point to move forward sustainable pavement practices.

The results from the environmental and economic quantification of different pavement technologies are presented for Task 3. The PaLATE analysis results from rehabilitations and constructions methods are compared for energy, CO_2, SO_2, NO_x, and CO. The economic quantification of rehabilitation technologies is presented through a LCCA comparison. The economic quantification of construction technologies is presented as a comparison of total pavement material required for construction. It was concluded that the PaLATE environmental results from Task 3 requires revision. MTO proposed two changes for the PaLATE environmental results during the presentation:

1. Bar charts for PaLATE results should show the energy or environmental emissions of different pavement layers.
2. Complete the life cycle analysis for concrete and asphalt pavement to estimate total emission over a life cycle period.

The presentation for Task 4 started with a brief overview of MTO green pavement rating system, GreenPave. The connection of GreenPave and sustainable pavement is explored. The equations to compute project level sustainable indicators GDLCC, GDLCC Type P, and parameter D are

introduced and explained during the presentation. The sustainable pavement framework for project level pavement engineering was also introduced and discussed to the audiences.

Task 5 of the presentation emphasized on the network level pavement engineering and PMS2. A brief overview of how PMS2 generate M&R analysis was explained at the presentation. Improvements to PMS2 to aid into more sustainable pavement are also discussed.

Lastly, Task 6 of the project presents MTO with three examples regarding computation of the sustainability indicators that were presented in Task 4 and Task 5. The calculation details are presented in this Chapter 7 of this report and the supplemental handout for the presentation.

9. Conclusions

Transportation infrastructure ages and deteriorates with time. With limited resources and funding, transportation agencies such as MTO faces challenge in maintaining its infrastructure with acceptable performance every day. As the concept of sustainable development is gaining more momentum, the consideration of economy, society and environment in pavement engineering practice are crucial steps toward sustainable transportation. This project, quantifying pavement sustainability, demonstrates MTO is in the state of implementing sustainable transportation infrastructures in Ontario.

This final report summarizes all work completed in the project. The main goal of this project is to develop a framework for MTO to quantify sustainable pavement practices. This framework considers 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 is to understand the state-of-the-art pavement engineering practices available. The literature review of this project considers material, design, construction and rehabilitation techniques that can be used in project level applications at MTO. Various green initiatives are reviewed in this project as well. These green initiatives provide MTO insights regarding how green rating system works 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. The intent of the workshop is to discuss the current state of sustainable pavement practice in Ontario and stepping forward with sustainable pavement in the future. Many useful findings and directions came out of this workshop.

MTO's green pavement rating system, GreenPave, is an important component of the sustainable pavement framework. This project emphasizes using GreenPave to achieve sustainable pavement. The quantification of typical environmental and economic savings between different pavement technologies helps in the development of GreenPave. The typical savings quantification demonstrates the relationship of economic, social, and environmental elements in a pavement technology. GreenPave evaluates how green a pavement design, but it does 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 project proposed two indicators to measure pavement sustainability at project level. These indicators assess pavement sustainability by combining GreenPave credits achieved by a project and life cycle cost simultaneously. The indicators proposed in this project provide a balance way to represent pavement sustainability through simple mathematics. The project level sustainable 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 pavement management system, PMS2. The role of PMS2 in this project is generating M&R analysis for Ontario highways. CPATT proposes ideas in improving the sustainability at network level such as proactive planning, use sustainable decision trees in PMS2, select the

correct implementation strategies, and compute GDLCC Type N as a pavement sustainability indicator at the network level. The network level frameworks also require conducting sustainable M&R analysis and potentially use PMS2 as the central database for storing GreenPave credits and sustainability indicators.

The final presentation of the project was held MTO on April 7, 2010. The presentation covers all the project findings from task 1 to task 6. MTO has suggested two improvements to the PaLATE environmental results from task 3. PaLATE environmental results were revisited to identify how different material contributes to energy and emissions at individual project and at life cycle perspective. At individual project basis, it is concluded that asphalt material contributed most of the energy and emission output in PaLATE. On the other hand, at life cycle perspective, the energy and emission outputs are mostly contributed by during construction.

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.

10. Acknowledgements

11. Acronym List

Table 32: Acronym list for the project

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
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 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
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

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Appendix A – Project Gantt Chart

ID	ℹ	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 ⇩

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ID	ⓘ	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

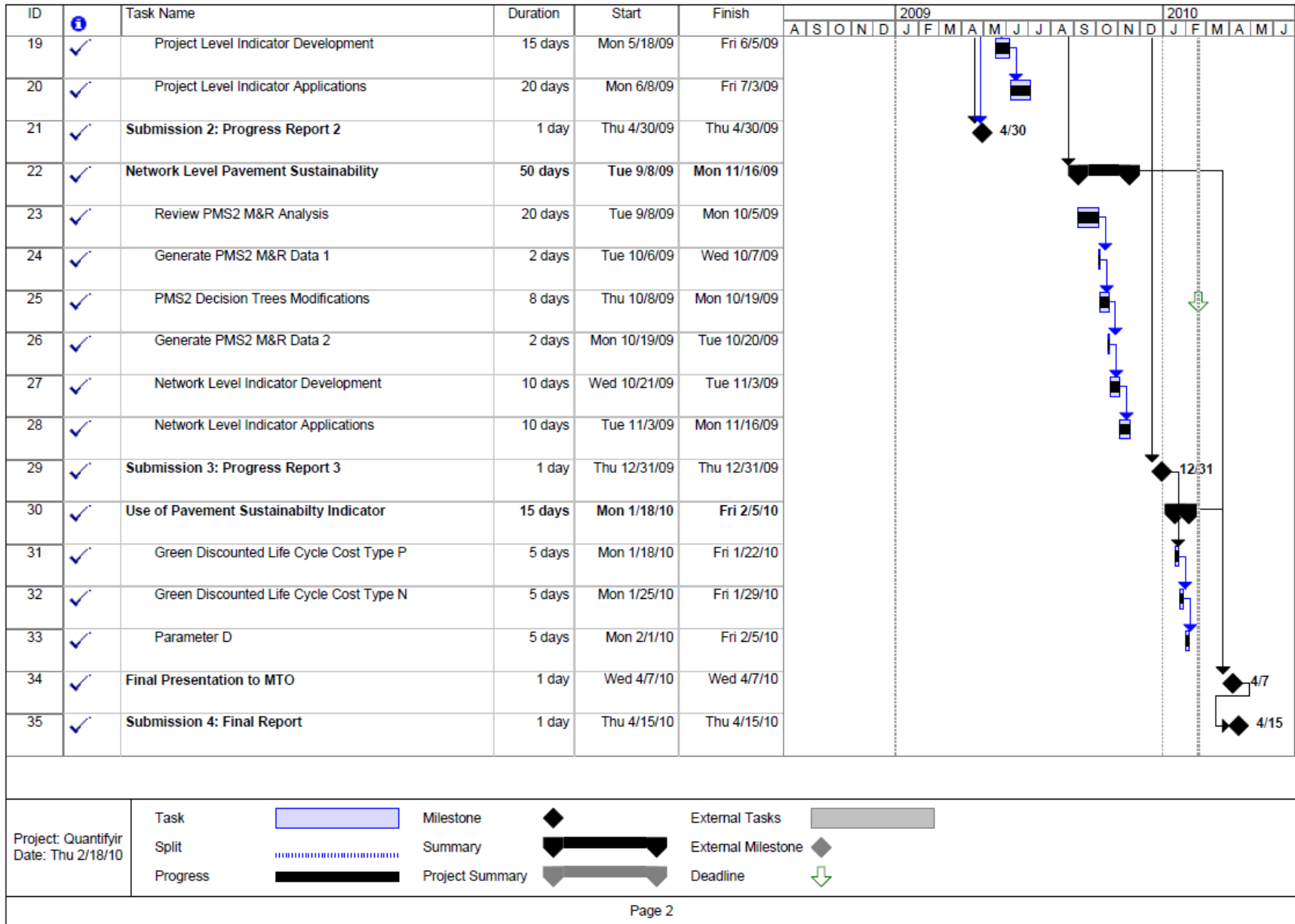|		
Task	Milestone ◆	External Tasks
Split	Summary	External Milestone ◆
Progress	Project Summary	Deadline ⇩

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Figure 22: Project Schedule Gantt Chart

Appendix B – Workshop Summary

Workshop Attendees

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		

1) **Possible Ideas For Sustainable Pavements**
- Use of Pervious Concrete
- Two Layer Concrete Systems
- Use of Cement OGDL
- Warm Asphalt Technologies
- Increasing Percentages of RAP
- In Place Recycling (use of RAP)
- Use of Recycled Asphalt Shingles
- Porous Asphalt
- Use of byproducts 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, Diamond Grinding
- Crack Mitigation through Chip Seal, Microsurfacing, Crack Sealing
- Fast Track Repairs
- Innovative Pre Cast Repair Products
- Role of Emissions in Production
- Long Life Pavement
- Quiet Pavements and noise reduction
- User Delay Costs
- Impacts of Climate Change

2) What Sustainable Technologies are Available?
- Cement: reducing CO2 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 & plastic to preserve virgin aggregate sources, Using mineral fillers for fine aggregate
- Use of warm 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
- GHG emission. Optimum balance between stationary/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 (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
  – Chip Seals
  – Microsurfacing
  – Slurry Seals
  – Thin hot mix overlays
  – Epoxy based
  – SAMI before overlay and/or reinforced chip seals
  – Surface correction, micro milling, diamond grinding
- Rehabilitation Technologies
  – In place recycling (CIR, HIR, FDR, rubblization)
  – Use of recycled and excess materials (i.e. granular bases, fill, shoulders)
  – Deep milling and paving
  – Precast concrete (roadway and structures)

3) Benefits of Sustainable Pavements
- Reducing CO2 emission and use of natural resources such as limestone
- Alternate fuel will reduce emission and truck fuel savings
- Use less potable water
- Reducing UHI effect with high solar reflectance
- Long life and lower embodied primary energy
- Saving money! – 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 (workers and travelling public)
- Porous pavement for stormwater infiltration

4) What are Degree of Utilization and Drawback?
- Low utilization due to government or environmental regulation for fuel usage
- SCMs: medium usage, can be better 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

5) 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
- 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

6) 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

- Information exchange/communication, tough sell to citizens and politicians (worst-first)
- Motivations of various members
- Existing regulations in place (MOE)
- 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 modelling data for preservation
- No incentives for sustainable design and construction
- Comfort level of designer to use innovative and sustainable techniques are missing

7) 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

8) Costs Required to Achieve Sustainability?
- There are none to slight additional costs initially but tapper 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

9) How Should Sustainability be Quantified Reasonably?
- Greenhouse gases 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

10) What Other Technologies Should be Explored?
- Portland-limestone cement to reduce demand of virgin 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

Appendix C – PaLATE Documentation

Background and Introduction

This document will explain 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. PaLATE is a Microsoft Excel workbook that contains several worksheets. Dr. Arpod Horvath and his research team at the University of California Berkeley, originally 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 derivations of quantities calculated by PaLATE, but provide a set of 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 33 provides a brief explanation of the three categories.

Table 33: 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 price to calculate costs.
Output	- Cost $ Results - Environmental Results	The 2 worksheets provide monetary result 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 and discussed in this document.

The worksheets that are of our interest for the LCA are summarized in Table 34.

Table 34: 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 process is 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 34 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 screwing up the referencing in the embedded calculation sheet. Therefore, it is preferred to use "copy" and "paste"

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 23 shows the general layout for the Design worksheet
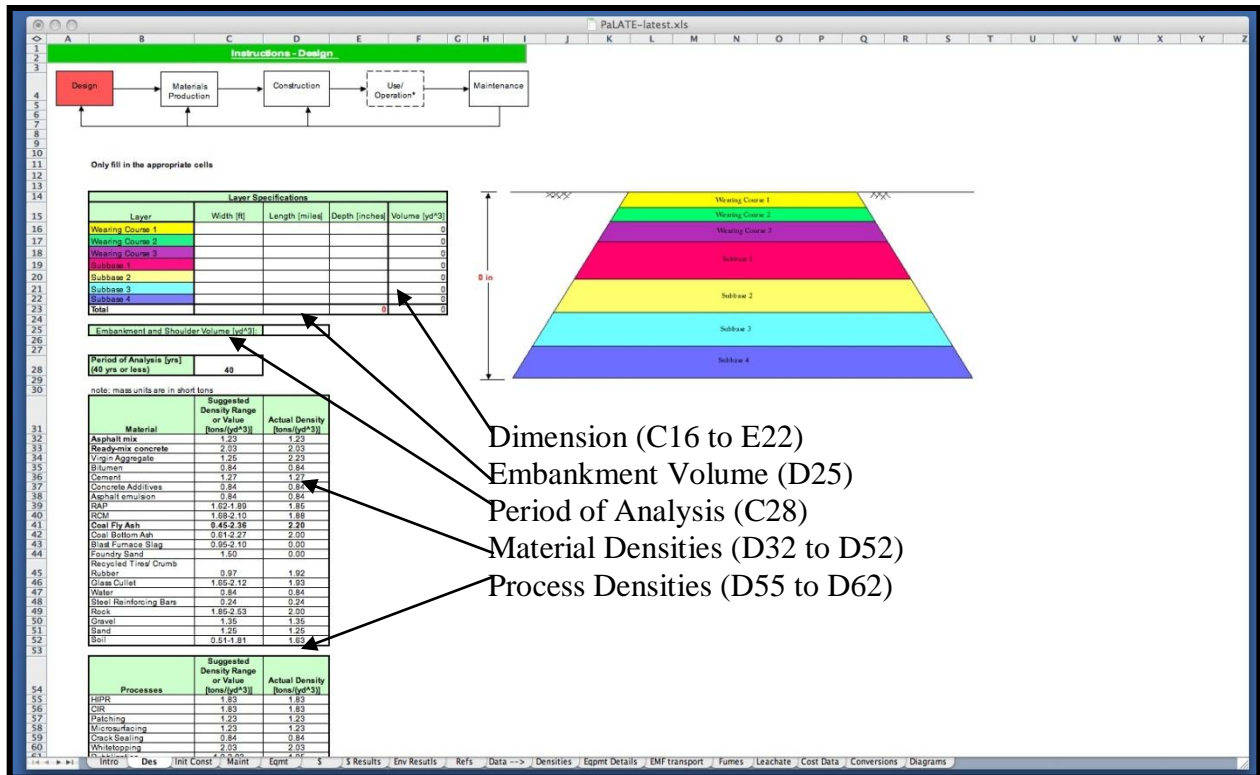
Figure 23: Design Worksheet

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 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 distance, 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 24 shows the layout of the Initial Construction worksheet.
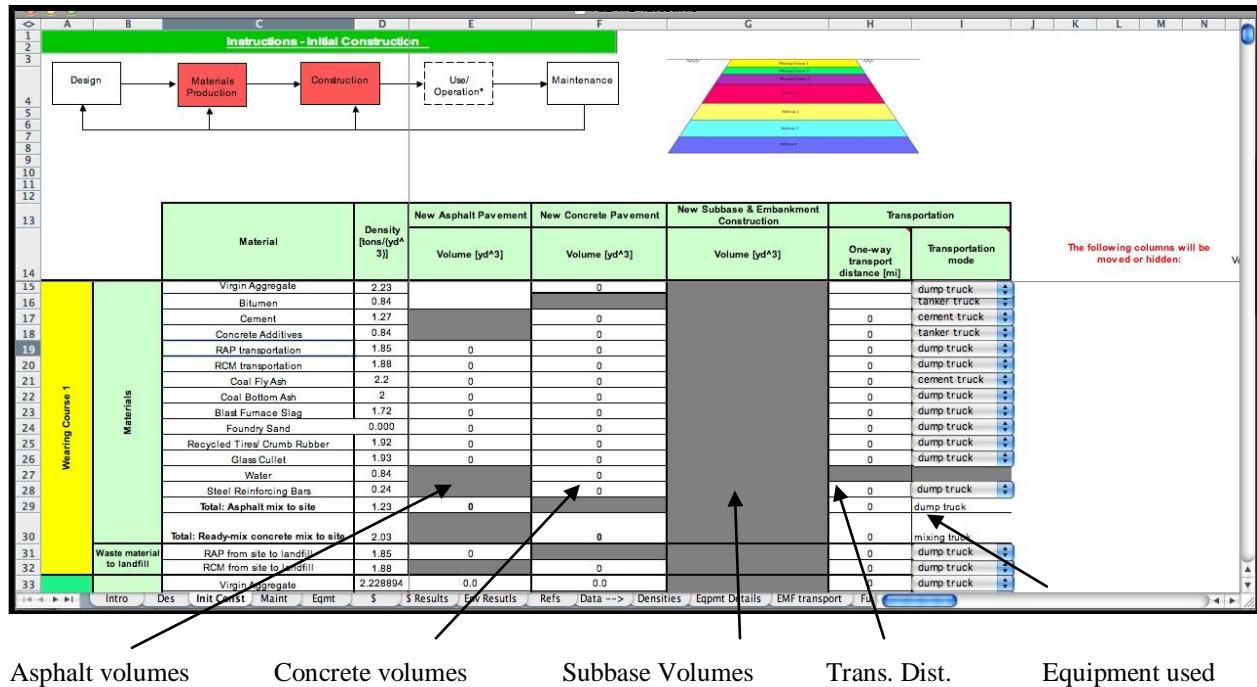
Figure 24: Initial Construction Worksheet

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 methods; it is okay to leave 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 HIR, CIR, FDR, microsurfacing, whitetopping, etc. Figure 25 shows the layout of maintenance worksheet
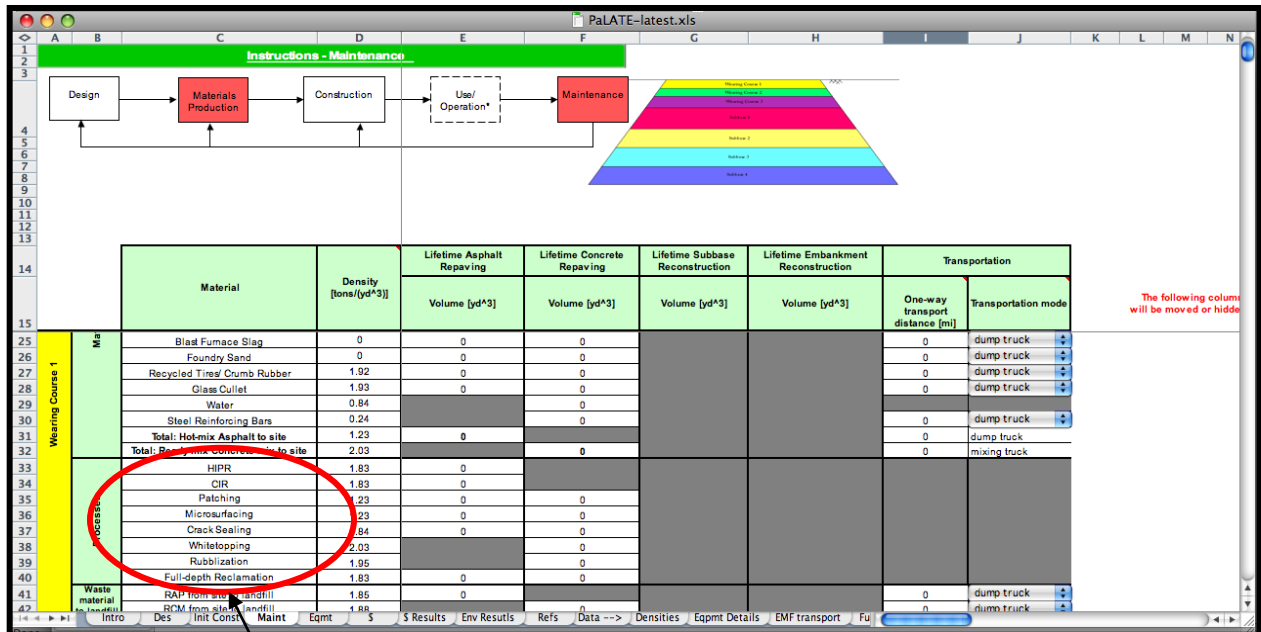
Maintenance & Rehabilitation Processes

Figure 25: 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 35.

Table 35: PaLATE Environmental Results

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 26 shows a sample result from a PaLATE analysis. Cold in-place recycling (CIR) was selected for demonstration here.

Figure 26: PaLATE Environmental Results for CIR
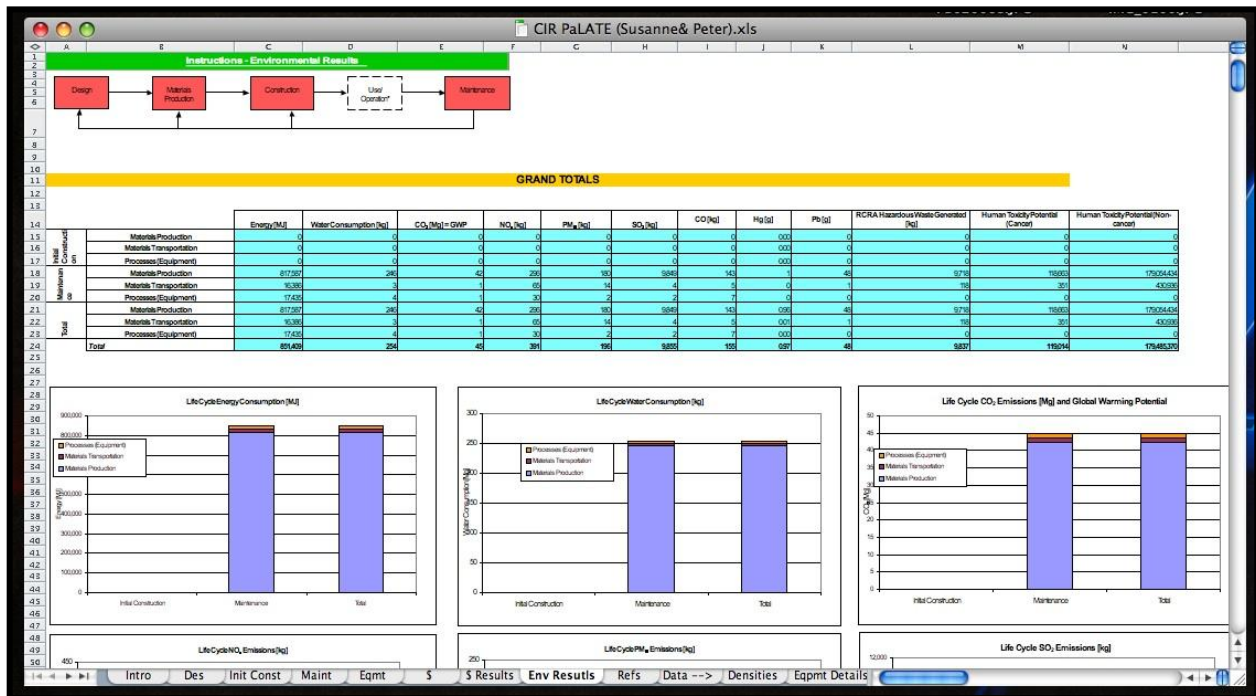
Define Typical Savings with PaLATE

For the quantifying pavement sustainability project, there are assumptions 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 36 shows the typical thickness used in new pavement construction. Table 37 shows the typical thickness used in different pavement rehabilitation processes.

Table 36: Pavement Thickness in New Construction (in inches & millimeters)

Layer	Asphalt Pavement	Porous Asphalt	Pervious Concrete	Concrete Pavement with RCA	Concrete Pavement
WC1	5.90 in 150 mm	3.94 in 100 mm	9.45 in 240 mm	9.85 in 250 mm	7.87 in 200 mm
WC2			3.94 in 100mm OGDL	3.94 in 100 mm OGDL	3.94 in 100 mm OGDL
WC3					
SB1 (Granular A)	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
SB2 (Granular B)	11.81 in 300 mm			11.82 in 300 mm	

Table 37: Asphalt Pavement Thicknesses in Rehabilitation (in inches & millimeters)

Layer	HIPR	CIR	CIREAM	FDR [C]	Mill & Overlay	EAS [C]
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
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
[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 37.

- A 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 6.21 miles or 10km; for bitumen is assumed 186.3 miles or 300km.

- 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, 40% Gravel
- Granular B was assumed to be 30% RAP, 30% RCM, 20% Gravel, 20% Rock

For Hot In-place Recycling (HIR)

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**

For Cold In-place Recycling (CIR)

From table 5, 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**

For 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**

For 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**

For 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.

For Mill and Overlay

Mill and overlay is the simplest 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 percentage 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 input for rubblization is

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**

New Construction Input

For new construction of an alignment, two typical PaLATE quantifications were done: New asphalt construction, and new concrete construction.

New Asphalt Construction

This is building a new asphalt roadway on subgrade. It requires 150mm HMA, 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**

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 input for porous asphalt are

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

New Concrete 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 input are

Virgin Aggregate →**Cell F15 = 0.651*Wearing Course 1 Volume**
Cement →**Cell F17 = 0.146*Wearing Course 1 Volume**
Water →**Cell F27 = 0.143*Wearing Course 1 Volume**
Virgin Aggregate →**Cell E33 = 0.95*Wearing Course 2 Volume**
Bitumen →**Cell E34 = 0.05*Wearing Course 2 Volume**
RAP to Site →**Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site →**Cell G81 = 0.95*Subbase 1 Volume**

New 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 = 0.95*Wearing Course 2 Volume**
Bitumen →**Cell E34 = 0.05*Wearing Course 2 Volume**
RAP to Site →**Cell G70 = 0.05*Subbase 1 Volume**
Gravel to Site →**Cell G81 = 0.95*Subbase 1 Volume**

New 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 to 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 = 0.95*Wearing Course 2 Volume**
Bitumen ➔**Cell E34 = 0.05*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**
Grave**l** 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 38 shows the results from literature.

Table 38: 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 – [Hassan, 2009] *Life-Cycle Assessment of Warm-Mix Asphalt: Environmental and Economic Perspective.*, Hassan, Marwa. TRB Paper #09-0506					
2 – [Ventura et al, 2009] *Environmental Comparison at Industrial Scale of Hot and Half-Warm Mix Asphalt Manufacturing Processes.*, Ventura et al. TRB Paper #09-1274					
3 – [Mallick et al, 2009] *Laboratory Study on CO2 Emission Reductions Through Use of Warm-Mix Asphalt.*, Mallick et al. TRB Paper #09-1951					
4 – [Tighe, 2008] *Environmental/Structural Evaluation of Warm Asphalt in the Canadian Climate*. Tighe et al. ISAP 2008					
5 – [NRC, 2005] *Road Rehabilitation Energy Reduction Guide for Canadian Roads*. Natural Resources 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 input are

Energy → Cell C18 =0.7*S43

CO2 → Cell E18 = 0.55*U43/1000

NO_x→ Cell F18 = 0.4*V43/1000

SO2 → Cell H18 = 0.7*X43/1000

Appendix D – PaLATE Output Summary

Table 39: PaLATE Output Summary

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
HIPR = 50mm HMA + 50mm HIPR	HIPR	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
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 New 200Conc+100 OGDL+150 Gran A		5237100	1886	341	3957	1902	21451	1865	6	393	19044	362015	1286090835
Asphalt New 150HMA+150GranA+300 GranB		3034128	689	176	1209	1543	28817	442	2	127	22631	409485	1175616717
Pervious Concrete		5325827	1774	347	4079	2105	21340	1916	6	393	19694	385205	1493678931
RCA Mix = 250mm Conc + 100mm OGDL + 450mmGran		6086435	1987	407	4401	2726	21474	2130	7	428	21022	411588	1684350910
Porous Asphalt 100Surface+400Reservoir		2601025	562	157	991	1529	19215	367	2	102	17222	263005	402478250

Appendix E – PaLATE Bar Charts
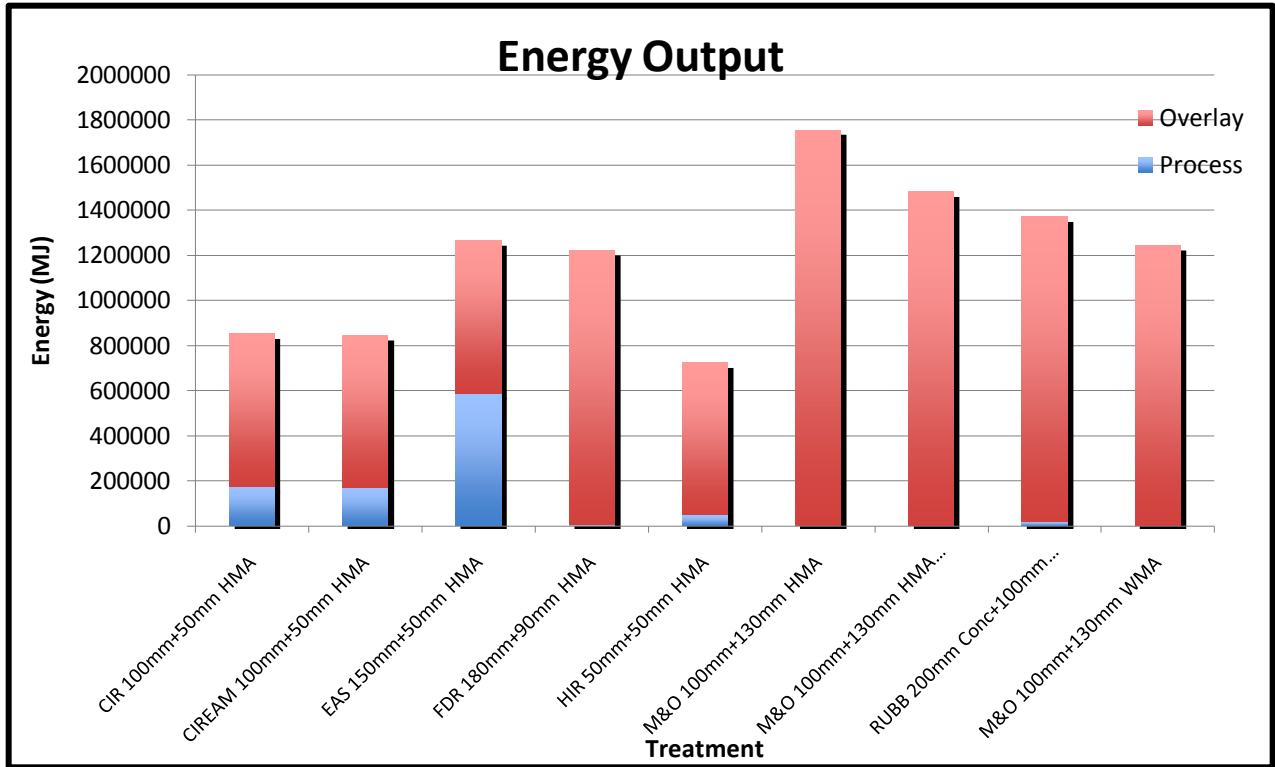
Figure 27: Energy Output for Rehabilitation
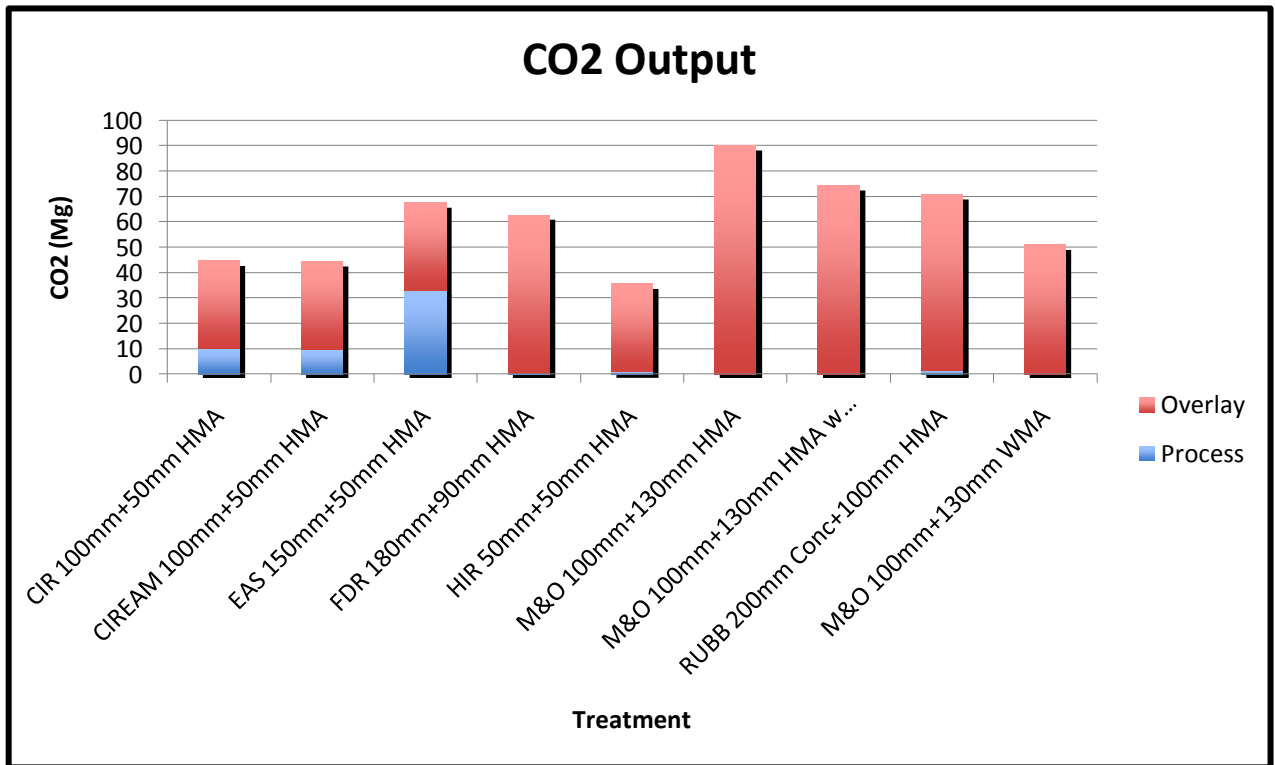
Figure 28: CO₂ Output for Rehabilitation
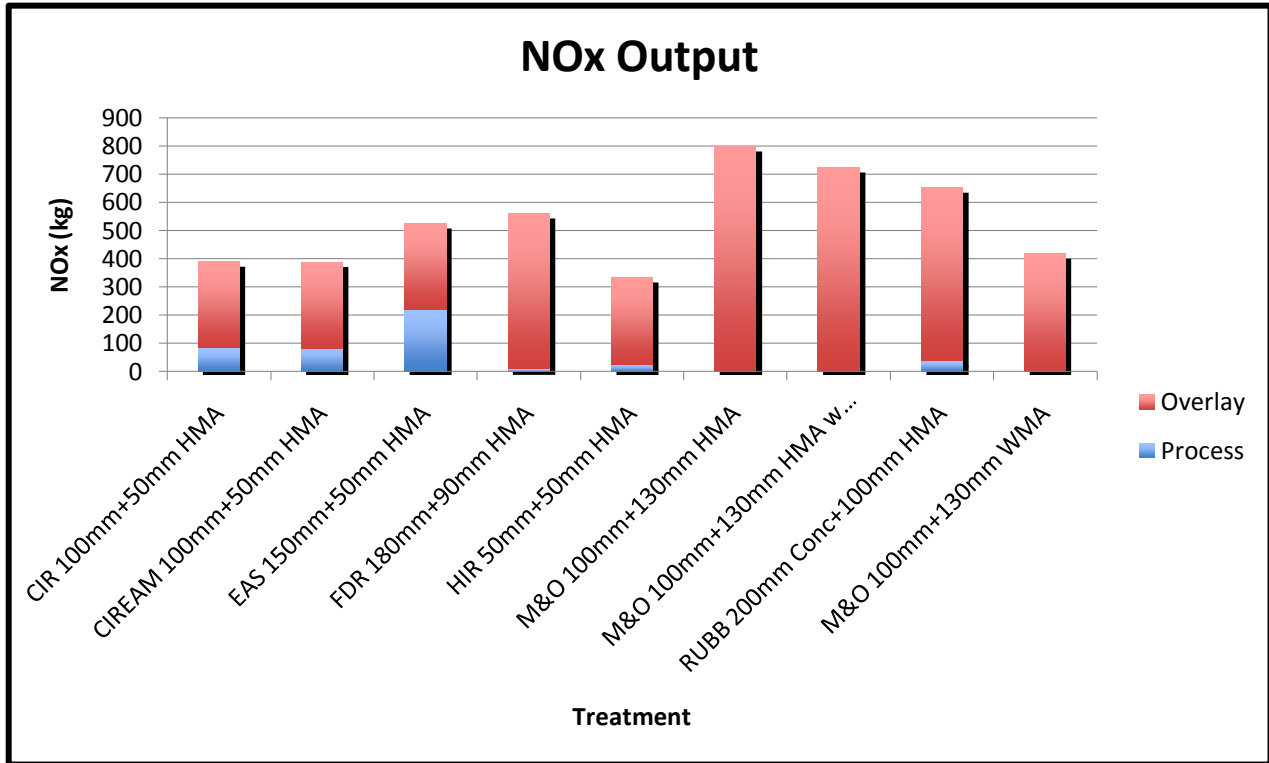
Figure 29: NO$_x$ Output for Rehabilitation
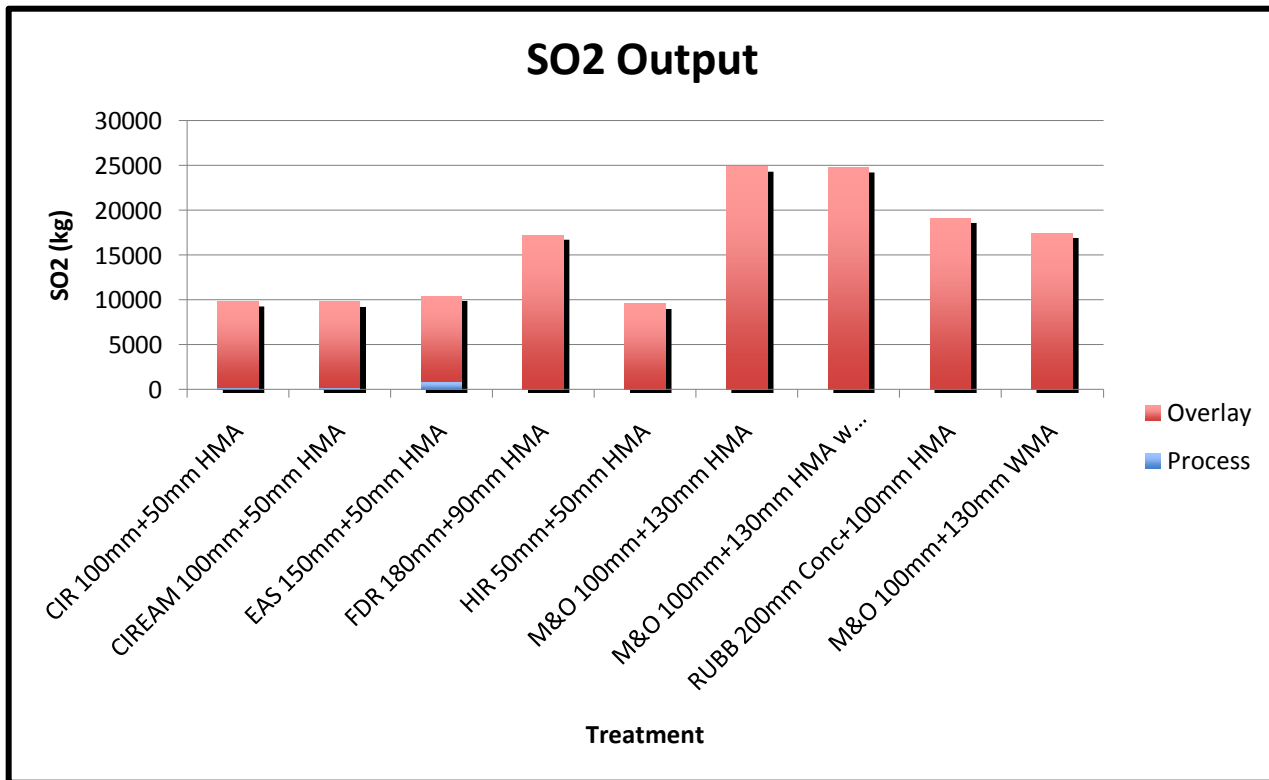
Figure 30: SO$_2$ Output for Rehabilitation
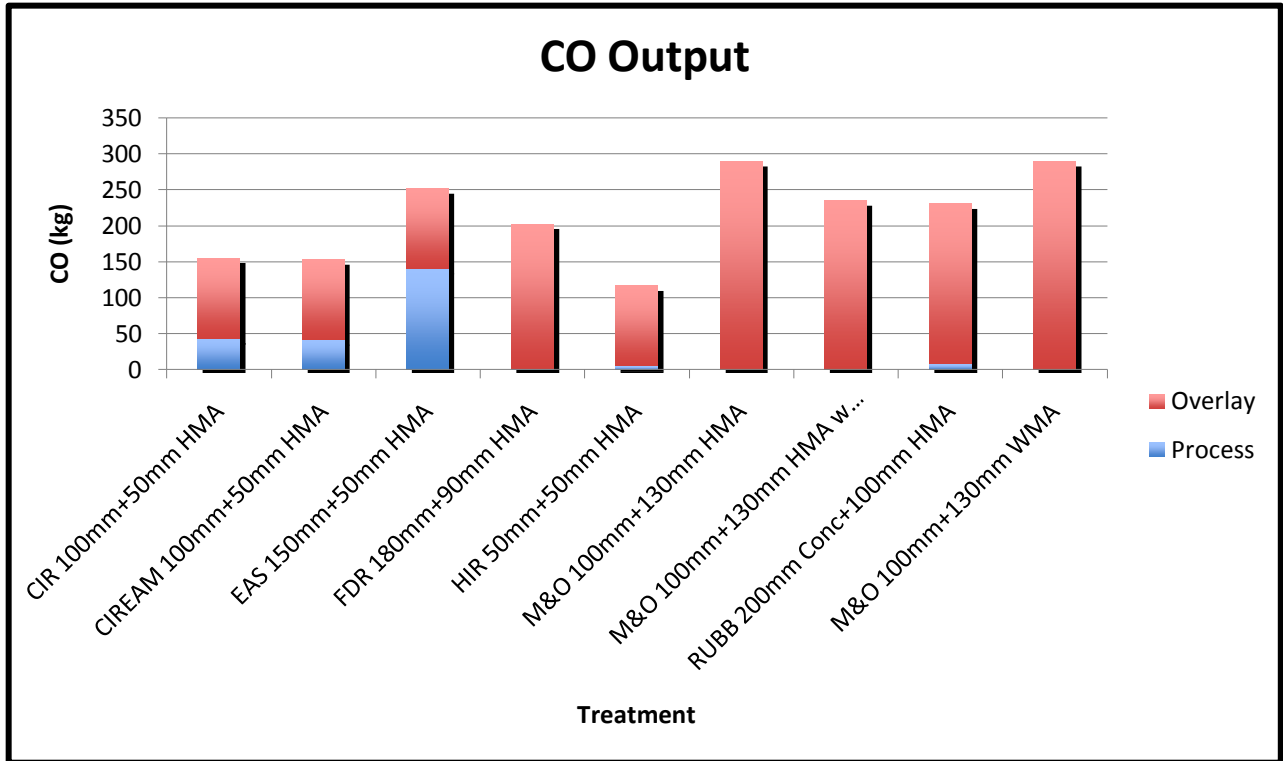
Figure 31: CO Output for Rehabilitation
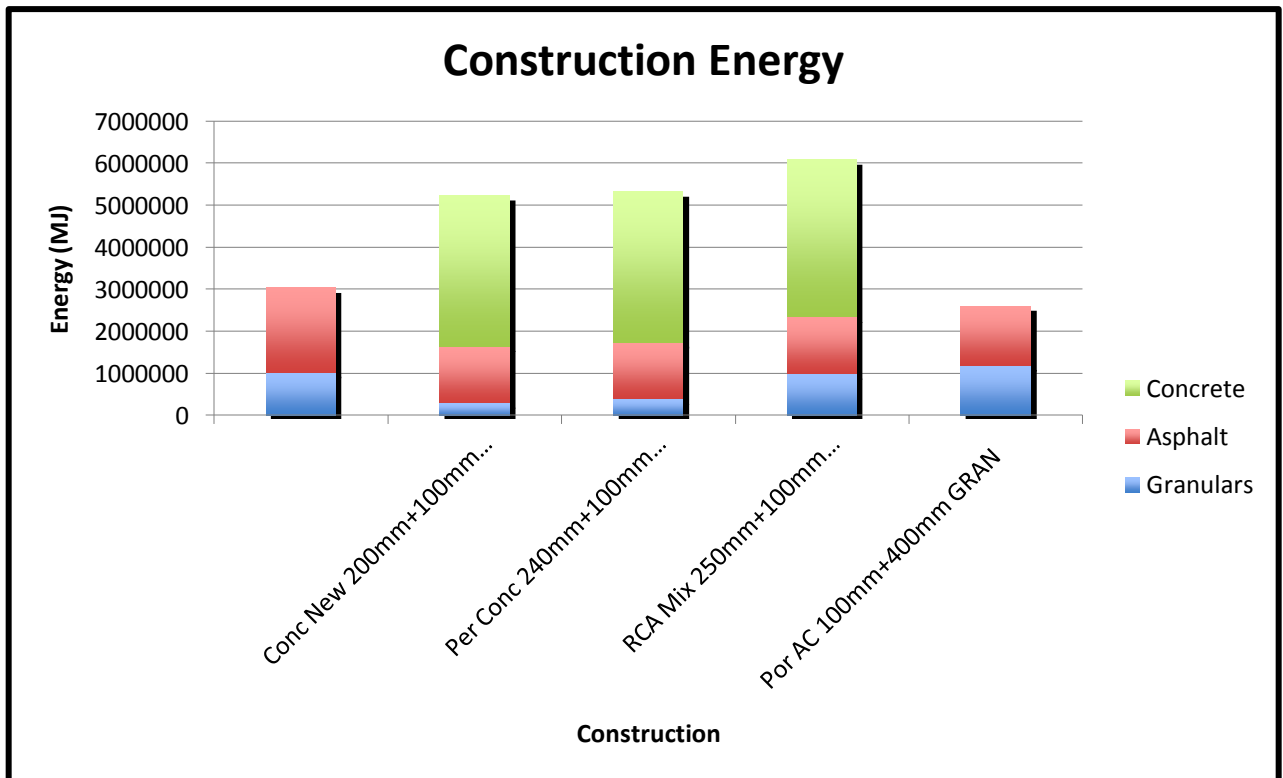
Figure 32: Energy Output for Construction
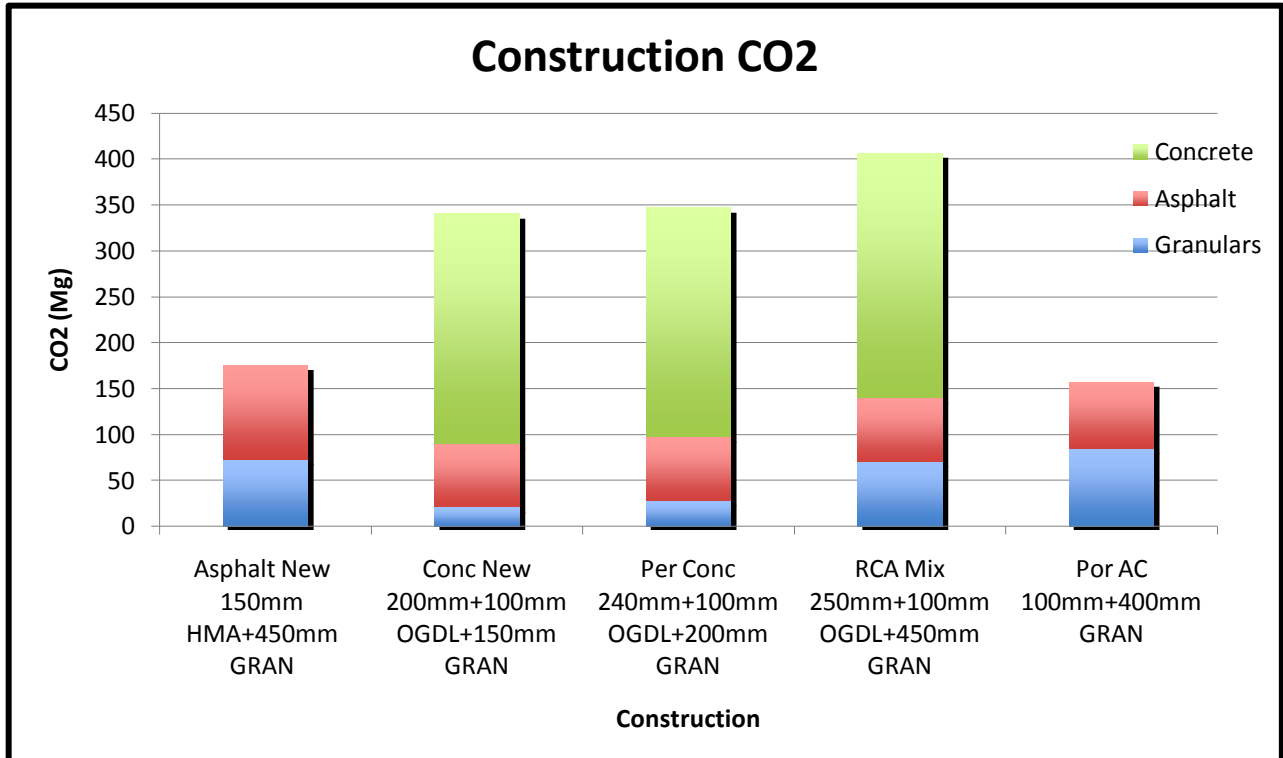
Figure 33: CO_2 Output for Construction
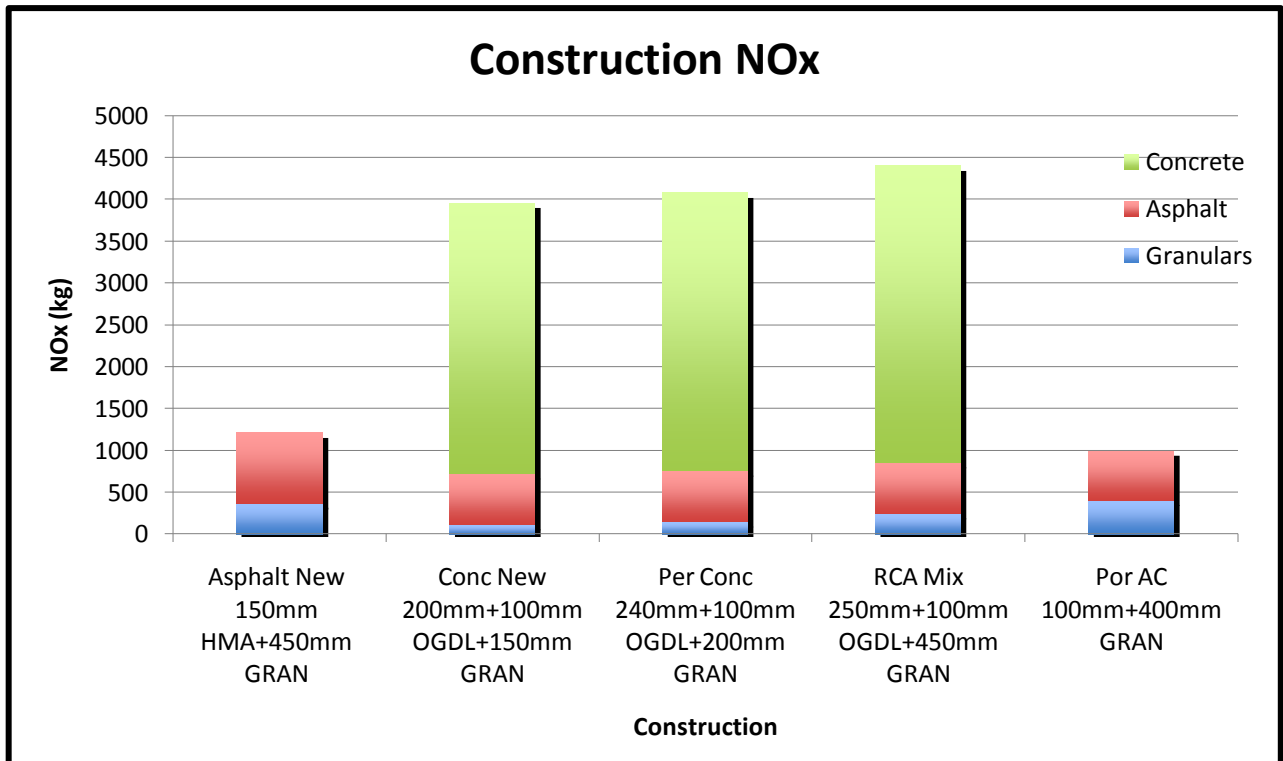
Figure 34: NO_x Output for Construction
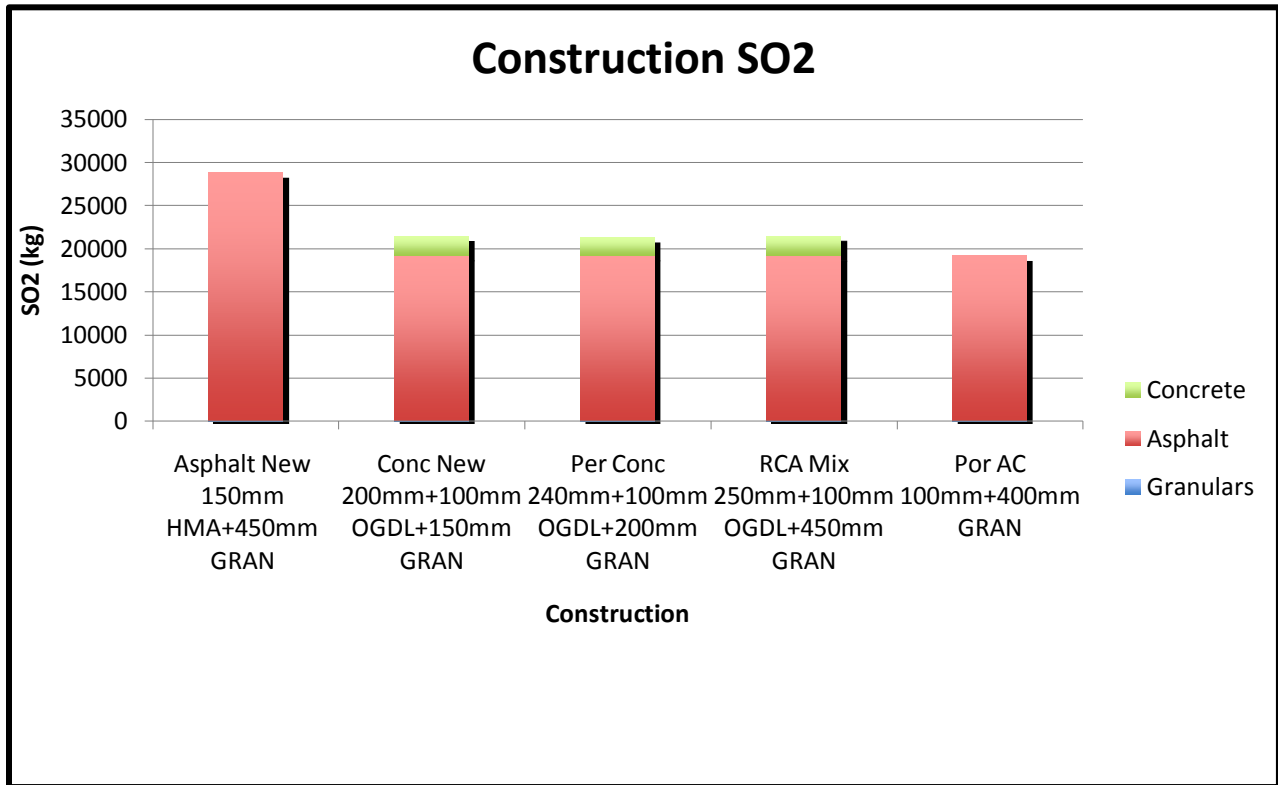
Figure 35: SO₂ Output for Construction
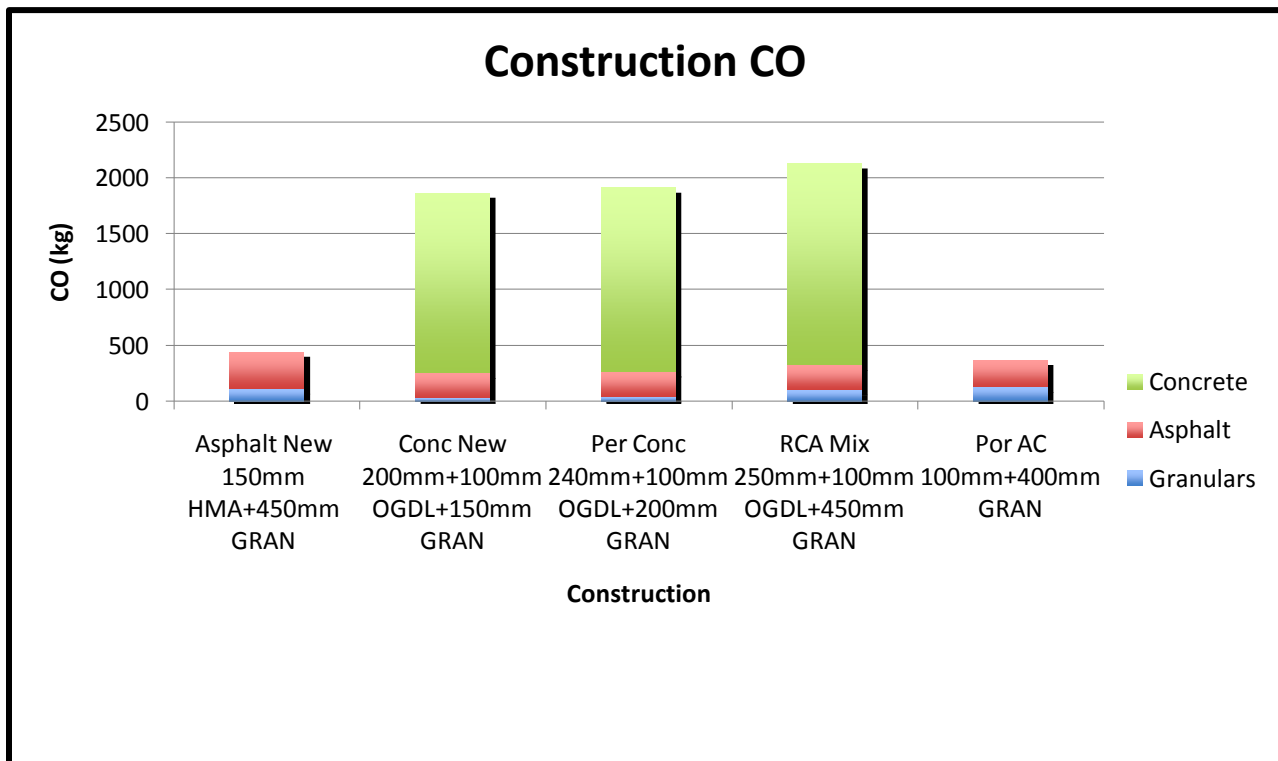
Figure 36: CO Output for Construction

Appendix F - Life Cycle Analysis for Emissions and Energy
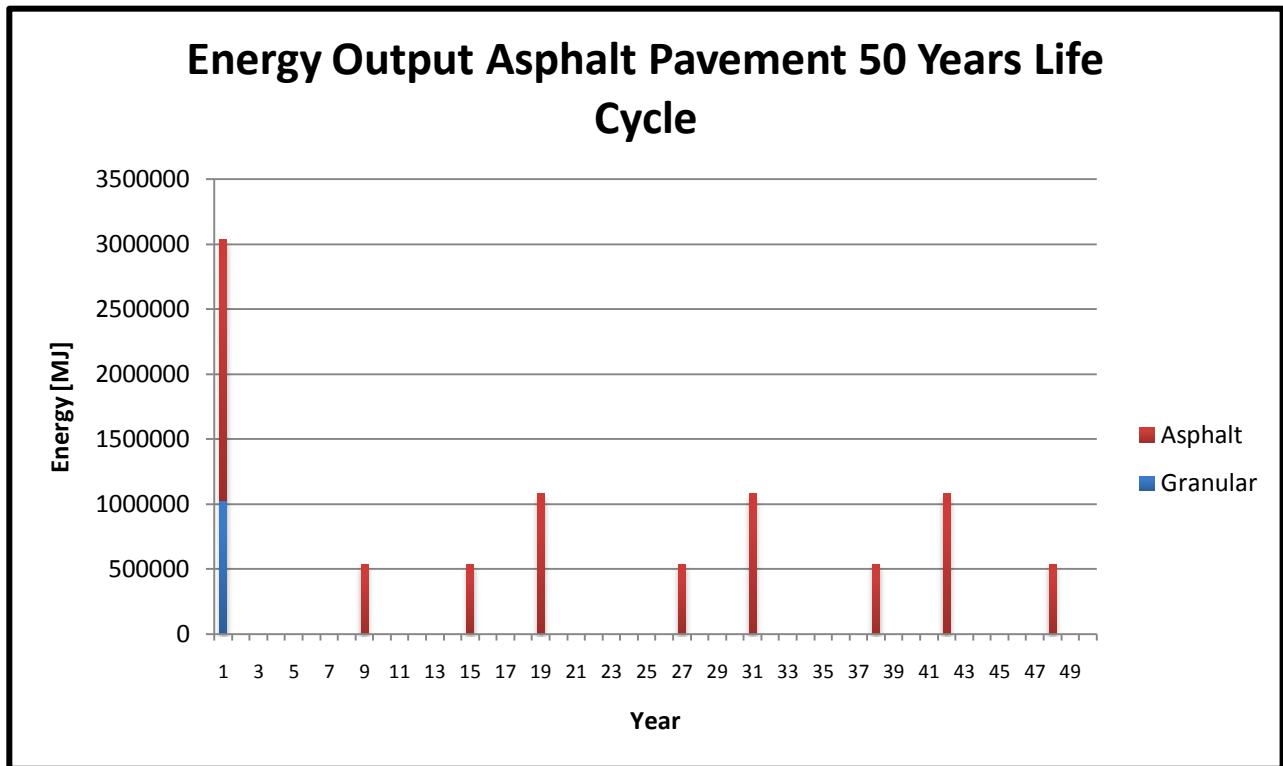
Figure 37: Energy Output Asphalt Pavement 50 Years Life Cycle
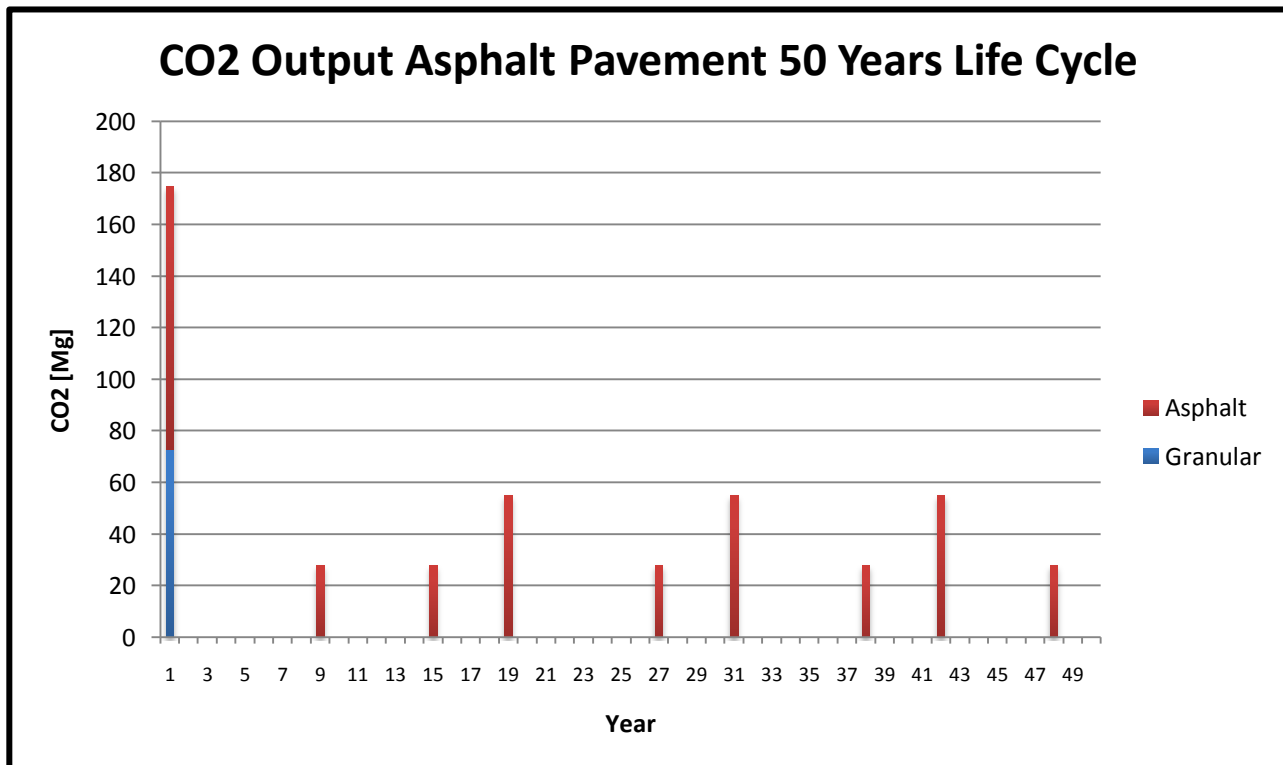
Figure 38: CO$_2$ Output Asphalt Pavement 50 Years Life Cycle
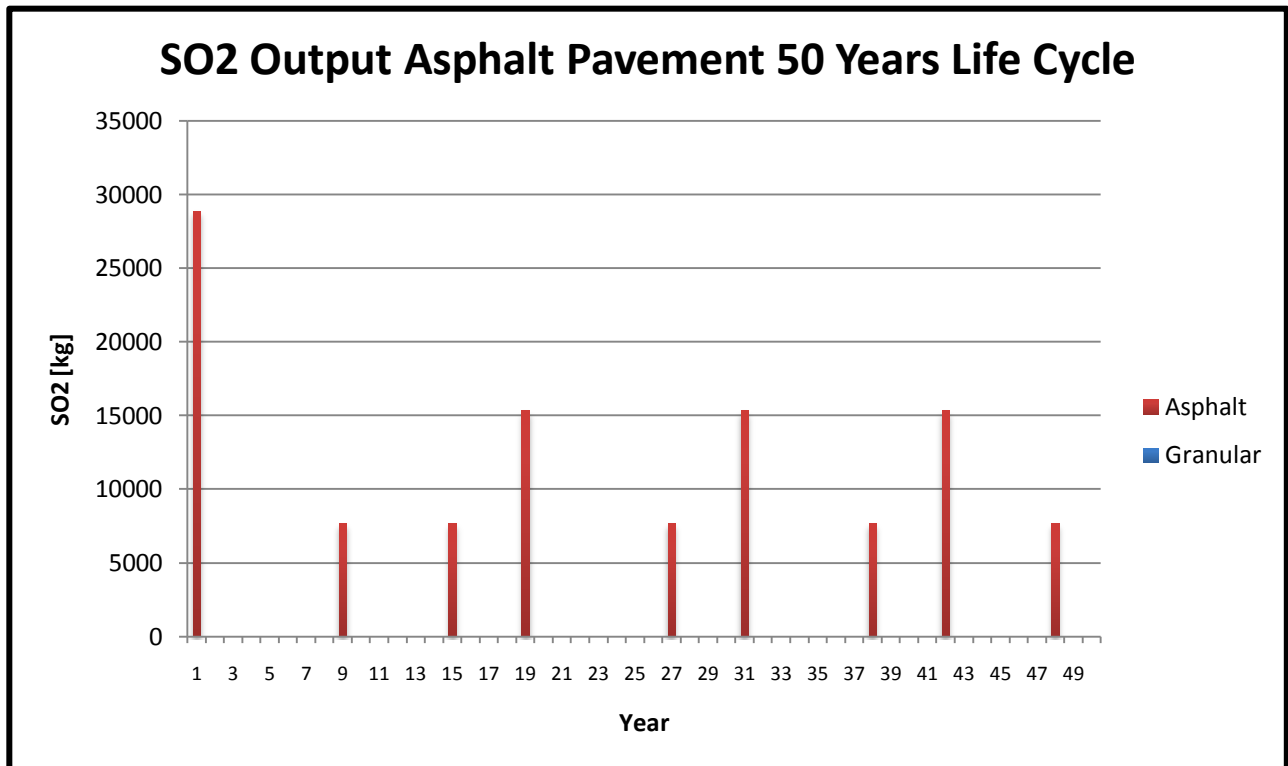
Figure 39: SO₂ Output Asphalt Pavement 50 Years Life Cycle
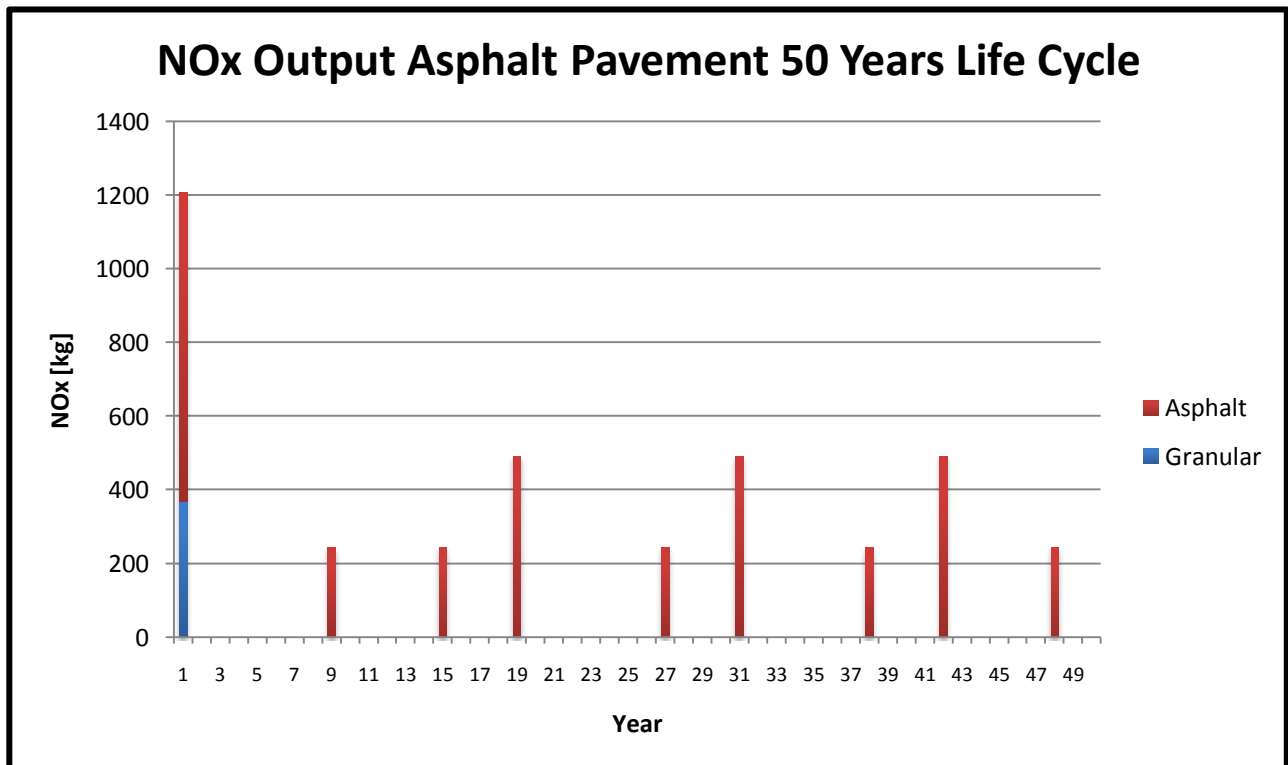
Figure 40: NOx Output Asphalt Pavement 50 Years Life Cycle
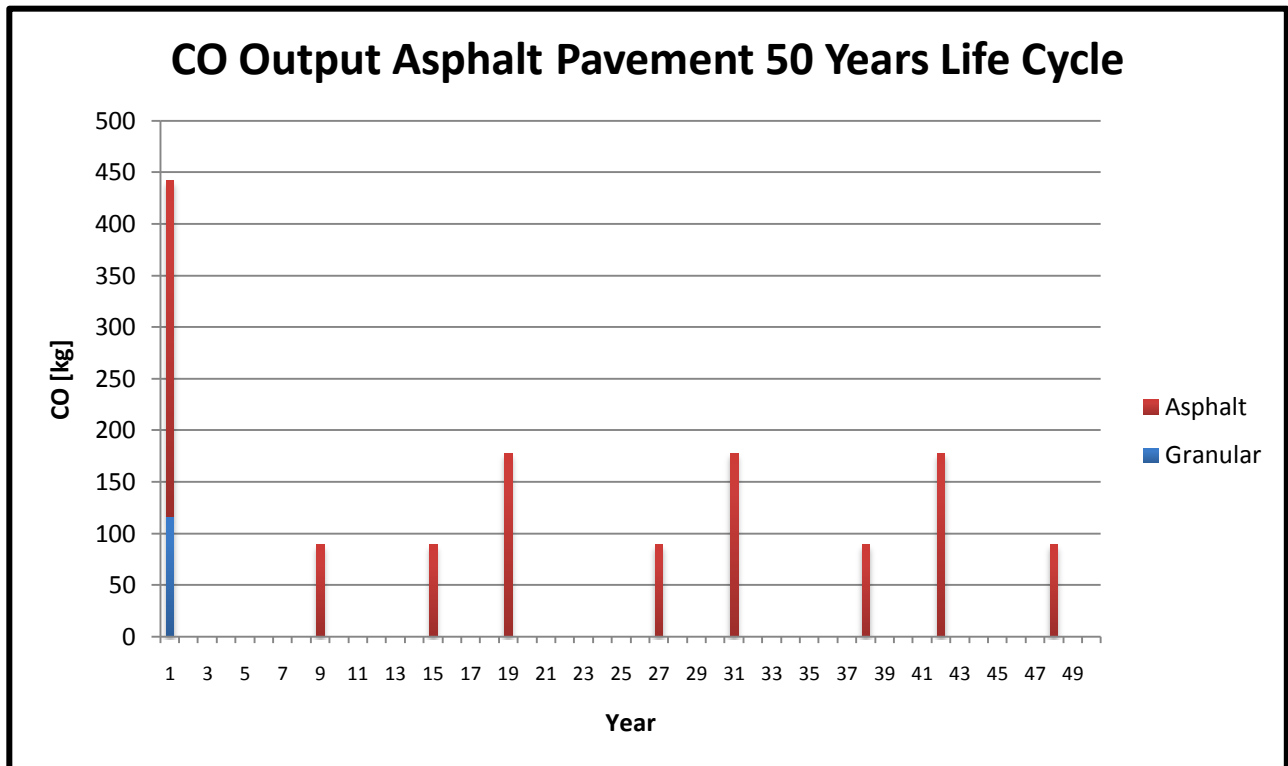
Figure 41: CO Output Asphalt Pavement 50 Years Life Cycle
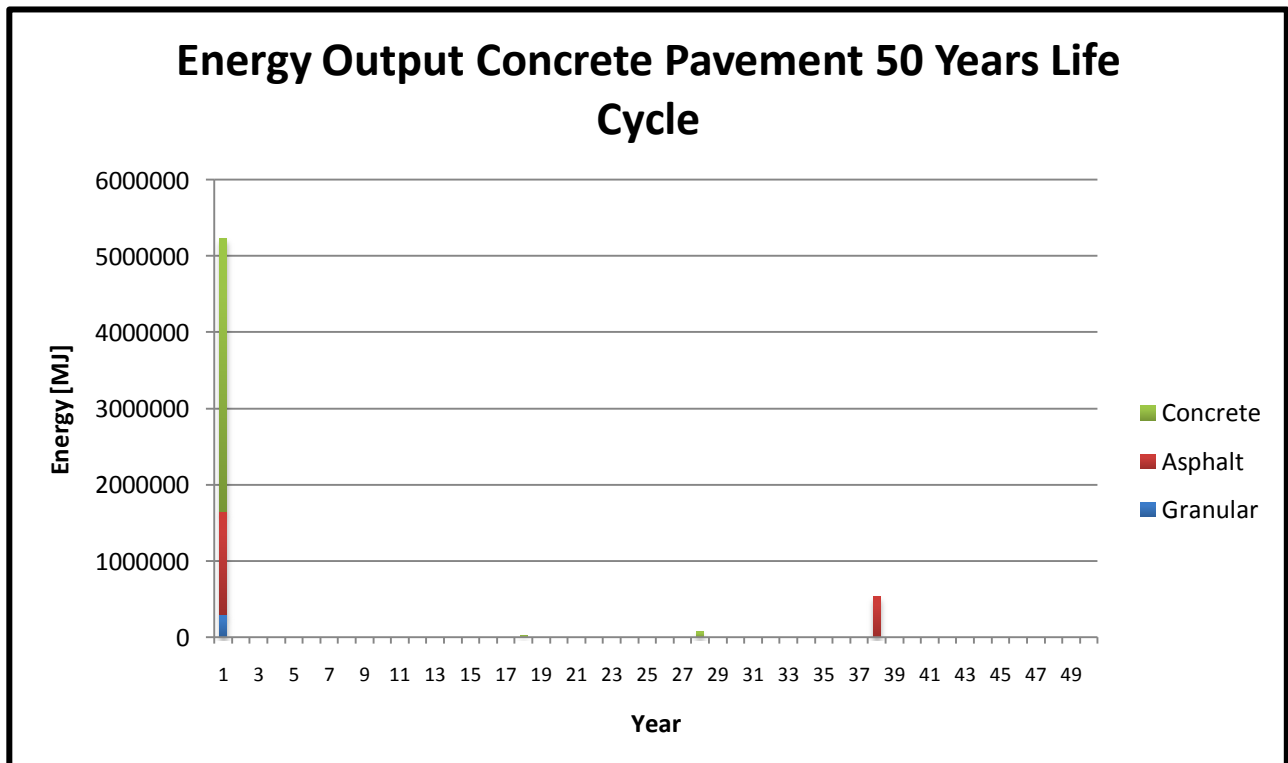
Figure 42: Energy Output Concrete Pavement 50 Years Life Cycle
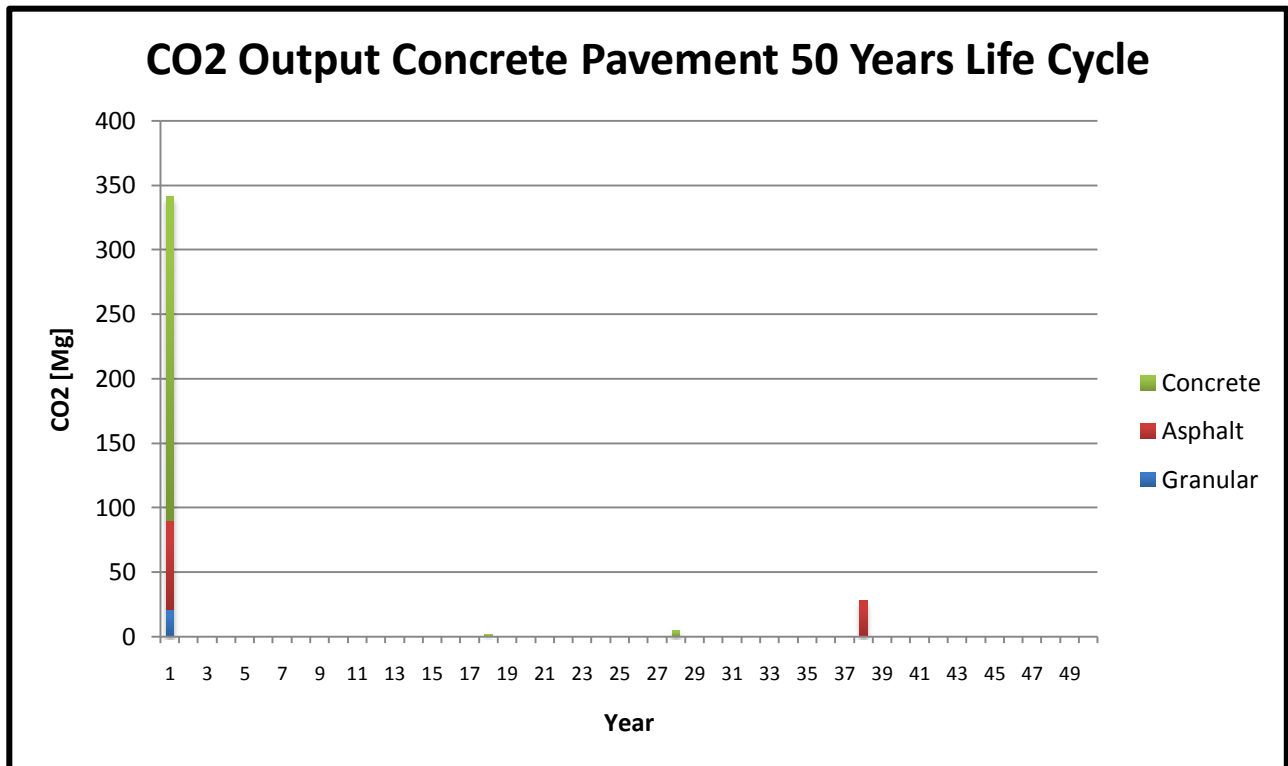
Figure 43: CO_2 Output Concrete Pavement 50 Years Life Cycle
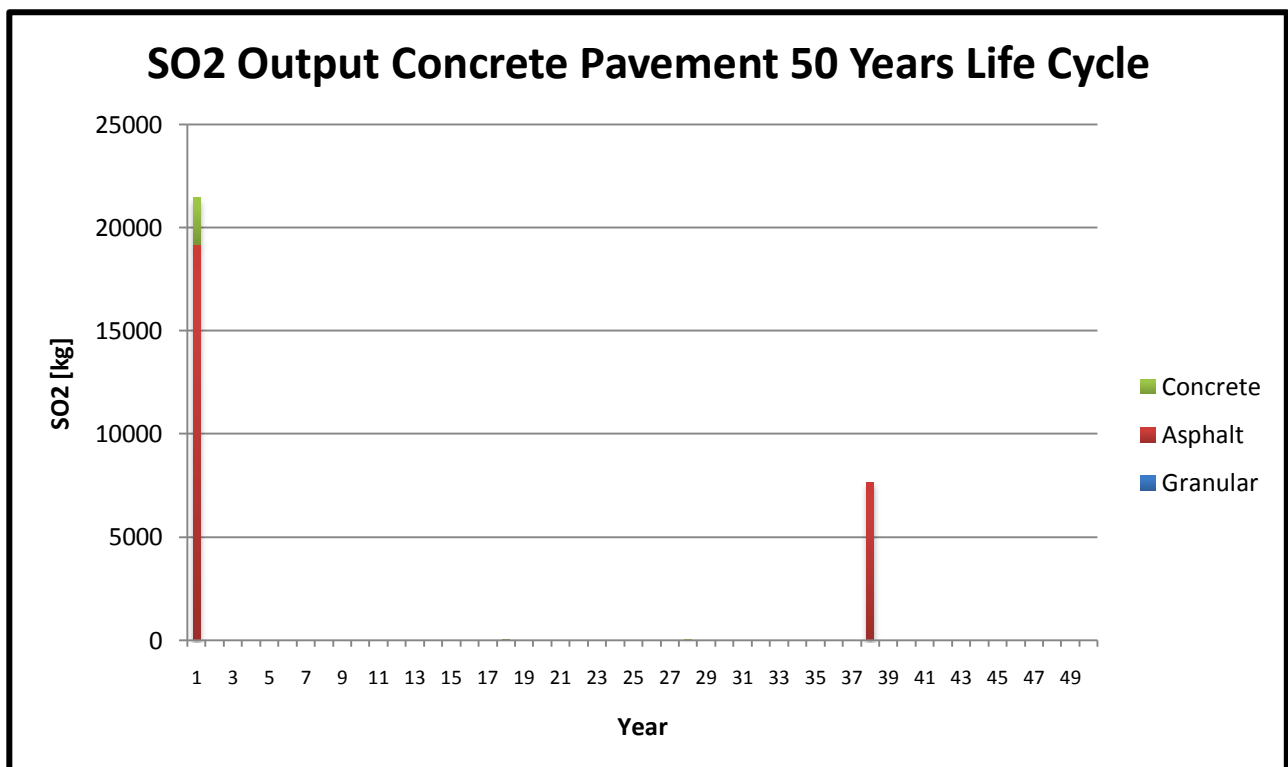
Figure 44: SO_2 Output Concrete Pavement 50 Years Life Cycle

NOx Output Concrete Pavement 50 Years Life Cycle
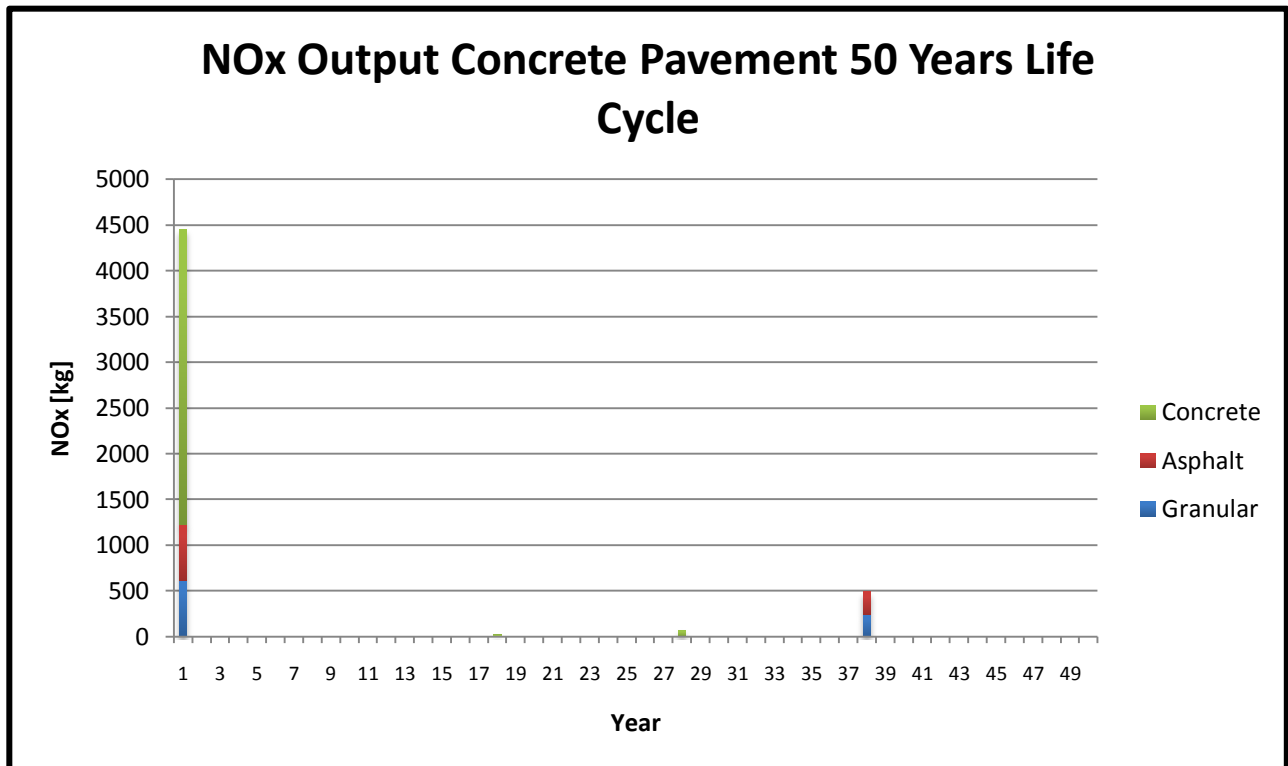
Figure 45: NO$_x$ Output Concrete Pavement 50 Years Life Cycle

CO Output Concrete Pavement 50 Years Life Cycle
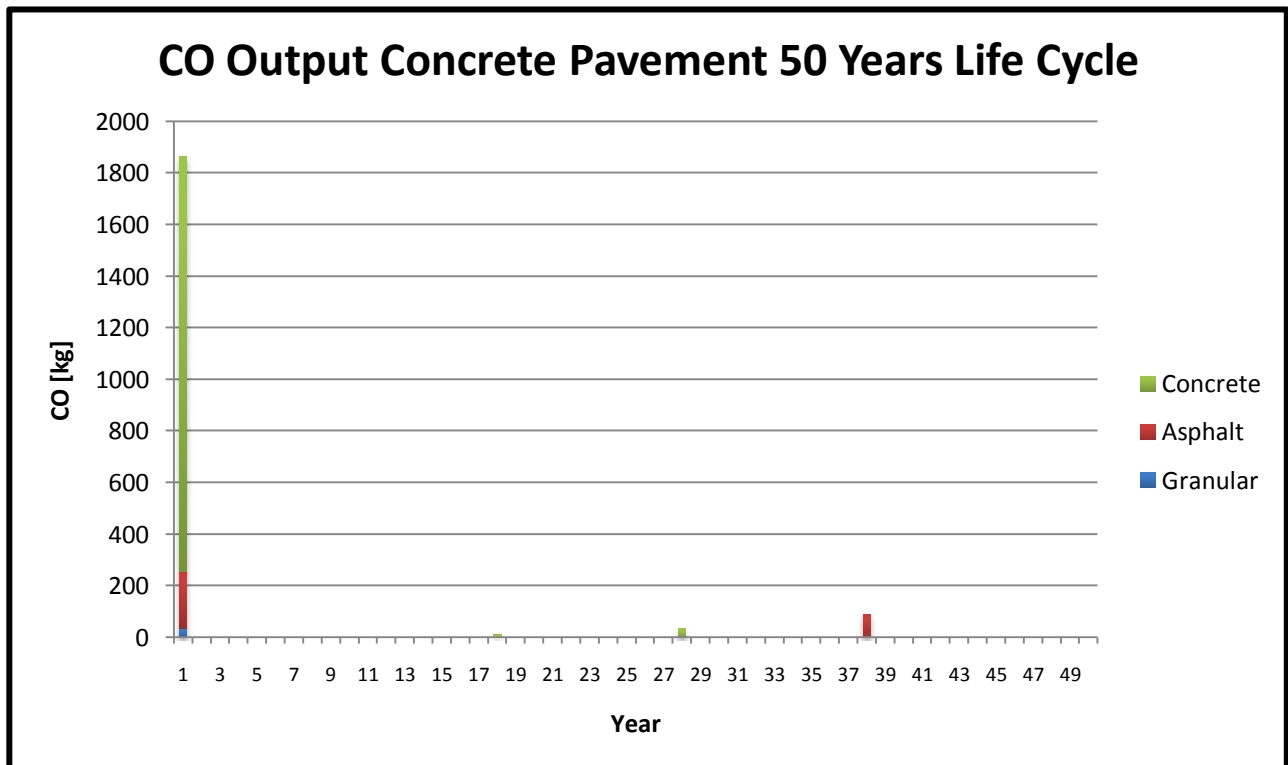
Figure 46: CO Output Concrete Pavement 50 Years Life Cycle

Appendix G – Life Cycle Cost Analysis

Table 40: 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 41: Modified LCC Schedule

Type	Environmental, Material Related Distresses	Construction Related Distress	Load Related Distress	Reconstruction FDR	Reconstruction EAS
Schedule ID	A1	A2	B1	C1	D1
Year 0	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		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	CIR+O1		
30				R&S	R&S
End @ Year	41	35	41	41	41

Table 42: LCCA in Present Worth Terms for Rehabilitations

Discount Rate   5.30%

Schedule ID	A	B	C	D	A1	A2	B1	C1	D1
Year 0	$308,798.11	$170,353.12	$195,685.62	$177,983.12	$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		$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									
Total PW	$535,234.06	$376,036.43	$412,270.14	$393,048.69	$431,588.57	$512,699.76	$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)	$(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	$255,815.23	$287,860.09	$270,157.59
Total Saved to Control					$(85,070.58)	$(1,825.67)	$(65,564.64)	$(73,957.85)	$(84,631.51)
% Saved to control					-18%	0%	-20%	-20%	-24%

Appendix H – Comprehensive GreenPave Results

Table 43: 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)	$496,055	3	2.00	Not Certified
			HM 250, Gran A 150, Gran B 850				
			Alternative 2 (New PCC)	$583,497	10	2.00	Bronze
			PCC 280, OGDL 150, Gran A 250				
			Alternative 3 (M&O)	$487,085	5	4.00	Not Certified
			Mill 90, HM 100mm				
2	128-85-00	CR	Alternative 1 (M&O)	N/A	6	4.00	Not Certified
			Remove HM, CPR as req'd, 90mm HM				
3	167-99-00	CR	Alternative 1 (M&O)	$508,500	5	4.00	Not Certified
			Mill 40mm, 180mm HM				
			Alternative 2 (FDR)	$598,500	9	7.60	Bronze
			Mill 70mm, Pulverize to 300mm, 200mm HM				
			Alternative 3 (EAS)	$643,000	13	6.80	Silver
			Mill 70mm, Pulverize to 150mm with EA, 170mm HM				
4	2478-04-00	CR	Alternative 1 (O1)	$497,288	5	4.00	Not Certified
			140mm HM				
			Alternative 2 (M&O)	$484,264	5	4.00	Not Certified
			Mill 50mm, 140mm HM				
			Alternative 3 (???)	$543,552	14	7.60	Silver
			Scarify, 150mm A, 140mm HM				
5	2381.02.01	CR	Alternative 1 (New AC)	N/A	3	2.00	Not Certified
			290mm HM, 150mm A, 600mm B				
6	2-99-00	ER	Alternative 1 (New AC)	N/A	3	2.00	Not Certified
			100mm HM, 200mm A, 250mm B				
7	185-99-00	ER	Alternative 1 (FDR)	$163,679	13	6.50	Silver
			FDR 250mm, 90mm HM				
			Alternative 2 (EAS)	$151,337	14	7.50	Silver
			Pulverize 250mm, Foam 125mm, 50mm HM				
			Alternative 3 (CIR)	$154,814	13	6.80	Silver

			CIP 80mm, 50mm HM				
8	194-99-00	ER	Alternative 1 (CIR)	$1,674,900	12	6.20	Silver
			CIP 80mm, 60mm HM				
			Alternative 2 (FDR)	$1,604,800	13	6.90	Silver
			IPP 200mm, 90mm HM				
			Alternative 3 (FDR)	$1,677,400	13	6.80	Silver
			IPP 200mm, 50mm Gran A, 90mm HM				
9	196-99-00	ER	Alternative 1 (New AC)	$1,674,900	3	2.00	Not Certified
			Widening 230mm HM, 260mm A, 650mm B				
10	452-98-00	ER	Alternative 1 (Rubb)	$292,010	9	5.60	Bronze
			Mill 147mm HM, Rubbilize Conc, 100mm A (40% RAP), 130mm 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				

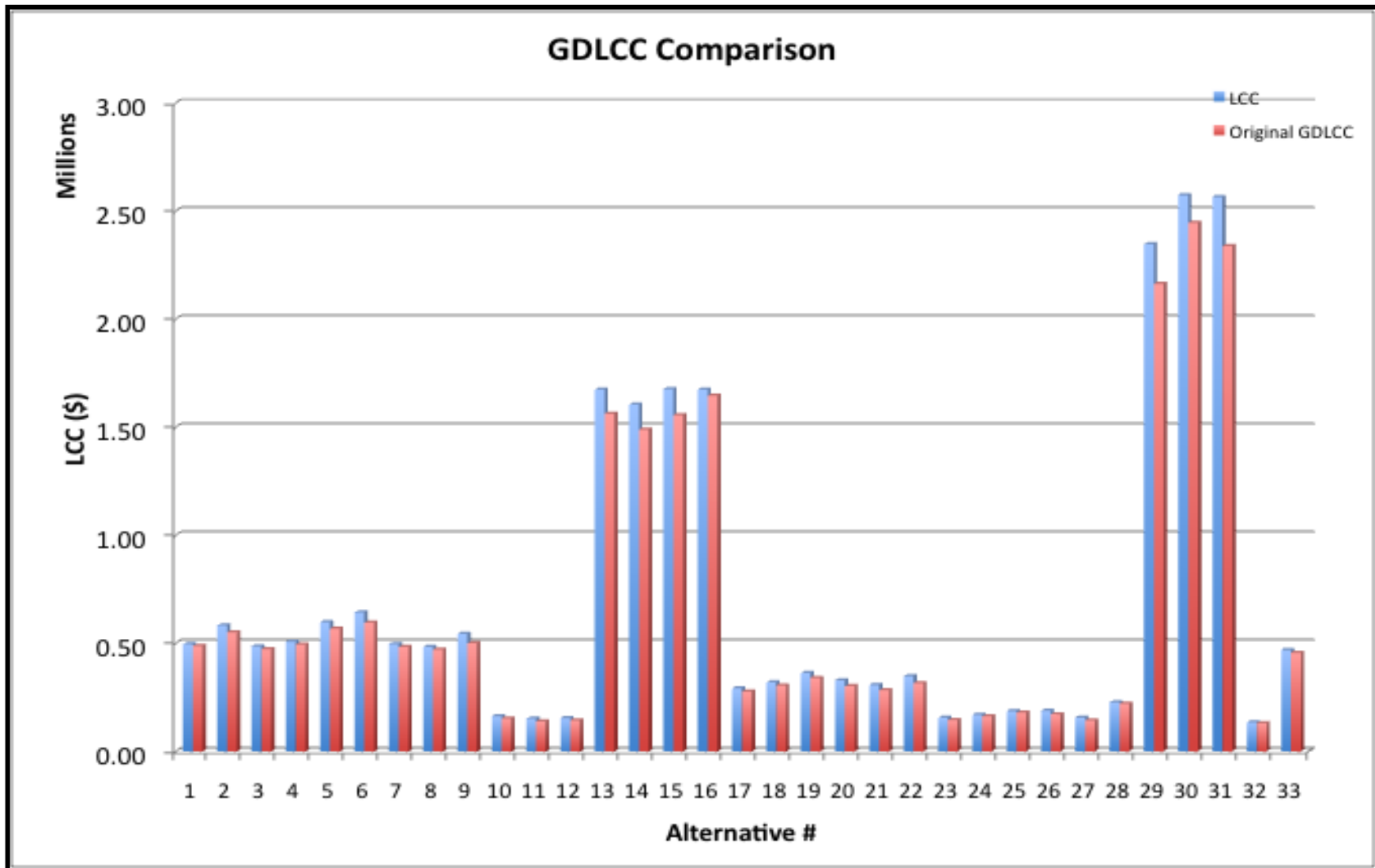| 20	6016-03-00	NWR	Alternative 1 (FDR)	N/A	12	8.30	Silver
			Pulverize (284mm), 50mm A, 60mm HM				
21	71-00-00	SWR	Alternative 1 (M&O)	N/A	9	5.20	Bronze
			Mill HM, remove 50mm A, 300mm HM, 200mm A				
			Alternative 2 (New PCC)	N/A	4	3.00	Not Certified
			Remove HM, 280mm Conc, 100mm OGDL				

Appendix I – GDLCC Plots
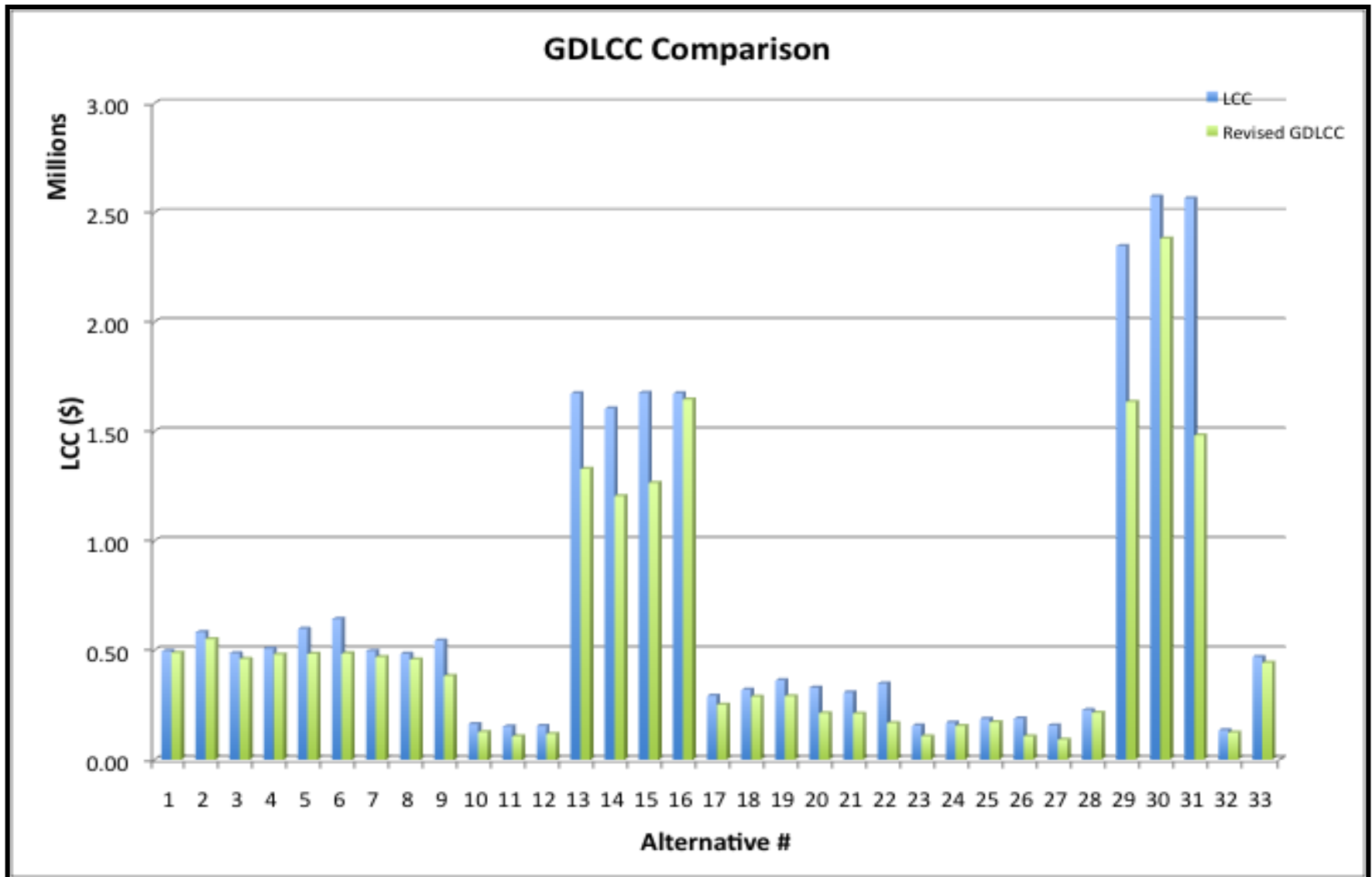
Figure 47: LCC Versus Original GDLCC Plot
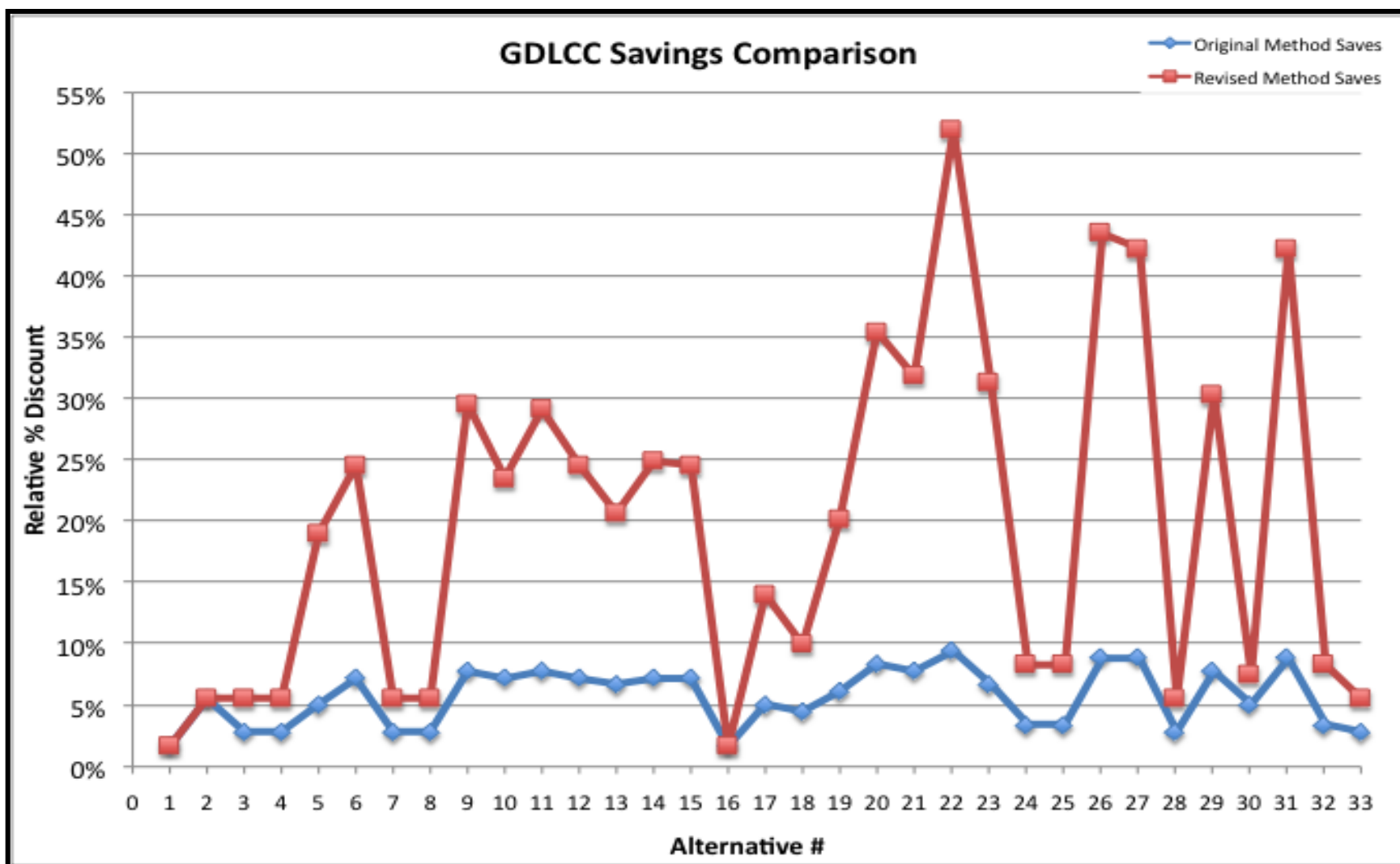
Figure 48: LCC Versus GDLCC Type P Plot

Figure 49: GDLCC Savings Comparison
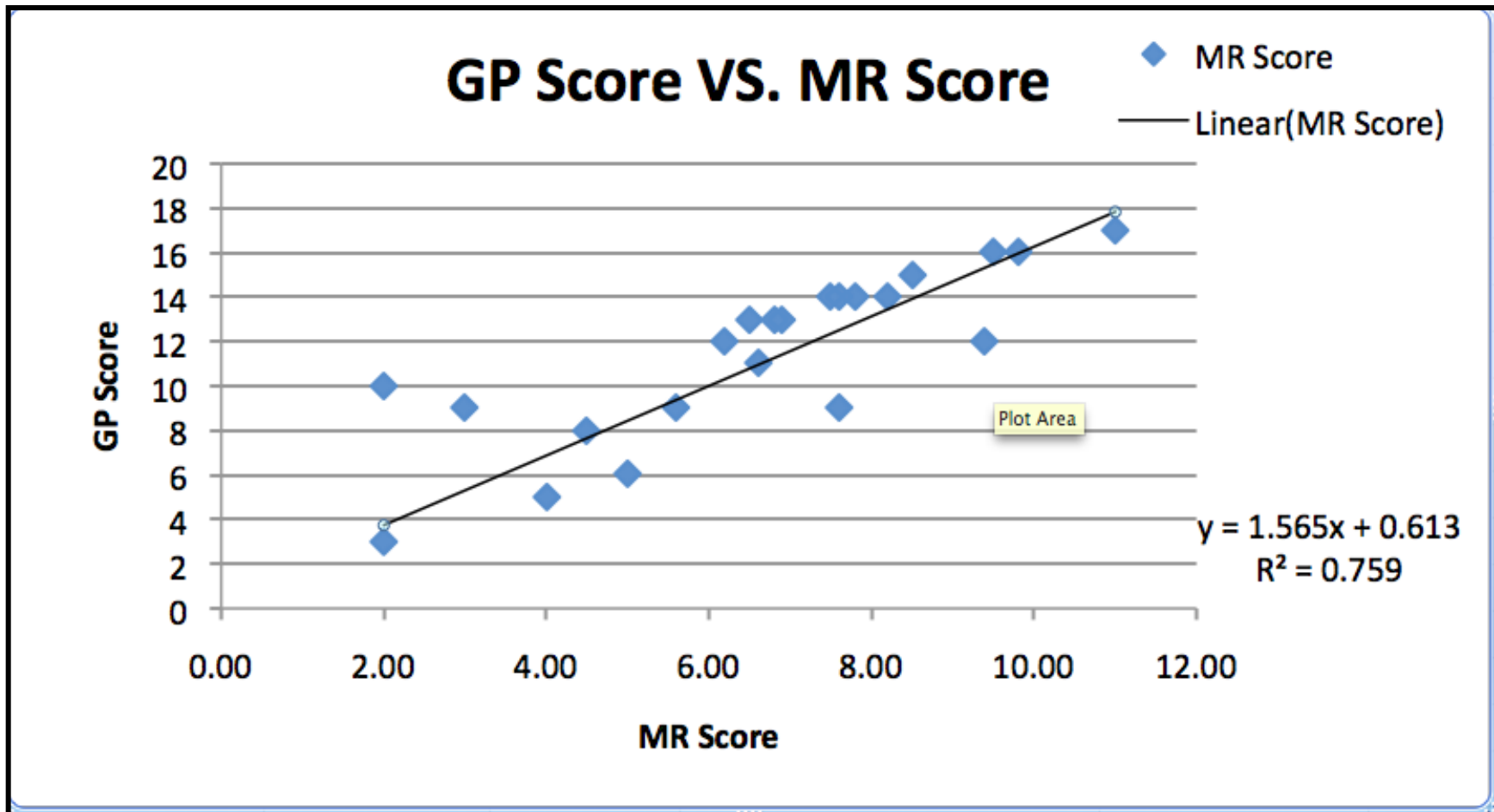
Figure 50: Linear Regression Model
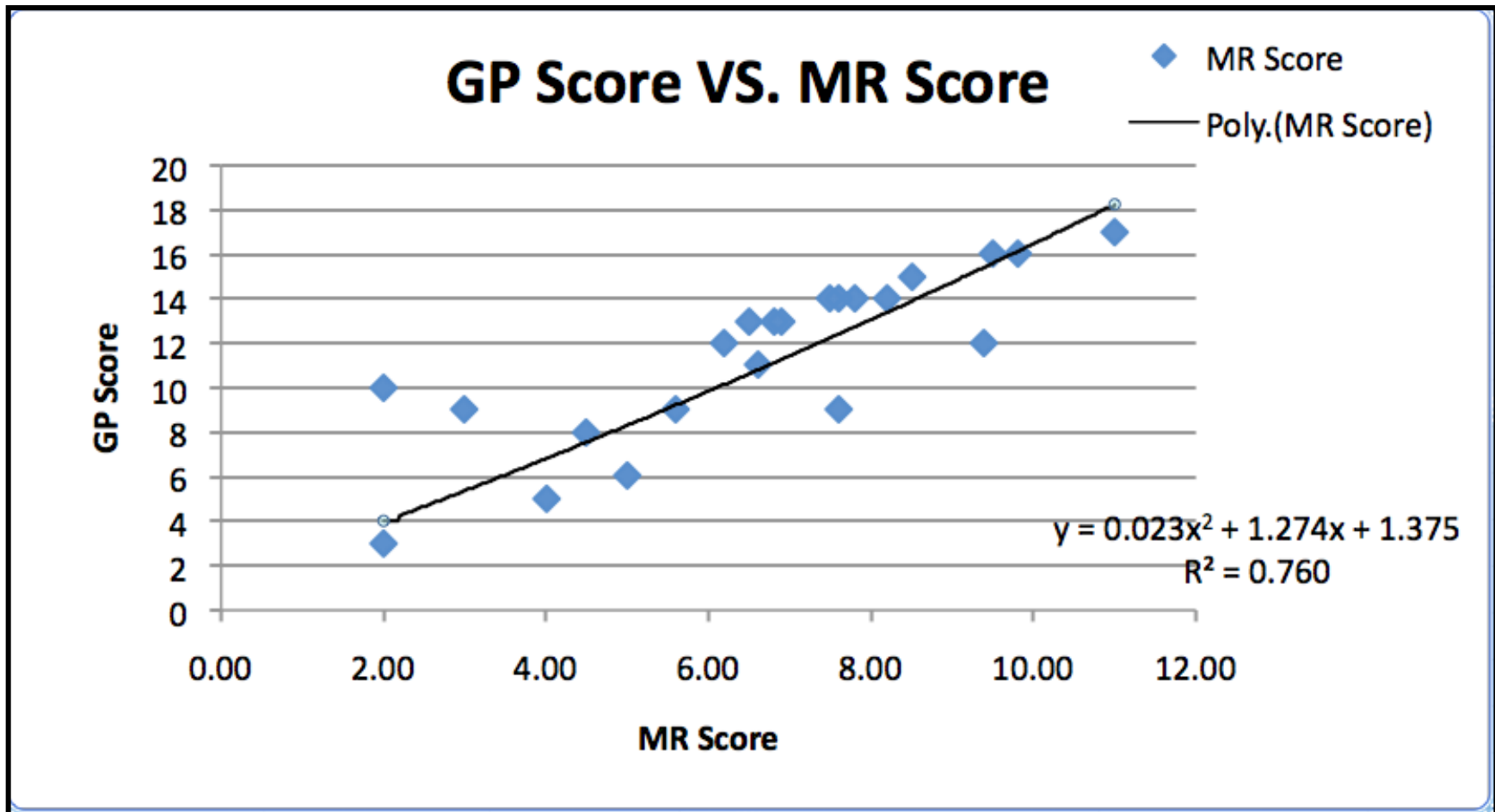
Figure 51: Quadratic Regression Model
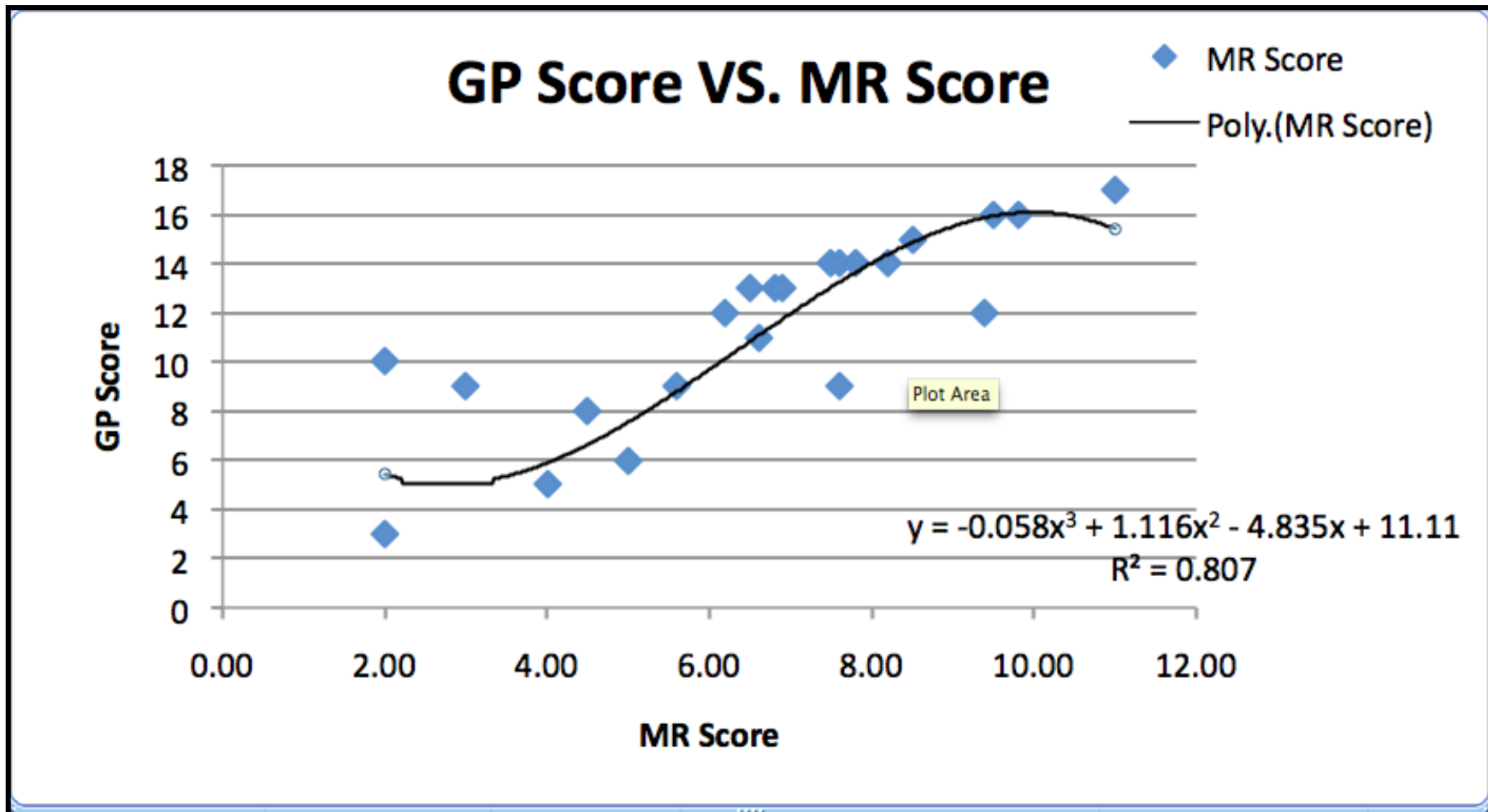
Figure 52: Cubic Regression Model

Appendix J – Sustainable Decision Tree Set

Table 44: Decision Tree Acronyms

Pavement Type	Acronym from PMS2 (Figure 15)	Acronym from Decision Trees in this Report (Figure 16, Figure 17, Appendix J)	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 53: Asphalt Freeway Conventional VS. Sustainable Decision Tree

Figure 54: Asphalt Arterial Conventional Vs. Sustainable Decision Tree
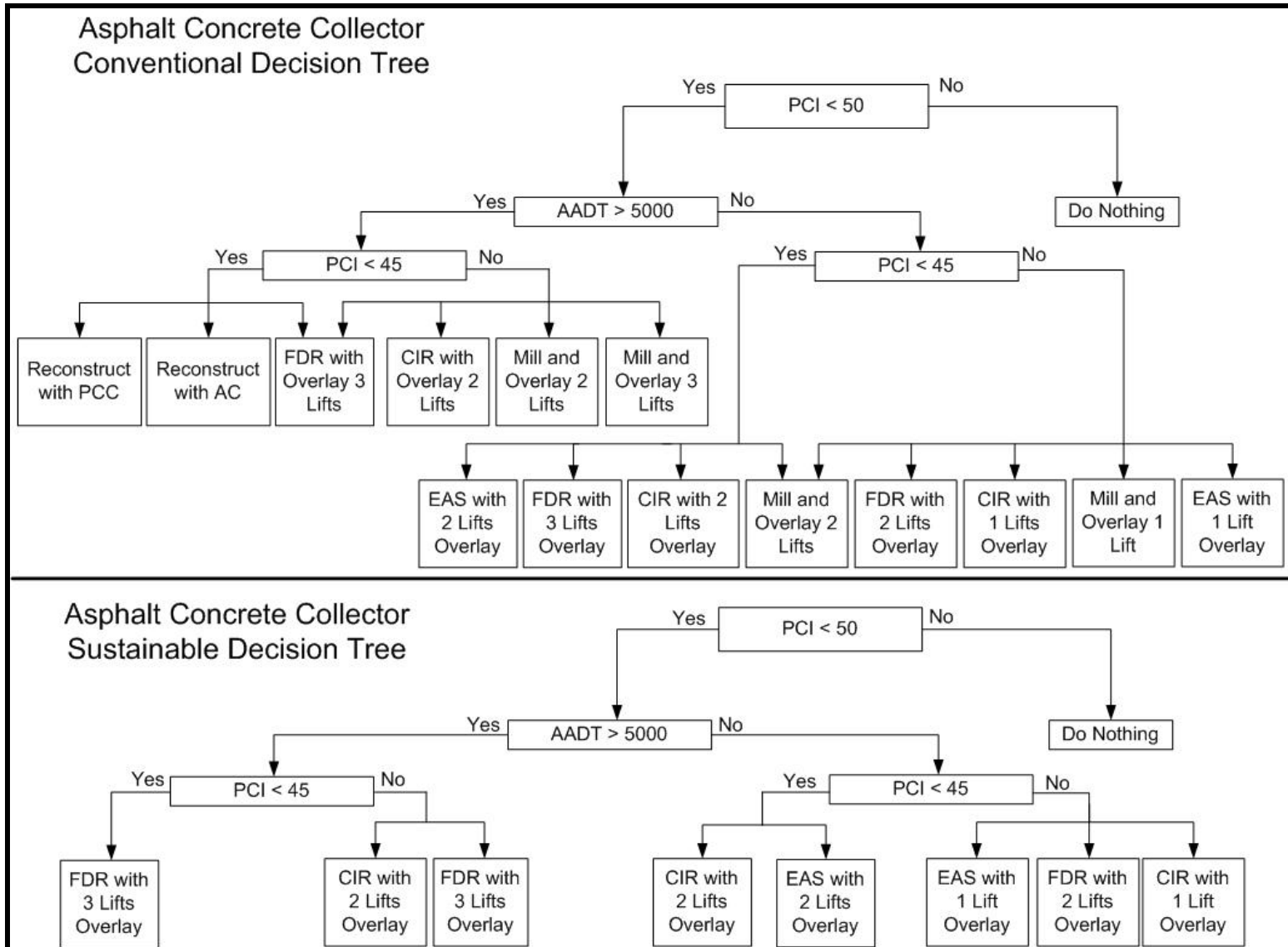
Figure 55: Asphalt Collector Conventional VS. Sustainable Decision Tree

Asphalt Concrete Local Conventional Decision Tree

```
                                      Yes ┌─────────────┐ No
                                          │  PCI < 45   │
                                          └─────────────┘
                                                 │              │
                 Yes ┌──────────────────────┐ No               ▼
                     │ Annual ESAL > 50,000  │           ┌────────────┐
                     └──────────────────────┘           │ Do Nothing │
                         │            │                  └────────────┘
                                  Yes ┌──────────────────┐ No
                                      │ AADT >200 and    │
                                      │ ESAL > 2,040     │
                                      └──────────────────┘
      ┌──────────┐  ┌──────────┐   ┌──────────┐ ┌──────────┐   ┌───────────────┐
      │ EAS with │  │ FDR with │   │ FDR with │ │ Overlay 1│   │ Reconstruction│
      │ 3 Lifts  │  │ Overlay 2│   │ 1 Lifts  │ │   Lift   │   │               │
      │ Overlay  │  │ Lifts    │   │ Overlay  │ │          │   │               │
      └──────────┘  └──────────┘   └──────────┘ └──────────┘   └───────────────┘
```
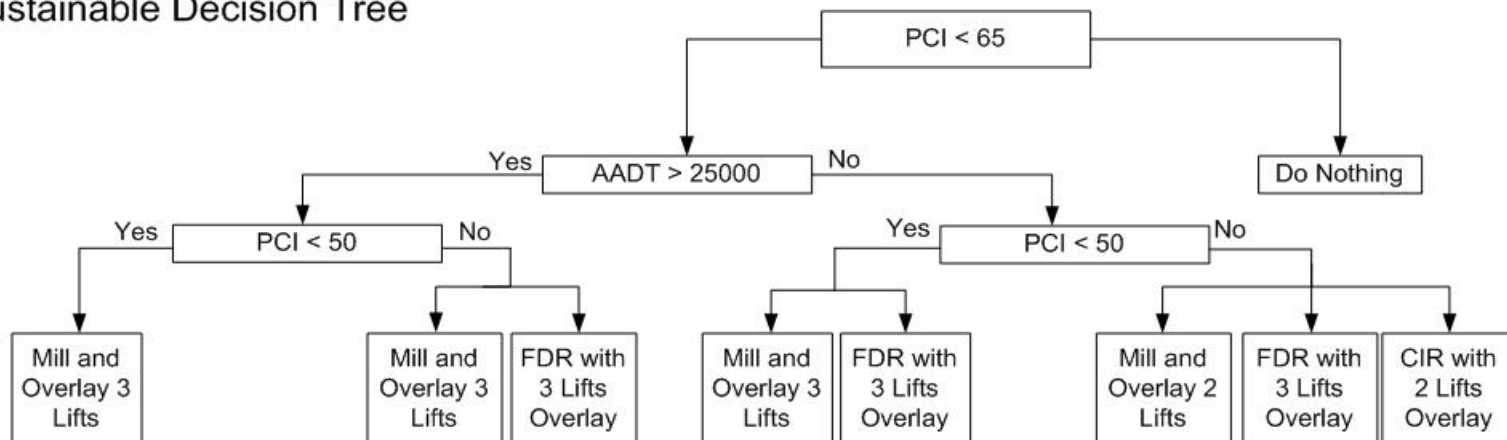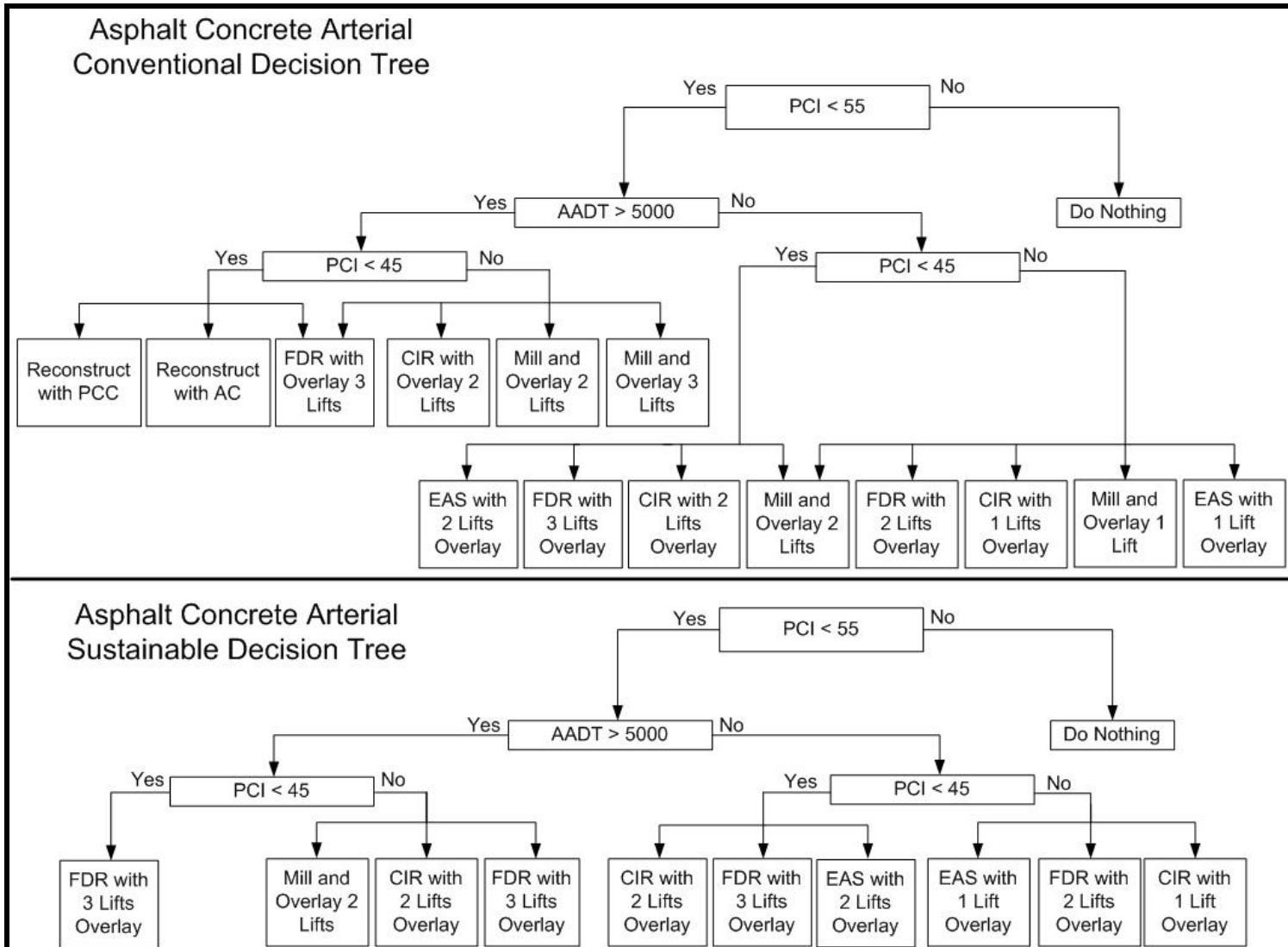
Asphalt Concrete Local Sustainable Decision Tree

```
                                      Yes ┌─────────────┐ No
                                          │  PCI < 45   │
                                          └─────────────┘
                                                 │              │
                 Yes ┌──────────────────────┐ No               ▼
                     │ Annual ESAL > 50,000  │           ┌────────────┐
                     └──────────────────────┘           │ Do Nothing │
                         │                              └────────────┘
                                  Yes ┌──────────────────┐ No
                                      │ AADT >200 and    │
                                      │ ESAL > 2,040     │
                                      └──────────────────┘
      ┌──────────┐              ┌──────────┐            ┌───────────────┐
      │ EAS with │              │ Overlay 1│            │ Reconstruction│
      │ 3 Lifts  │              │   Lift   │            │               │
      │ Overlay  │              │          │            │               │
      └──────────┘              └──────────┘            └───────────────┘
```

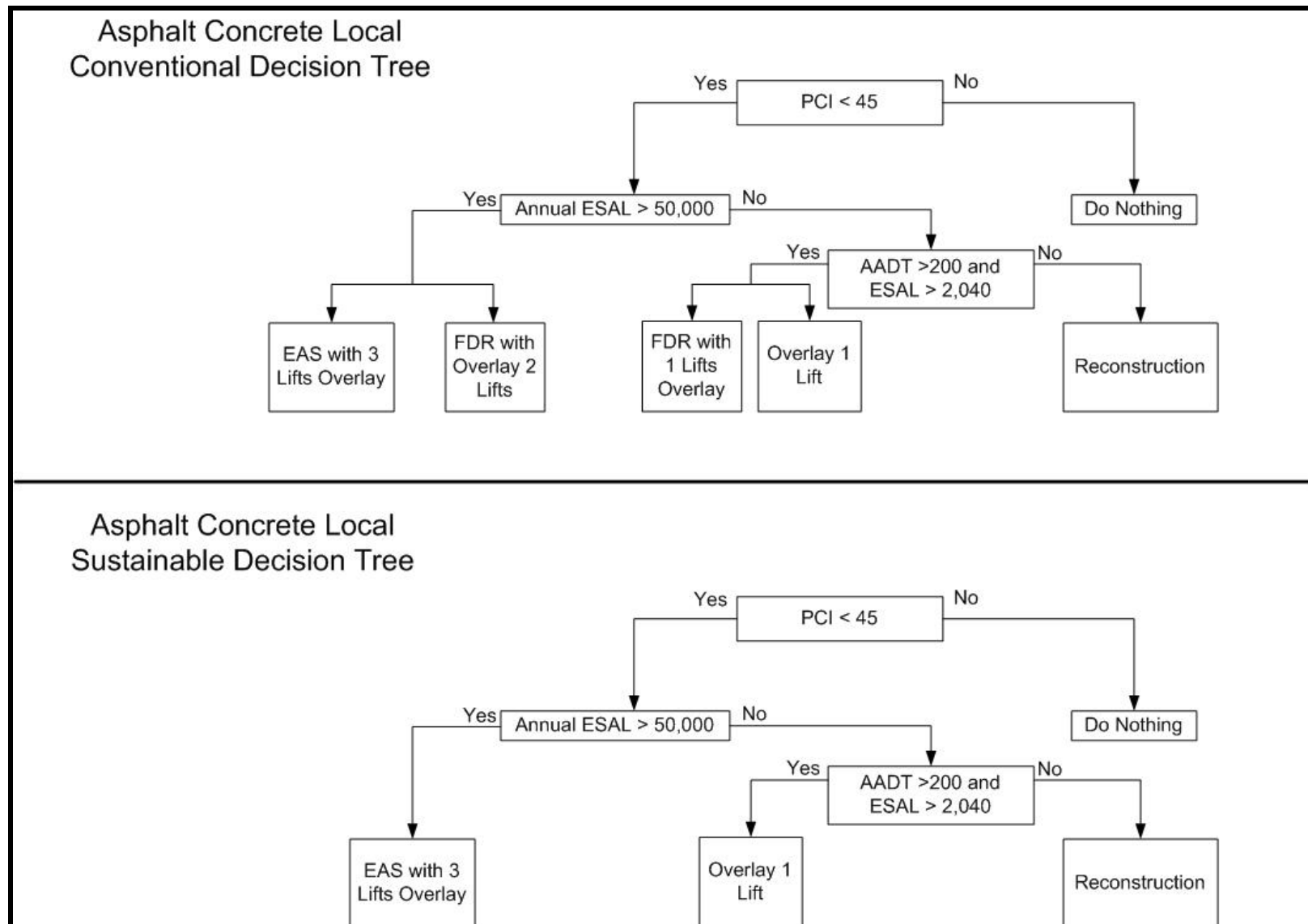Figure 56: Asphalt Local Conventional VS. Sustainable Decision Tree
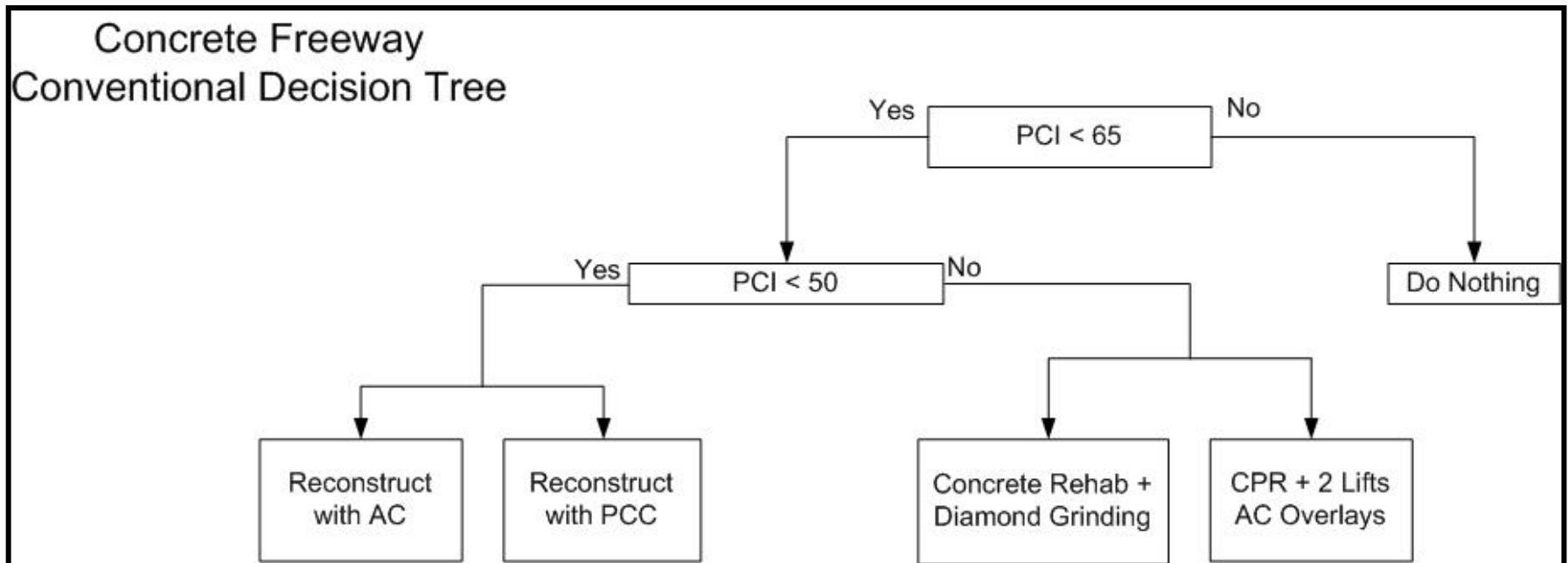
Figure 57: Concrete Freeway Decision Tree
*Note there is lack of treatments that has model in PMS2 for concrete freeway. Therefore, at this stage of the project, no sustainable decision tree can be proposed

Figure 58: 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 K – Minimum PCI Service Life for Network Level Analysis

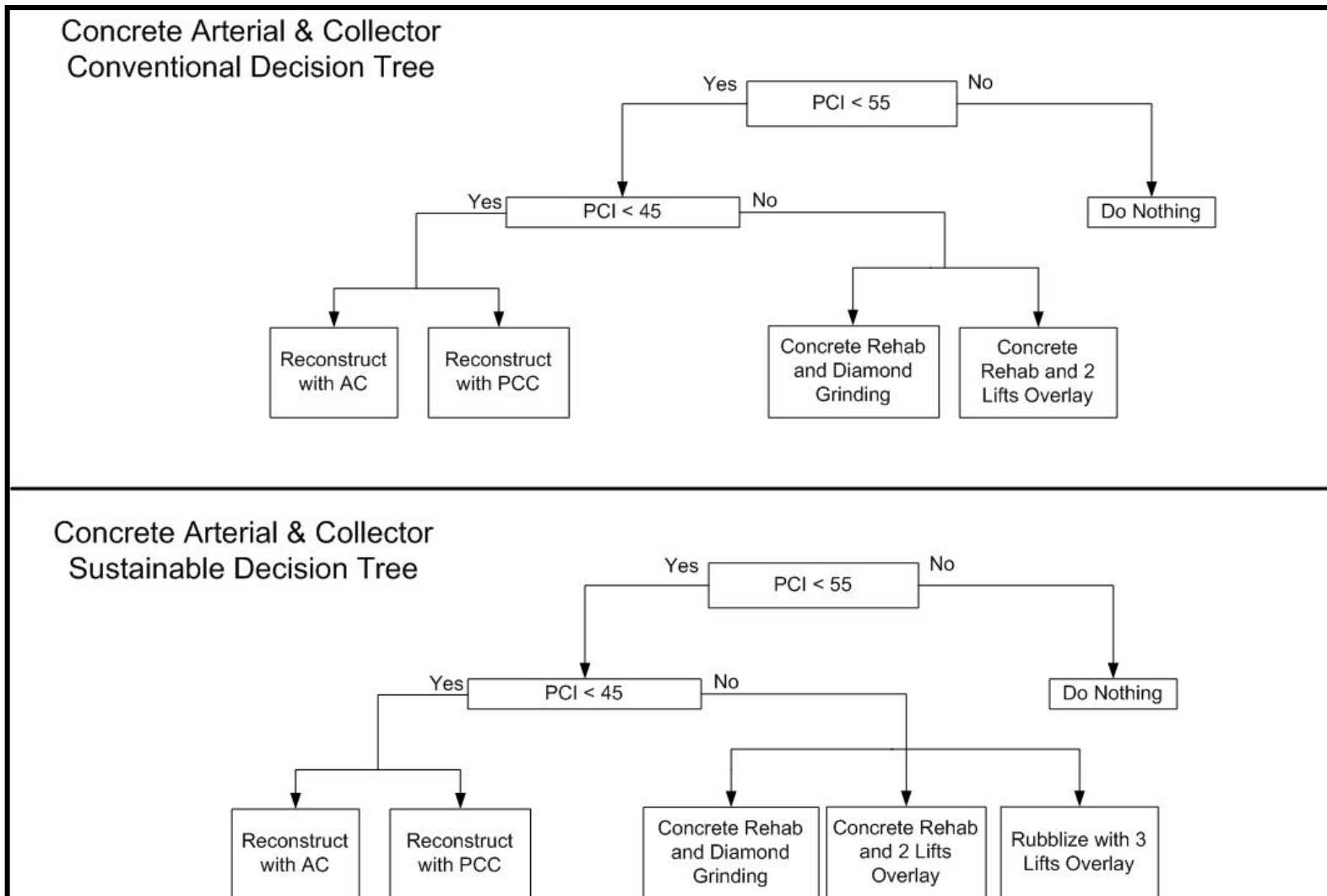Table 45: Minimum Service Lives in PMS2

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 code name ends with the letter "F", it denotes a freeway option

Appendix L – Treatment Average GP and MR Credits

Table 46: 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 47: 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 48: 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 49: 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 50: 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 51: New Concrete Construction Typical Credits

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

Table 52: Overlay Typical Credits

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

Table 53: Rubblization with Overlay Typical Credits

Project ID	GP	MR
452-98-00	9	5.6