ENVIRONMENTAL, PERFORMANCE AND LIFE CYCLE COST ANALYSIS OF THREE MAINTENANCE TECHNIQUES OF ASPHALT PAVEMENTS

By

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ENVIRONMENTAL, PERFORMANCE AND LIFE

CYCLE COST ANALYSIS OF THREE MAINTENANCE

TECHNIQUES OF ASPHALT PAVEMENTS

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INTRODUCTION

GENERAL PROBLEM STATEMENT

Pavement maintenance techniques are used to extend the life of a pavement resulting in the delay of a costly reconstruction project. Three maintenance techniques used to rehabilitate HMA pavements are Cold In Place Recycling (CIPR), Two Course Overlays (TCO) and Mill and Fill (MF). Decisions as to which maintenance technique to use, are often left to the discretion of the engineer. There is a need to evaluate these techniques on the basis of environmental effects caused by their use, their performance i.e. condition of pavement after use, and life cycle costs associated.

RESEARCH OBJECTIVES

There are many different maintenance techniques available for pavements. Different maintenance techniques have different environmental impacts and cost associated with them. When comparing these options, one should quantify the environmental, social and economic benefits of the different options. A maintenance technique is sustainable if it optimizes the use of natural resources, reduces energy consumptions, reduces green house emissions, limits pollution, improves health, safety, and prevents risk of accidents and ensures a high level of user comfort and safety.

Different maintenance techniques vary in terms of dimension and thickness of pavement. Furthermore, different techniques consume different type and amount of materials and thus have different environmental effects. It is not possible to determine those environmental effects without the use of any tool. Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is one of such tool and we used it in our study.

The primary objective of this study was to evaluate the three different maintenance techniques and compare the environmental effects, performance and life cycle cost associated with each maintenance technique. This was carried out through quantification of different harmful gases by emissions and energy and water consumption due the use of particular maintenance technique, determination and evaluation of Pavement Condition Index (PCI) after the use of the maintenance technique, and Life Cycle Cost Anaylis LCCA of each technique.

SCOPE

Environmental effects of these techniques were evaluated using an Excel based program called PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic effects) (9) ,developed by Arpad Horvath in University of California Berkeley. The program can be used to evaluate environmental effects associated with each maintenance technique for material production, transportation and processing of each maintenance technique. PaLATE is a hybrid model to quantify environmental effects. It quantifies the effects globally which may not have much effect in site specific analysis and comparison. The asphalt refined somewhere else has global effect but it may not be relevant to the site where it is being used. PaLATE does not take care of this aspect. Twenty four different routes in New York State were selected for pavement condition evaluation, Twelve CIPR routes, eight TCO routes and four MF routes. Field surveys were carried out according to the ASTM D 6433-07 Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. Using the field survey data, the PCI of each route was calculated and evaluated to determine which maintenance technique has the least distress.

The economic analyses of the different techniques was evaluated using Real Cost, a Excel based program, developed by U.S Department of Transportation, Federal Highway Administration (FHWA) Office of Asset Management (16). Real Cost was used for LCCA by deterministic approach. The costs and service life of each technique used in LCCA was provided by the NYSDOT CIPR study (22).

CHAPTER 2

BACKGROUND

Different maintenance techniques are used to repair or rehabilitate HMA pavements. Three common techniques are HMA Overlays, mill and fill and cold in-place recycling. The choice of maintenance technique depends on the type of distress and the condition of the pavement. These maintenance techniques differ in definition, method of construction, their suitability to repair the distresses and their environmental and economical impact. This chapter deals with these.

HMA OVERLAY

HMA overlays are used extensively for resurfacing of asphalt pavements. They consist of placing one or more layers of HMA oven an existing pavement. HMA overlays can treat either functional or structural distress.

Functional Overlay

When an overlay, usually, 2 to 4 inches thick, is used to restore ride quality, pavement section, and restore uniform surface then it is called a functional overlay. Functional overlays prevent further deterioration of pavements. Functional overlays are used to eliminate distresses like shrinkage cracking, raveling, bleeding, polished aggregate, edge cracking and reflection cracking (2).

Structural Overlay

When an overlay is used to provide additional load carrying capacity to an existing HMA pavement, then it is considered a structural overlay. Structural overlays are further categorized into structural overlays and heavy structural overlays. The typical thickness of a structural overlay varies from 4 to 6 inches and that of heavy structural overlay varies from 5 to 16 inches. The thickness depends on traffic, present condition index, and future quality of pavement expected. Structural overlays are used to treat edge cracking, reflection cracking, rutting, potholes and alligator/fatigue cracking but can be used to treat minor distresses too.

Mill AND Fill (MF):

HMA overlays are extensively used for resurfacing the existing pavement. When a new overlay is placed after milling the pavement, the maintenance technique is called mill and fill. Milling or cold planing can eliminate differential compaction and removes high points in an existing surface to produce a relatively smooth surface. Milling also provides RAP for recycling operations, allows curb and gutter lines to be maintained, and efficiently removes deteriorated portions of pavement.(18). The typical mill depth is 2 to 4 inches.

According to Basic Asphalt Recycling Manual (BARM)(7), mill and fill can treat raveling, bleeding, shoulder drop off, rutting, corrugations, shoving, deteriorated and stripped asphalt, swells, bumps and sags, corrugations and depressions efficiently.

COLD IN-PLACE RECYCLING (CIPR)

Cold In-Place Recycling (CIPR) is the maintenance technique in which the existing pavement is removed, crushed, blended with emulsified asphalt and then re-laid and compacted in the same location. No heat is used in the process. The typical depth of CIPR is 3 to 5 inches (7), usually followed by an HMA overlay.

In CIPR, the existing pavement is ripped and pulverized adding additional stone, if necessary, then mixing with asphalt emulsion and the resulting mixture is placed and compacted. The recycled layer is used as base layer and a wearing surface is required (1). According to BARM (7), CIPR is faster, more economical, less disruptive to traffic and environmentally preferable due to the consumption of less energy and water and, less emissions of green house gases. In addition, pavements in poor condition can be recycled and the old asphalt concrete materials used in new pavements (1). Recycling can be advantageous as it saves material cost, does less harm to the environment, and doesn’t increase the dead load on structures as done by HMA overlays. Furthermore, utility structures like curbs and gutters don't have to be reconstructed (1).

According to the BARM (7) pavement distresses which can be treated by CIPR are:

- raveling
- potholes
- bleedings
- skid resistance
- rutting
- corrugations
- shoving
- fatigue, edge and block cracking
- slippage, longitudinal and transverse thermal cracking
- reflection and discontinuity cracking
- poor ride quality caused by swells, bumps, sags, and depressions

Although, CIPR can rehabilitate most types of pavement distresses but cracked pavements which are structurally sound and have well drained bases are the best candidates.(7)

Construction of CIPR

The construction steps for CIPR are as follows (7):

1. The construction area is prepared
2. The pavement material is pulverized
3. Additives and new aggregates, if required, are added and mixed
4. The mixture so obtained is placed and compacted
5. A wearing course is placed over the compacted layer.

Recycling Trains

CIPR is typically performed using single unit, two unit or multi unit trains. Each is briefly described below.

Single Unit Trains

With a single unit train, the milling machine cutting head removes the pavement to the required depth and cross slope, sizes the RAP and blends the recycling additive with the RAP. Single unit trains do not have screening and crushing units, so the control of the maximum particle size of the RAP is difficult. A spray bar in the cutting chamber adds the liquid recycling additive. The amount is based on treatment volumes and anticipated forward speed of the unit. Single unit trains are not recommended for CIPR of highly deteriorated pavement because of less control over RAP size and recycling additives. Single unit trains cut, mix and place all in one operation.(7)

Single unit trains are simple in operation and have high production capacity. Moreover, they are preferred in urban areas because of their smaller and less disruptive traffic.(7)

Two Unit Trains

Two unit trains consist of a milling machine and a pugmill mix-paver. They do not contain crushing and screening units. A milling machine removes the RAP and the mix is deposited into the pugmill of the mix-paver. Through computer control, additives are added based on weight of RAP and not volume or speed of the train. The mix paver contains a pugmill which mixes the materials and has automatic controlled screed for mix placement and initial compaction. Two unit trains are simple to operate and have high production capacity but, due to the lack of crushing and screening unit, RAP aggregate oversize is not easily controlled. (7)

Multi Unit Trains

Multi unit trains consist of a milling machine, a screening and crushing unit and a pugmill mixer. The milling machine mills the pavement to the required depth and cross slope. RAP is crushed and screened to control maximum size. In the pugmill, recycling additives are mixed with the RAP. The mixture so obtained is placed and compacted. (7)

Recycling using multi unit trains have the highest process control and very high productivity. However, the train can be quite long and disrupt traffic operation in urban area. Multi unit trains are generally limited to rural projects.

PaLATE AND ENVIRONMENTAL EFFECTS USING PaLATE

PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) is a computer based decision tool which can be used to compare the economic feasibility and environmental effects of different construction and maintenance options of pavements (10). It was developed by Dr. Arpad Horvath at University of California, Berkeley. It utilizes a life cycle assessment framework that draws on engineering, environmental and economic information and data to evaluate the use of different alternatives available for construction and maintenance of pavements (10). PaLATE can be used to evaluate the environmental and economic impact of using different materials and different maintenance strategies. The amount of virgin materials in different courses can be varied to compare the impact of using recycled materials instead of virgin materials. PaLATE takes user input for the design, initial construction, maintenance, equipment use and costs of a roadway and characterizes the life cycle environmental effects and costs of a given project (10).

PaLATE Operation

PaLATE takes density of the materials used, length, breadth, thickness of different layers, or volume, haul distances of materials, type and size of equipments used along with their fuel consumption and productivity. These inputs are used to calculate emissions of different gases and consumption of water and energy by linking those input quantity to the worksheets where the data for emissions and consumptions are stored.

Working Concept of PaLATE

According to Horvath (10), PaLATE incorporates information and analysis to calculate environmental effects. Among the two frameworks, one is based on Economic Input-Output Analysis (EIO-LCA). In this model the entire economy is divided into a square matrix of 480 commodity sectors. Each row and column represents a sector and each cell represents economic transaction in dollars between two respective sectors. The circular effect in the economy resulting from sale or purchase of one sector to produce a dollar of output is represented in the table. This economic model is linked to various environmental effects like consumption of energy and water, emissions of greenhouse gases and other environmentally harmful products. Furthermore, input and output are considered to have linear relationship so the variation in output is related to the input linearly. EIO-LCA emission factors are available in metric tons per dollar of sector output, thus PaLATE uses U.S. producer prices ($/Metric ton) from 1997 Means Building Construction Cost Data and other unspecified sources to calculate emissions per mass of material used (10).Carnegie Mellon maintains a web website www.eiolca.net that has specified two prices for the United States EIO-LCA model, one is industry benchmark producer price and the other is industry benchmark purchaser price. The 1997 models use the 1997 US dollars as monetary unit and 2002 model use the 2002 US dollar as monetary unit. The 1997 models have about 480 commodity sectors but 2002 models have only 428 commodity sectors. PaLATE uses the 1997 model.

In the website www.eiolca.net, one can specify the type of activity and its economical value and get the results of circular effects in different sectors. One can get the values in dollars for different sectors or in terms of quantity of consumptions and emissions. For example if one million dollars are invested for highway or tunnel construction what part of it will be used for power generation, truck transportation, oil extraction, sand, gravel clay mining and so on. Furthermore, results of emissions of greenhouse gases resulting from the million dollars investment in highway construction can be calculated.

PaLATE has the dollar value incorporated in the model and when one enters the quantity it links with the dollar value and using the information from EIO-LCA database, calculates emissions and consumptions.

Environmental Effects Calculated by PaLATE

PaLATE presents the life cycle inventory of the environmental effects (environmental effects resulting during the whole life of pavement) of the following categories (9).

1) Energy consumption in (MJ)
2) Water consumption in (Kg)
3) $C0_2$ emissions in tones also called Global Warming Potential
4) NOx emissions in Kg
5) PM_{10} emissions in Kg
6) SO_2 emissions in Kg
7) CO emissions in Kg
8) Hg emissions in grams
9) P_b emissions in gram
10) RCRA Hazardous waste generated in Kg
11) Human Toxicity Potential cancer (HTP-Cancer) in terms of aldehydes benzon and pyerene in g
12) Human Toxicity Potential cancer (HTP-Cancer) in terms of aldehydes benzon and pyerene in g

Materials production for initial construction and maintenance, the transportation of raw materials and mix for initial construction and maintenance, processing of these materials are the sources of the above listed environmental effects. Activities like production of asphalt cement, emulsion and aggregates and HMA mix production are grouped under production. In addition the production of RAP when used, is also considered under production and not process. Transportation refers to the transportation of constituent materials, RAP and HMA mix. Paving of HMA at site using pavers and rollers, recycling using recycling trains are grouped under the process.

Sources of Environmental Effects

There are several activities involved in construction and maintenance of pavement. These activities are responsible for those environmental effects. The sources of consumptions and emissions of these environmental effects are summarized in table 1 below.

TABLE 1 Source of Environmental Effects (Emissions and Consumptions)

Environmental effect	Sources
Energy consumption	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling
Water consuption	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
$C0_2$ emissions	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
NOx emissions	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
PM_{10} emissions	Aggregates, asphalt cement, emulsion, productions and transportation, transportation of RAPand CIPR
SO_2 emissions	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
CO emissions	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
Hg emissions	Asphalt and emulsion production, RAP used, transportation of aggregates and HMA , transportation of RAP
Pb emissions	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
RCRA Hazardous	Aggregates, asphalt cement, emulsion, RAP, HMA, productions and transportation, paving of HMA and recycling, CIPR
HTP cancer	Aggregates, asphalt cement, emulsion , RAP production and transportation. No information about paving of HMA and CIPR
HTP non-cancer	Aggregates, asphalt cement, emulsion , RAP production and transportation. No information about paving of HMA and CIPR

Studies Using PaLATE:

As hybrid environmental effects models are relatively new, there are few studies in the literature on PaLATE.

Alkins, Lane and Kazmierowski, from Ministry of Transportation Ontario (11), used PaLATE to quantify the emissions of green house gases from different maintenance techniques. These techniques were Mill & HMA, Cold in-Place Recycling (CIR) and Cold In-Place Recycled Expanded Asphalt Mix (CIREAM). The study was based on a 1 Km section with a pavement cross section of 7.5 m width and existing 150mm HMA depth. For milling the top 100mm was milled and 130mm of HMA overlay was overlaid. For CIR/CIREAM pavement was recycled 100mm and 50mm thick HMA overlay was placed.

Figures 1 and 2 below present some environmental effects of the three different maintenance techniques.

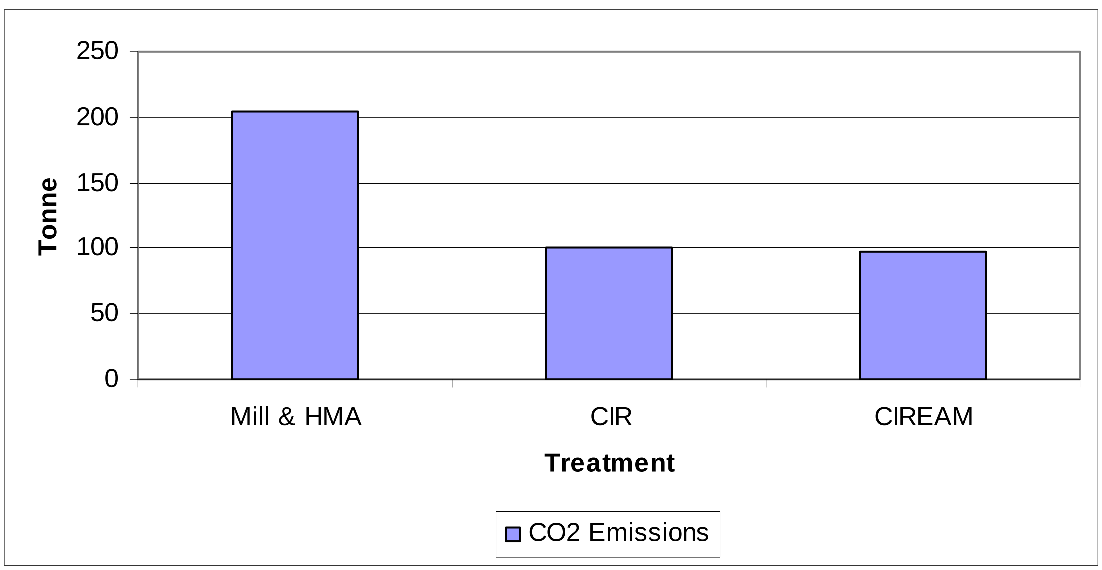


FIGURE 1 CO_2 Emissions for different maintenance techniques (11).

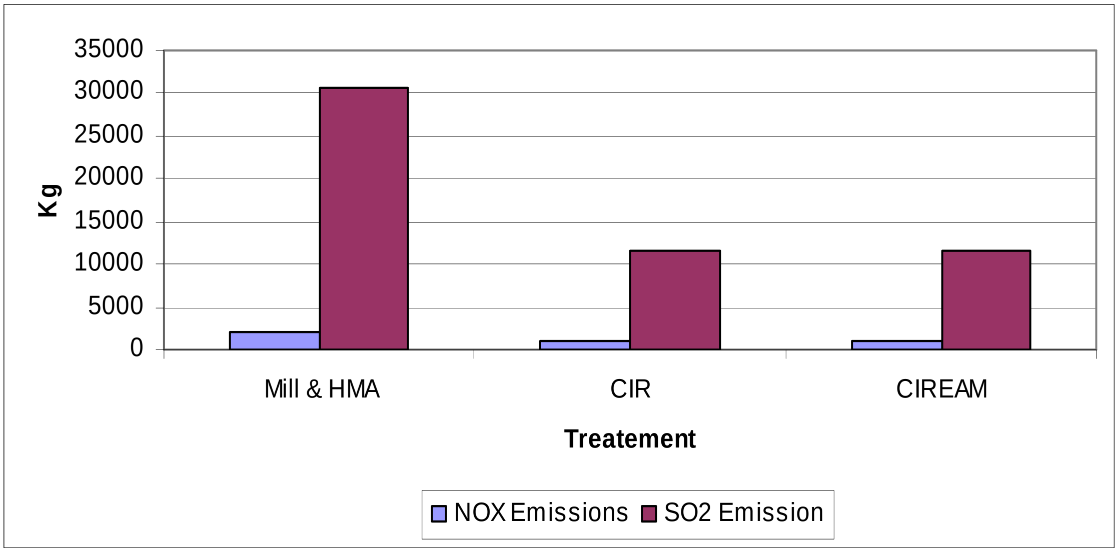


FIGURE 2 NO_X and SO_2 emissions according to maintenance techniques (11).

Comparison of quantity of green house gases like CO_2, NOx, and SO_2 produced from three different technique mill and HMA, Cold in place recycling CIPR and Cold in place recycling expanded asphalt mix (CIREAM) was done. The results indicated that CIR and CIREAM significantly emit less CO_2, NOx and SO_2 compared to traditional mill and HMA(11).

A case study was done by Gardner and Carpenter (12), fot the emissions of two options using PaLATE. The initial construction for first option was to mill and rubblize concrete pavement and pave with new 3.5 inch thick HMA. The maintenance involved in the first option was to crack seal at 4,8,16 and 20 years and resurfacing with wearing course in 12th and 24th year. The initial construction for second option was to remove concrete slab and fill 12 inches gravel followed by 5.5 inches of HMA overlay. The maintenance involved for second option was hot in place recycling (HIPR) in 12th and 24th year.

PaLATE was used to compare the two options for energy consumption and water consumptions and emissions of green houses gases, lead and RCRA hazardous wastes.

The results showed that rubblization uses 3.5MJ less energy than use of Virgin materials during initial construction. During maintenance, HIPR uses 1.5 MJ less energy less than crack sealing and resurfacing. Water consumption during initial construction for first option (milling existing concrete pavement, rubblizing with pavement millings, widening with virgin material and pave with 3.5” HMA) is 700Mg less than that for second option (removal of existing slab, construction of 12” gravel and crushed gravel, and paving with 5.5” HMA) On the other hand, maintenance for second option consumes about 400 Mg less water than that for the first option. Similarly, the study shows that the emission of harmful elements and gases is less during initial construction for first option in compared to second option while emissions of those during maintenance is more during maintenance for first option compared to second option.

In another study done by the Gormon group (17) , PaLATE was used to calculate the consumption of energy and water and emission of environmentally harmful byproducts for a 3 mile long pavement section for single chip seal, microsurfacing, 2 inches CIPR with microsurfacing, 2 inches HIPR with microsurfacing and 2 inch HMA overlay.(17)

The total consumptions and emissions for these maintenance treatments from the study are summarized below in table 2 below.

TABLE 2 Total Consumptions and Emissions for Maintenance Treatments (17)

Effect	Single Cheap Seal	Microsurfacing	2" CIPR w/Microsurfacing	2" HIPR w/Microsurfacing	2" HMA overlay
Energy (MJ)	65,202.00	102,558.00	181,700.00	357,609.00	5,782,265.00
Water(Kg)	9.00	15.00	23.00	22.00	2,018.00
$C0_2$ emissions(kg)	5.00	7.00	13.00	17.00	313.00
NOx emissions(Kg)	44.00	68.00	82.00	163.00	2,319.00
PM_{10} emissions(Kg)	109.00	167.00	273.00	189.00	889.00
SO_2 emissions(Kg)	254.00	371.00	933.00	458.00	40,793.00
CO emissions(Kg)	218.00	319.00	791.00	411.00	1,182.00
Hg emissions(g)	1.56	2.28	5.78	2.83	8.22
Pb emissions(g)	74.00	108.00	271.00	133.00	394.00
RCRA Hazardous waste(Kg)	15,663.00	22,866.00	57,780.00	28,315.00	82,665.00
HTP cancer(g)	5,342.00	8,417.00	8,484.00	65,111.00	1,315,173.00
HTP non-cancer(g)	65,275,512.00	102,867,436.00	102,950,644.00	203,815,952.00	675,134,839.00

The result shows that single chip seal is most environment friendly among the alternatives. If we compare CIPR and HIPR, consumption of energy and amount of emission of CO_2, NOX, hazardous wastes, HTP (both cancer and non-cancer) is less for CIPR than those for HIPR. On the other hand, consumption of water and emissions of PM_{10}, SO_2, CO, Pb is more for CIPR than those for HIPR.

PAVEMENT CONDITION INDEX (PCI)

Distress is the condition of pavement structure that reduces the serviceability or leads to a reduction in serviceability (5). ASTM D 6433-07 has listed nineteen different distresses which are quantified to calculate the PCI of asphalt pavement. These distresses are described in Appendix A.

Based on the distresses observed and measured on the surface of the pavement, a numerical value for the pavement is obtained using a standard procedure. This numerical value is called Pavement Condition Index (PCI). PCI rates the surface condition of the pavement on a scale from 0-100 (8). A pavement with PCI 0 is the worst possible condition and one with 100 is that with best possible condition.

Pavement condition rating is the description of the pavement condition based on the PCI range. Following are the pavement condition ratings based on PCI range according to ASTM D 6433-07

- 0-10 Failed
- 10-25 Serious
- 25-40 Very poor
- 40-45 Poor
- 55-70 Fair
- 70-85 Satisfactory
- 85-100 Good

One drawback to the procedure is PCI does not measure skid resistance or roughness and also cannot measure the structural capacity. However, it can be used to monitor the rate at which the pavement is deteriorating and to identify maintenance strategies. (8)

Determination of Sample Units

According to ASTM D 6433-07 following steps are followed to determine the sample units to be surveyed:

1) Branches of roadway are identified according to use.
2) Each branch is divided into sections based on pavement design, construction history, traffic, and condition
3) The pavement section is divided into sample units.
4) The number of sample units to be inspected is determined. The number of sample units selected may be entire or 10% of the section that provides a confidence level of 95% usually.
5) The formula below provide the number of sample units to be surveyed to get 95% confidence level of the PCI of the section.

   $n= Ns^2 / ((e^2/4)(N-1)+s^2)$

   where,

   e= acceptable error in estimating the section PCI, e= ±5 points

   s= standard deviation of PCI from one sample unit to other within a section. For initial inspection, 10 for asphalt pavement.

   N= total number of sample units in the section
6) The spacing interval of the units to be samples is given by the formula i= N/n

   Where i= spacing interval

   N= total number of sample units in the section, and

   n=number of sample units to be inspected

   The first sample location is selected at random and other samples are spaced equally throughout the section.
7) Additional sample units are to be inspected only when non representative distresses are found.

Inspection Procedure

Each sample unit is inspected, sketched and the area of the sample unit is recorded. Each distress type present is measured for quantity and severity level as described in appendix X1 of ASTM 6433-07.

Calculations of PCI

As explained in ASTM D 6433-07 the PCI is calculated following the steps described below:

1) The total quantity of each distress at each severity level is added and recorded as total severity.

2) The total quantity of each type of distress at each severity level is divided by the sample unit area and converted to percentage to get the percent density of each distress at each severity level.

3) The deduct value for each distress type and severity level is determined from the curves in appendix X3 of ASTM 6333-07. The deduct value depends on the type of distress, its percent density and severity level.

4) The total deduct value is determined using the following procedure:

- All deduct values are arranged in descending order
- The allowable number of deducts is calculated from the equation
  $m=1+(9/98)(100-HDV)$
  where HDV= highest deduct value in a row
- If m came out to be a mixed number the whole number of deduct values and a deduct value obtained by multiplying it by the fraction part of m is added to get the total deduct value (TDV)
- All other values are discarded.
- If less than m deduct values are available all of the deduct values are used.

5) The maximum corrected deduct value (CDV) is calculated for each total deduct value. The corrected deduct value is calculated from the curve in appendix X3 of ASTM 6433-07 where CDV is calculated from the combination of total deduct value (TDV) and the number of deduct value greater than 2.

6) CDV is obtained iteratively by reducing the smallest individual deduct value greater than 2.0 to 2 and by repeating the process of getting TDV and CDV until q=1.
Where, q= number of deduct values greater than 2
7) Out of the CDV calculated in each row, the maximum CDV is the largest CDV.
8) PCI is calculated by the formula PCI= 100- max CDV

Other PCI Studies

A search of the available literature indicated that few DOTs use ASTM D 6433 to calculate PCI. Many agencies have developed their own procedure to describe the condition of the pavement and are based mainly on roughness measurements.

One of the few papers found where CIPR was compared to MF was by Alkins, Lane and Kazmierowski from Ministry of Transportation Ontario (11) , PCI was calculated using the formula below to compare the performance of mill and overlay, and Cold in-Place Recycling (CIR) and Cold In-Place Recycled Expanded Asphalt Mix (CIREAM).

$PCI = 100-(10-DMI)*W_{DMI}-(IRI-IRI_o)*W_{IRI}$

Where,
PCI = Pavement Condition Index
DMI = Distress Manifestation Index
IRI = International Roughness Index
W= A weighting assigned based on severity.

Figure 3 below shows the predicted age of pavement after the two treatment techniques. The figure shows that the PCI for milled and overlaid pavement is greater than that one for CIR/CIREAM maintenance over HMA pavement. Thus, it shows that mill and overlay lasts longer than CIR/CIREAM.

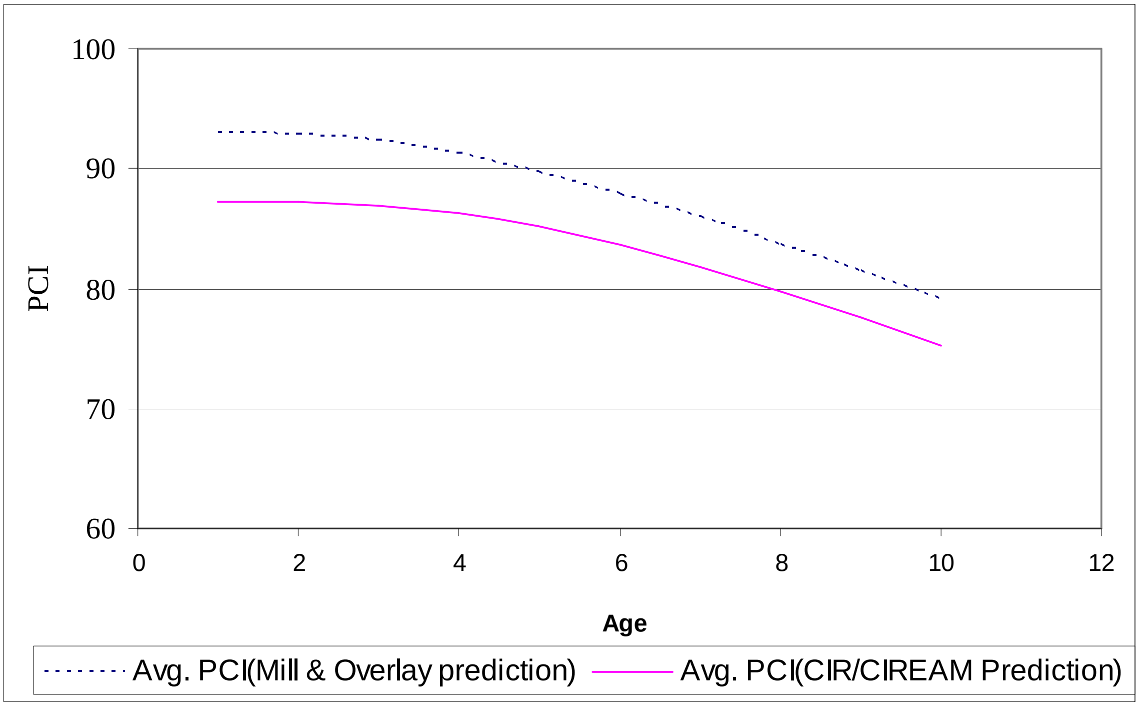


FIGURE 3 Pavement condition index (PCI) comparison (11).

LIFE- CYCLE COST ANALYSIS (LCCA) IN PAVEMENT DESIGN.

Life Cycle Cost Analysis (LCCA) is a decision support tool that helps to choose an alternative amongst many. The modified definition of LCCA, according to the 1998 Transportation Equity Act for the 21st Century (TEA-21), is “a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring and resurfacing cost over the life of the project segment.”

According to Life Cycle Cost Analysis Primer (15) “LCCA is an engineering economic analysis tool useful in comparing the relative merit of competing project implementation alternative.”

In summary, LCCA is an analysis technique the results of which can be used to make better investment decision.

Approaches of LCCA

There are two approaches to LCCA, deterministic approach and probabilistic approach.

Deterministic Approach

In this approach all the inputs required to calculate the life cycle cost are considered fixed or determined and their variability is not taken into consideration. Maintenance techniques have different variable lives, costs and discount rates, vary over time but all the variability are disregarded and average values are used to calculate the life cycle cost in this approach.

Probabilistic Approach

There are uncertainties associated with the input parameters to calculate life cycle cost. In a probabilistic approach, the variability of these input parameter are considered and the probable cost is calculated.

Economic indicators of LCCA

There are several economic indicators of LCCA like benefit-cost ratio (B/C ratio), Internal rate of return(IRR), Equivalent Uniform Annual Costs(EUAC) and Net Present value(NPV). In this study Net Present Value was used as an economic indicator to compare the LCC of three different techniques because it is simple to calculate and understand and the current cost is used in the study.

Net Present Value (NPV)

It is the difference between the discounted sum of benefits and discounted sum of cost. If the Net Present value from a program is not positive it should not be used.

NPV= PV benefits – PV costs

In LCCA the differential cost between two alternatives is compared, and the benefits associated with two procedures, and the minor maintenance cost should be the same for all alternatives. Therefore the NPV is

NPV= Initial cost + sum of discounted rehabilitation costs discounted to year 0

$$NPV = \text{Initial cost} + \sum_{k=1}^{N} \text{Rehab Cost}_k (1/(1+i)^{n}{}_k$$

Where, i = discount rate

n = year of expenditure

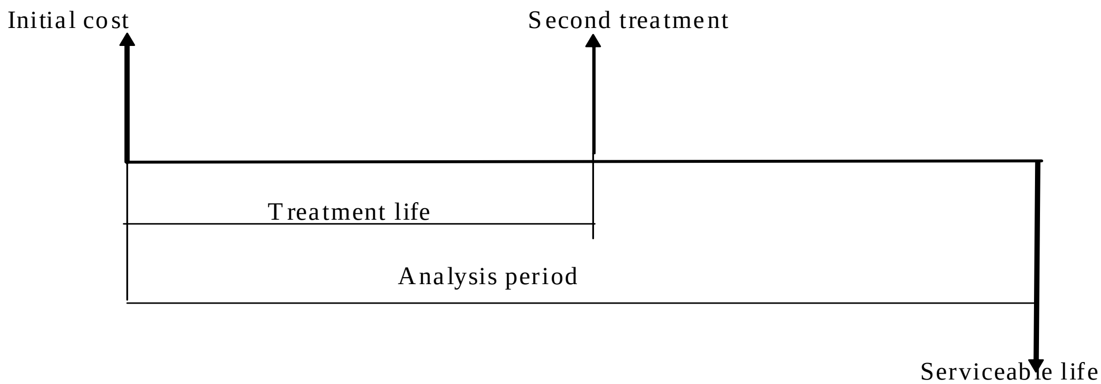


FIGURE 4 Time line diagram for LCCA (14).

Types of Cost

There are cost associated with design, construction and maintenance and costs resulting due to delay, accident crash during construction and maintenance. These costs are discussed below.

Agency cost

Agency costs are expenditures that are made for the design, inspection, initial construction and maintenance of pavements. The initial design and rehabilitation strategy chosen determines the construction quantities and cost. Thus, for LCCA, we are concerned with agency cost. LCCA comparisons are made between two alternatives that are mutually exclusive. If the cost is common for the alternatives they cancel out and can be ignored. Costs which are not common are accounted for in LCCA. For example, routine maintenance cost is almost always the same for all rehabilitation strategies so it can be excluded from analysis(14) .

User Cost

The cost to be beared by the users while travelling is user cost. Due to pavement construction and rehabilitation, vehicles are queued , they take more time to reach destination and have to take detours. User cost typically has three components a) Vehicle Operating Cost (VOC) b) User Delay Cost and 3) Crash Costs.

User cost is usually excluded in LCCA because in most of the cases it is same for all maintenance techniques and it was excluded in our study.

Remaining Value of Pavement

In LCCA the analysis period may not be an exact multiple of the life of the maintenance technique. Thus, the remaining value of the pavement should be included in the analysis. Furthermore, RAP millings also have some economic value. The remaining value is called salvage value. Salvage value is the value of the investment alternative at the end of the analysis period. The salvage value of the pavement consists of two components residual value and serviceable life.

Residual value

Residual value is net value from recycling the pavement at the end of the analysis period. In many cases, the residual value would be the same for the alternatives and can be excluded from LCCA (14).

Serviceable Life

Serviceable life is the value resulting from the remaining life of the maintenance technique at the end of the analysis period; when the analysis period is not the exact multiple of the life of the maintenance technique. At the end of the analysis period, the service life of the pavement or any maintenance technique may not be over. Thus, it will have some value which should be accounted for in LCCA (14).For example, for an analysis period of 35 years if two maintenance techniques are chosen one with service life of 10 and another with that of 15, at the end of the analysis period these two will have two different remaining service value or negative cost.

LCCA Procedures

According to interim technical bulletin of LCCA (14) the steps involved in LCCA are

1. Establishing alternative pavement design strategies for analysis period
2. Determining performance periods and activity timing
3. Estimating agency cost
4. Estimating user cost
5. Developing expenditure stream diagrams
6. Computing net present value
7. Analyzing result
8. Re-evaluating design strategies

All these steps are described in detail in the Interim technical bulletin published by USDOT FHWA in 1998.

Studies of LCCA

LCCA, due to its dependence on current costs and agency policy, is more of a decision support tool and therefore, there are few studies in our specific area of investigation.

In the study carried out by Alkins, Lane and Kazmierowski from Department of Transportation Ontario(11), LCCA for Mill and Overlay and CIR/CREAM was calculated in terms of cost per Km. LCCA of these two techniques is summarized below in table 3 below.

TABLE 3 LCCA of CIR/CREAM and Mill and Overlay/HMA (11)

	Technique	
	Mill and overlay	**CIR/CIREAM**
Initial cost in $(per km)	173,000	100,000
Service life in years	18	15
Analysis period in years	50	50
Discount rate in %	5	5
Life Cycle Cost (LCC) in $	98,402.31	76,555.58

The table shows that the LCC for CIR/CREAM is less than that for Mill and overlay.

Similarly, in a case study done by Gardner and Carpenter (12), LCCA for two different options were calculated using PaLATE. The two options are summarized below:

First option:

Initial construction:

Mill of the existing concrete pavement

- Rubblize concrete
- Widen with virgin material
- Pave with 3.5" HMA

Maintenance:

- Crack seal in year 4 and year 8
- Resurfacing 1" HMA on in year 12
- Crack sealing in year 16 and 20
- Resurfacing 1" HMA in year 24

Second option:

Initial construction

- Removal of concrete slab and landfill
- Construct 12” gravel and crushed gravel full width
- Pave with 5.5” of HMA

Maintenance

- HIPR in year 12
- HIPR in year 24

The LCCA showed that all the three, initial construction cost, maintenance cost and total cost is higher for the first option than those for the second option.

REAL COST

LCCA can be performed manually using a simple calculator or any available software that can be used to calculate the LCC. In our study, we used Real Cost to determine LCC by deterministic approach.

Real cost is an Excel based software developed by US Department of Transportation Federal Highway Administration (FHWA) Office of Asset Management. It allows the user to compare the effects of cost, service life, and economic inputs on life-cycle cost. The program incorporates the FHWA’s LCCA methodology as described in the Interim Technical Bulletin (14). Real cost can be used to calculate both agency cost and user cost. It can be used to perform the deterministic sensitivity analysis and probabilistic risk analysis. Real cost can compare only two options at a time.

Real cost requires the project details such as analysis options, analysis period, discount rate, inclusion or exclusion of user cost, inclusion or exclusion of remaining service life and some other project details. In addition to these details, it requires the agency cost of initial construction and maintenance and their service lives. In our study, we used the deterministic approach because it uses current price and is simple.

Real cost calculates three types of Life Cycle Cost (LCC). The first one is undiscounted sum in which all the costs are summed up without discounting the future costs, the second one is the NPV in which the current cost and discounted future costs are summed and the third one is Equivalent Uniform Annual Cost (EUAC). EUAC is presented in terms of annuity i.e., annual expenditure during the analysis period.

Real cost gives the deterministic and probabilistic results but doesn't interpret them. The interpretation of the result should be done by the user to figure out the best alternative (15).

CHAPTER 3

TEST METHODOLOGY

ENVIRONMENTAL EFFECTS USING PaLATE

During the lifetime of a pavement, maintenance is inevitable. Maintenance techniques used consume energy, water and produce environmental byproducts because of their use. PaLATE was used to quantify the consumption of water, energy and emissions from TCO, MF and CIPR.

The environmental effects using PaLATE resulting from the three different maintenance techniques were evaluated for a single treatment and the amount of environmental effects thus obtained were used to compare and analyze the environmental impact of each maintenance technique.

Pavement selection for evaluation

To calculate the environmental effects of the three maintenance techniques, typical pavement cross sections of each technique were required. Environmental effects for a 1 mile long 24 feet wide pavement with no shoulder were calculated using PaLATE. Shoulders were not included in the analysis because of their variability regarding their width, thickness and composition. Moreover, not all options require treatment of shoulders but TCO requires. Selection of different pavement cross-sections and inclusion of pavement shoulders would impact environmental outputs. The cross-sections, and their identifying codes used in the analysis, are shown in Table 4.

TABLE 4 Codes and Descriptions Used in Study

Code	Description
TCO	Two 1.5 inch thick lifts of HMA placed over exiting 24 feet wide pavement having 10% RAP in both courses
TCO-NR	Two 1.5 inch thick lifts of HMA overlay placed over exiting 24 feet wide pavement with no RAP in the mix
MF	Top 3 inches of existing pavement milled and two 1.5 inch layers of HMA placed over it with 10% RAP in it
CIPR	Top 4 inches of existing pavement cold in place recycled with 2% asphalt emulsion and 1.5 inch HMA overlay placed over the entire 24 feet width with 10% RAP in HMA
CIPR-AS	Top 4 inches of existing pavement cold in place recycled with 3% asphalt emulsion, 10% new add-stone and 1.5 inch HMA overlay placed over the entire 24 feet width with 10% RAP in HMA

Project Information

Project information is needed to run PaLATE. The following project information was used in the analysis. Different haul distances would impact results.

1) Haul distance from asphalt refinery to HMA plant was assumed to be 100 miles.
2) Haul distance of emulsion was assumed to be 125 miles because it is transported directly from refinery to the site without passing through mix plant.
3) The project site was assumed to be 25 miles from the HMA plant
4) The haul distance of millings to HMA plant was assumed to be 25 miles.
5) Haul distance of 25 miles from quarry to HMA plant was used for aggregate
6) For CIPR, add-stone is added on site so the total haul distance for add-stone was considered to be 25 miles.

Material Inputs

Material inputs required to run PaLATE are densities of the materials used (loose for hauling and compacted for in-place), percentage of binders, amount of Reclaimed

Asphalt Pavement (RAP) used in each course and amount of add-stone used in CIPR. Default values are available in PaLATE but the analysis used typical project information listed below:

1) HMA was assumed to have 6% asphalt and compacted unit weight of 150 pcf.
2) For HMA with RAP, both binder mix and surface mix were assumed to have 10% RAP with 6.0% asphalt except for TCO-NR which had no RAP in it.
3) The density of asphalt mix in haul truck was assumed to be 110 pcf.
4) The density of RAP in haul truck was assumed to be 107 pcf.
5) The density of both bitumen and asphalt emulsion were assumed to be 62.2 pcf.
6) CIPR with add-stone was assumed to have compacted unit weight of 150 pcf and 3 % asphalt emulsion.
7) CIPR without add-stone was assumed to have compacted unit weight of 150 pcf and 2.5% asphalt emulsion.
8) 20% add-stone was used in CIPR with add-stone.
9) The add-stone used in CIPR was assumed to have loose unit weight of 89 pcf.

Equipment Inputs

The final input parameters required to run PaLATE are the capacity, fuel consumption and productivity of the equipment used by the three different maintenance techniques. PaLATE has a sheet of default equipment with productivity, capacity and fuel consumption. Not all equipment used was present in PaLATE. Missing equipment inputs were obtained from contractors. Table 5 below shows the information of the equipment inputs used in the analysis.

TABLE 5 Equipment Details, Capacity, Productivity and Fuel Consumption

Equipment	Engine capacity(hp)	Productivity(ton/hr)	Fuel Consumption(l/hr)	Fuel Type
Asphalt Paver	175	250	22.71	Diesel
Tandem Vibratory roller	120	250	9.5	Diesel
Pneumatic roller	100	250	6	Diesel
CIPR train	850	250	170	Diesel
Milling planer	1050	150	113.6	Diesel
HMA plant		250	1700	0il

PAVEMENT CONDITION INDEX (PCI) AND ITS USE

Pavement Condition Index (PCI), which quantifies the distresses in a pavement and gives a picture of the condition of the road, was used to evaluate the performance of the three different maintenance techniques TCO, CIPR and MF. Determination of PCI involves site selection and field surveys which consist of visual inspection and measurement of distresses. The PCI is calculated from the data obtained from the field surveys. These steps are described below.

Survey of the Selected Site

As a part of a study on CIPR pavements (X) twenty four pavements in New York states were selected for PCI evaluation. Among the twenty four routes, twelve were repaired using CIPR, eight were repaired using TCO and four were repaired using MF. Each site was evaluated as recommended in ASTM D 6433-07. Approximately 10% of each route was surveyed. Each route was divided into sample units. Each sample unit was 100 feet long and 25 feet wide so that the area of each sample unit was 2500 square feet. The first sample unit was chosen randomly and the other sample units were located 0.2 miles apart from the previous one. The survey team surveyed, quantified and recorded the distress data depending on the type and severity of distress according to section 8.1 and Appendix X1 of ASTM 6433-07.

The region, route, length of route and number of sample units for each pavement, by treatment technique, is shown in Table 6.

TABLE 6 Summary Table of Routes, Lengths and Sample Units

Maintenance											
CIPR				TCO				MF			
Region	Route	Length mile	No. of sample units	Region	Route	Length mile	No. of sample units	Region	Route	Length mile	No. of sample units
9	7	3.92	20	7	11	5.07	25	7	3	3.2	14
1	9	4.05	21	1	22	2.65	13	7	11	5.04	25
7	12	2.65	14	7	37	3.31	17	7	12	5.44	28
1	23	4.88	25	7	81	2.18	11	9	9L	4.52	22
7	26	5.19	25	1	86	3.43	8				
7	30	2.1	11	7	126	2.71	14				
1	67	2.46	12	1	197	2.78	14				
7	342	1.15	6	1	9N	4.8	25				
1	346	2.37	12								
2	349	3.33	14								
2	920V	2.12	10								
1	9N	9.81	50								
	Total	44.0	220		Total	26.9	127		Total	18.2	89

Calculation of PCI

The individual survey sheets from each sample unit of each route were provided by the survey team. The survey sheets quantify the amount and severity of each distress present. The PCI for each survey unit was calculated as per the section 9 "Calculation of PCI for Asphalt Concrete Pavement" of ASTM D 6433-07. After calculating the PCI for each section, the average PCI for each route was calculated and then the average for each technique was calculated.

Analysis of PCI

The PCI thus calculated was used to evaluate the effectiveness of each maintenance technique. Higher values of PCI indicate that the maintenance technique is performing better. Statistical analysis was performed to evaluate whether the difference in performance is statistically significant.

LIFE CYCLE COST ANALYSIS (LCCA)

LCCA was performed to evaluate which maintenance technique is the most economical. Real Cost, was used to determine the LCC of the three maintenance techniques. To run Real Cost inputs needed are analysis period, discount rate, service life and cost of each technique and discount rate.

Pavement Sections

The pavement sections chosen for LCCA were the same as those for PaLATE. Each pavement section was 1 mile long, 24 feet wide and the shoulders were excluded in the analysis. The cross section was dependent on the type of maintenance technique. For CIPR, the thickness of maintenance was 4 inch with 1.5 inches HMA overlay. For TCO, two 1.5 inches thick HMA overlays were used and for MF a 3 inches HMA overlay was laid after milling the top 3 inches of the existing pavement. Different sections and variable cost would affect the results.

Treatment Costs

Treatment costs can vary widely and would affect Life Cycle Cost (LCC). Typical treatment costs obtained from local contractors are shown in table 7. The cost provided includes material and process costs

TABLE 7 Unit Cost of Different Processes

Process	Unit	Cost
HMA	Ton	$64.00
HMA without RAP	Ton	$67.00
4" CIPR	Sy	$5.01
4" CIPR with 20% add-stone	Sy	$6.45
3" milling	Sy	$2.25

Using the costs in the table above, total cost for each 1 mile long 24 feet wide pavement section excluding shoulders was calculated. The total calculated cost is shown in table 8 below.

TABLE 8 Treatment Costs of Maintenance Techniques

Treatment	Materials	Unit cost	Area/Mass	Cost	Total Treatment cost
CIPR-AS	1.5" HMA	$64/ton	1,188 tons	$76,032.00	
	CIPR 4"	$6.45/sy	14080 sy	$90,816.00	$166,848.00
CIPR	1.5" HMA	$64/ton	1,188 tons	$76,032.00	
	CIPR 4"	$5.01/sy	14080 sy	$70,540.80	$146,572.80
MF	3" HMA	$64/ton	2376 tons	$152,064.00	
	3" milling	$2.25/sy	14,080sy	$31,680.00	$183,744.00
TCO	3" HMA	$64/ton	2376 tons	$152,064.00	$152,064.00
TCO-NR	3" HMA	$67/ton	2376 tons	$159,192.00	$159,192.00

Treatment Life

According to the CIPR study in New York(22), the treatment life of NYSDOT CIPR pavements were projected to average 11 years with a minimum of 4 years and maximum of 30 years. Treatment lives of MF and TCO were not available. Therefore treatment life was made a variable in the analysis by considering life cycle cost for estimated treatment lives of 8,11,14,17 and 20 years.

Salvage Value

Salvage value consists of two components, residual value and serviceable value. Residual value is the value of the materials as milling. Since the value of asphalt millings is same for each maintenance technique, only the serviceable life was considered during the analysis assuming the residual value to be same for each maintenance technique. The analysis period used may or may not be the multiple of service life of a treatment technique. If it is not the multiple of service life then at the end of the analysis period there will be remaining value from the service life which is called serviceable value. The salvage value for serviceable life depends upon the remaining life at the end of the analysis period.

Discount Rate

Discount rates typically vary from 1% to 8%.Two discount rates were used in our analysis, 3.0% and 6.0%.

Analysis Period

According to the technical bulletin on life cycle cost analysis in pavement design (14), the analysis period should be long enough to incorporate the true costs and should exceed the design life of the alternatives. An analysis period of 20 years was selected.

Inputs for LCCA

Based on above the information, the following inputs were used for the LCCA:

1) The analysis period was 20 years.
2) Each treatment was assumed to last for 8, 11, 14, 17 and 20 years
3) The discount rates were 3% and 6%
4) The initial pavement construction cost and minor maintenance cost was assumed to be same and therefore could be excluded from the analysis
5) The analysis was performed on a per centerline mile basis

Output and Analysis of Life Cycle Cost (LCC)

LCCA was used to determine which maintenance treatment is more economical and a sensitivity analysis was used to show the effect of service life and discount rate on NPV.

Like stated earlier, inclusions of shoulders and different cross sections and variable cost would affect results.

CHAPTER 4

PaLATE RESULTS AND ANALYSIS

PaLATE RESULTS AND COMPONENTS OF ENVIRONMENTAL RESULTS

PaLATE was used to determine the environmental effects and emissions of Cold-in-place recycling, two course overlay and mill and fill. The total of each environmental result is comprised of three components, materials production, materials transportation and process (equipment). Materials production involves refining crude oil to asphalt at the refinery, extracting aggregates from the quarry, production of RAP by milling and production of HMA at the HMA plant. Transportation involves hauling virgin aggregates and asphalt cement from the source to the HMA plant, hauling the HMA mix from the plant to the site, and hauling RAP. Process includes the construction procedure such as placing the mix, compacting the mix and recycling the existing pavement using recycling trains.

PaLATE quantifies twelve different factors responsible for environmental effects. They are energy consumption, water consumption, carbon dioxide emissions, nitrogen oxides emissions, PM_{10} emissions, sulfur dioxide emissions, carbon monoxide emissions, lead emissions, mercury emissions, RCRA hazardous waste generation, HTP (cancer) and HTP non –cancer. A summary of the environmental results obtained from PaLATE for each maintenance technique is presented in the tables 9-13 below.

TABLE 9 Summary of Environmental Results for MF

Environmental factor	Materials Production	Materials Transportation	Process	Total
Energy [MJ]	3,404,972	201,065	13,182	3,619,218
Water Consumption [kg]	1,108	23	1	1,132
CO_2 [Mg]	186	15	1	202
NO_x [kg]	1,245	801	36	2,082
PM_{10} [kg]	470	158	3	630
SO_2 [kg]	36,823	48	2	36,874
CO [kg]	692	67	8	767
Hg [g]	4.57	0.10	0.00	4.67
Pb [g]	219	5	0	223
RCRA Hazardous Waste Generated [kg]	45,918	978	0	46,897
Human Toxicity Potential (Cancer) (g)	730,545	4,310	0	734,854
Human Toxicity Potential (Non-cancer)(g)	378,982,282	5,287,683	0	384,269,965

TABLE 10 Summary of Environmental results for TCO

Environmental factor	Materials Production	Materials Transportation	Process	Total
Energy [MJ]	3,336,275	142,272	13,182	3,491,729
Water Consumption [kg]	1,108	24	1	1,133
CO_2 [Mg]	167	11	1	178
NO_x [kg]	992	567	36	1,595
PM_{10} [kg]	452	112	3	567
SO_2 [kg]	36,806	34	2	36,843
CO [kg]	638	47	8	693
Hg [g]	4.52	0.10	0.00	4.62
Pb [g]	217	5	0	221
RCRA Hazardous Waste Generated [kg]	45,423	1,025	0	46,449
Human Toxicity Potential (Cancer) (g)	730,545	3,050	0	733,594
Human Toxicity Potential (Non-cancer)(g)	378,982,282	3,741,526	0	382,723,808

TABLE 11 Summary of Environmental Results for TCO-NR

Environmental factor	Materials Production	Materials Transportation	Process	Total
Energy [MJ]	3,739,668	157,245	14,540	3,911,453
Water Consumption [kg]	1,236	27	1	1,264
CO_2 [Mg]	187	12	1	200
NO_x [kg]	1,101	626	40	1,768
PM_{10} [kg]	541	125	3	669
SO_2 [kg]	40,607	38	3	40,647
CO [kg]	711	52	9	772
Hg [g]	5.02	0.11	0.00	5.13
Pb [g]	241	5	0	247
RCRA Hazardous Waste Generated [kg]	50,502	1,133	0	51,636
Human Toxicity Potential (Cancer) (g)	811,654	3,371	0	815,024
Human Toxicity Potential (Non-cancer)(g)	460,936,194	4,135,286	0	465,071,479

TABLE 12 Summary of Environmental Results for CIPR*

Environmental factor	Materials Production	Materials Transportation	Process	Total
Energy [MJ]	3,020,074	79,847	91,031	3,190,952
Water Consumption [kg]	1,121	14	9	1,144
CO_2 [Mg]	160	6	7	173
NO_x [kg]	923	318	209	1,450
PM_{10} [kg]	298	63	15	376
SO_2 [kg]	18,790	19	14	18,823
CO [kg]	643	27	45	715
Hg [g]	4.67	0.06	0.00	4.73
Pb [g]	220	3	0	223
RCRA Hazardous Waste Generated [kg]	46,726	575	0	47,301
Human Toxicity Potential (Cancer) (g)	365,272	1,712	0	366,984
Human Toxicity Potential (Non-cancer)(g)	189,491,141	2,099,834	0	191,590,975

* includes 1.5 inch HMA overlay

TABLE 13 Summary of Environmental Results for CIPR-AS*

Environmental factor	Materials Production	Materials Transportation	Process	Total
Energy [MJ]	3,387,941	98,986	91,031	3,577,959
Water Consumption [kg]	1,248	17	9	1,274
CO_2 [Mg]	182	7	7	197
NO_x [kg]	1,022	394	209	1,626
PM_{10} [kg]	412	78	15	504
SO_2 [kg]	18,874	24	14	18,912
CO [kg]	717	33	45	795
Hg [g]	5.15	0.07	0.00	5.22
Pb [g]	245	3	0	248
RCRA Hazardous Waste Generated [kg]	51,640	713	0	52,353
Human Toxicity Potential (Cancer) (g)	374,530	2,122	0	376,652
Human Toxicity Potential (Non-cancer)(g)	306,365,831	2,603,176	0	308,969,007

* includes 1.5 inch HMA overlay

ENVIRONMENTAL EFFECTS

Environmental effects and emissions are divided into three categories for analysis. The first one is consumption which includes energy consumption and water consumption, the second one is green house gases which include carbon dioxide, nitrogen oxides and carbon monoxide, and the third one is other factors which includes emissions of all other factors. During material production, consumptions and emissions for mix production is negligible compared to aggregate and asphalt cement (AC) and emulsified asphalt cement (EAC) production. Production of AC and EAC make up the majority of material production outputs. Therefore, they are listed separately while discussing production.

Consumption

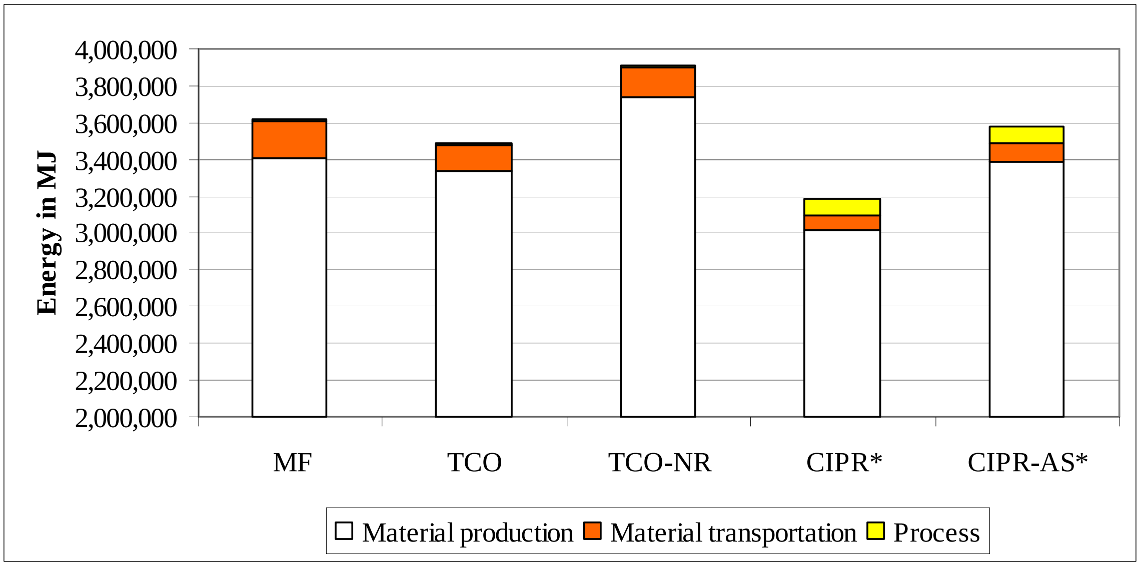
Energy consumption

Energy is consumed in each stage for each maintenance technique, the production of AC and EAC, aggregates and RAP and their transportation and construction. Table 14 summarizes the energy consumption for each technique including that for asphalt production. Figure 5 presents the results graphically.

TABLE 14 Energy Consumption During Each Maintenance Technique

	Energy Consumption in MJ				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	3,404,972	3,336,275	3,739,668	3,020,074	3,387,941
Transport.	201,065	142,272	157,245	79,847	98,986
Process.	13,182	13,182	14,540	91,031	91,031
Total	3,619,218	3,491,729	3,911,453	3,190,952	3,577,959
AC and EAC production	2,535,900	2,535,900	2,818,035	2,619,886	2,890,159
Mat. Prod as % of total	94	96	96	95	95
AC and EAC % of Material prod.	74	76	75	87	85

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 5 Energy consumption for different maintenance techniques.

As shown in table 14 and figure 5, most energy is consumed during the material production stage and the major portion is for AC and EAC production. Ninety four to 96 percent of total energy is consumed during production and out of that 74 to 87 percent is for AC and EAC production. Total energy consumption is the highest for TCO-NR followed by MF, TCO, CIPR-AS and CIPR. Energy consumption during transportation depends on the amount of material hauled and is highest for MF followed by TCO-NR ,TCO, CIPR AS and CIPR. Processing energy is higher for TCO-NR, followed by MF,CIPR-AS and CIPR. CIPR is the most energy efficient technique followed by TCO, MF, CIPR-AS and TCO-NR.

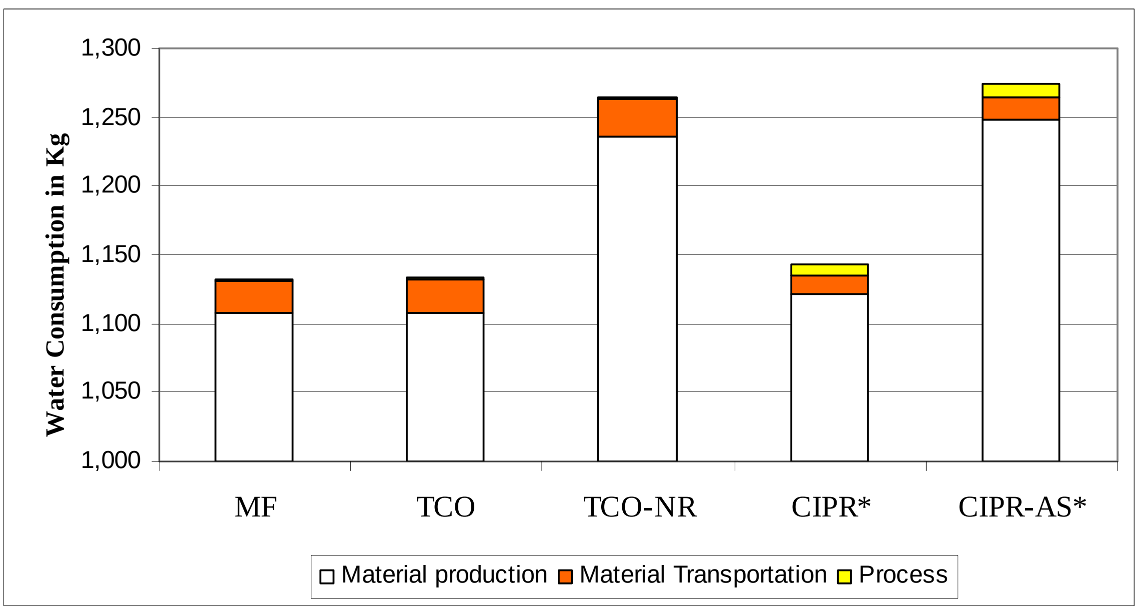
Water consumption

Water consumption is linked to the production of aggregates, AC and EAC, transportation of constituents and while paving and recycling. Table 15 and figure 6 summarize the water consumption during each maintenance technique and table 15 breaks down water consumption from production into consumption during AC and EAC production.

TABLE 15 Water Consumption for Maintenance Techniques

	Water Consumption in Kg				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	1,108	1,108	1,236	1,121	1,248
Transport.	23	24	27	14	17
Process.	1	1	1	9	9
Total	1,132	1,133	1,264	1,144	1,274
AC and EAC production	1,064	1,064	1,183	1,100	1,213
Mat. Prod as % of total	98	98	98	98	98
AC and EAC % of Material prod.	96	96	96	98	97

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 6 Water consumption for maintenance techniques.

From figure 6 and table 15 above, 98 percent of total water consumption is during materials production and 96-98 percent of the total water consumed during materials production is due to production of AC and EAC. Water consumption during transportation and process is negligible. MF and TCO consumes the least amount of water followed by CIPR, TCO-NR and CIPR-AS.

Green House Gases

Water vapor, carbon-dioxide, methane, ozone and chloroflorocarbons are the chief green houses gases. Carbon monoxide and nitrogen oxides are weak direct greenhouse gases but have very important indirect effects in global warming according to the green houses gases website (23). PaLATE determines emissions for 3 of these, carbon dioxide, carbon monoxide and nitrogen oxide,

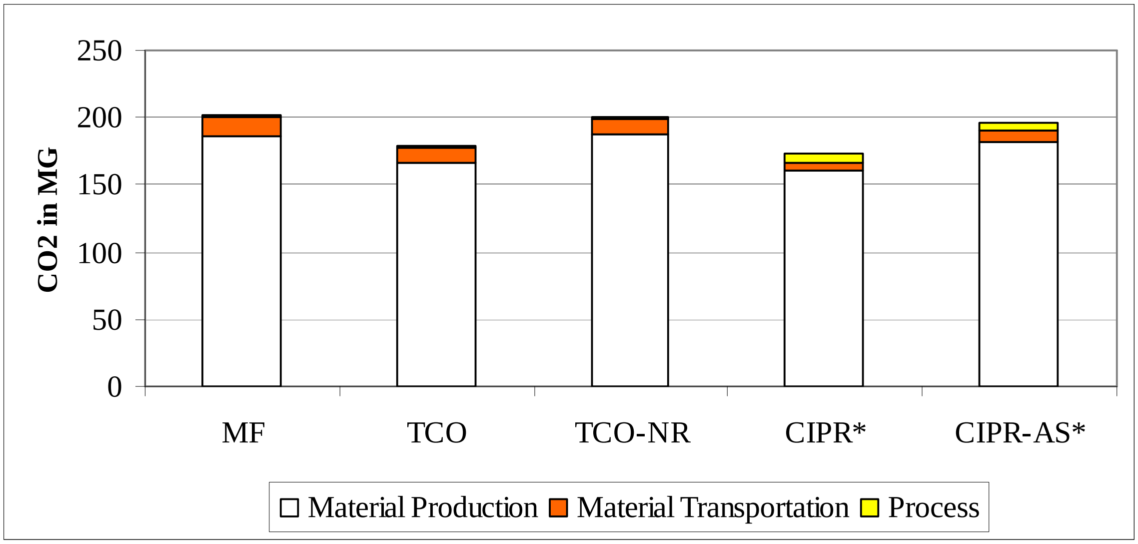
Cabon dioxide emission

CO_2 is produced during each phase, materials production, transportations and processes. Table 16 and figure 7 below summarize CO_2 production from each maintenance technique.

TABLE 16 Carbon-dioxide Production

	CO_2 production in MG				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	186	167	187	160	182
Transport.	15	11	12	6	7
Process.	1	1	1	7	7
Total	202	178	200	173	197
AC and EAC production	140	144	160	149	164
Mat. Prod as % of total	92	93	94	93	93
AC and EAC % of Material prod.	75	86	85	93	90

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 7 Carbon-dioxide emissions for maintenance techniques.

From table 16 and figure 7 it can be seen that 92 to 94 percent of total carbon dioxide emission is during materials production and 75 to 93 percent is due to the production of AC and EAC. Total carbon dioxide emissions are the highest for TCO-NR and lowest for CIPR. Production of CO_2 during transportation and process are less than 10% of total. Emissions during transportation are highest for MF, followed by TCO, CIPR-AS and CIPR. Emissions during process are higher for CIPR-AS and CIPR than that for MF, TCO and TCO-NR. CIPR is the best maintenance technique for prevention of carbon dioxide emission. followed by TCO, CIPR-AS, MF and TCO-NR.

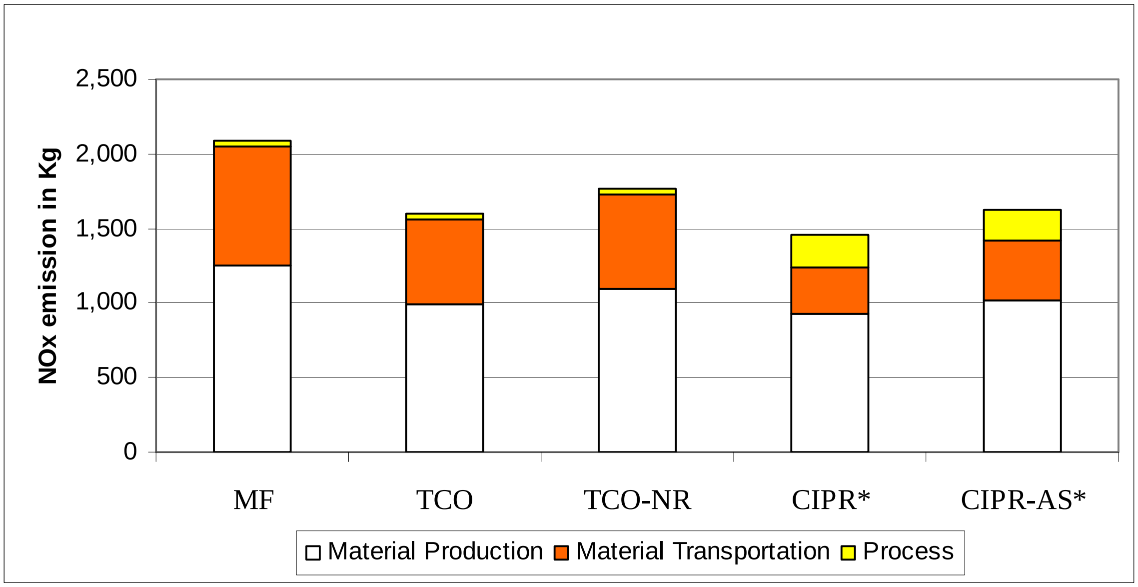
NO_x *emission*

Table 17 and figure 8 summarize the NO_x emissions during each construction stage for the maintenance technique evaluated. Like water, NO_x emissions are linked to production of AC and EAC, transportation of constituent materials and process.

TABLE 17 NOx Emissions for Maintence Techniques

	NOx emission in Kg				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	1,245	992	1,101	923	1,022
Transport.	801	567	626	318	394
Process.	36	36	40	209	209
Total	2,082	1,595	1,768	1,450	1,626
AC and EAC production	801	801	890	827	913
Mat. Prod as % of total	60	62	62	64	63
AC and EAC % of Material prod.	64	81	81	90	89

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 8 NOx Emissions for Maintenance Techniques.

Although the contribution of AC and EAC production is a major source of NOx emissions, NOx is not as high a percentage as the other outputs. Materials production accounts for 60 to 64 of total outputs and AC and EAC accounts for 64 to 81 percent of material production followed by TCO-NR , CIPR-AS, TCO and CIPR. NOx emissions due to process are the same for CIPR-AS and CIPR and is greater than that for MF, TCO and TCO-NR. CIPR produces the least total amount of NOx emissions followed by TCO, CIPR-AS, TCO-NR and MF.

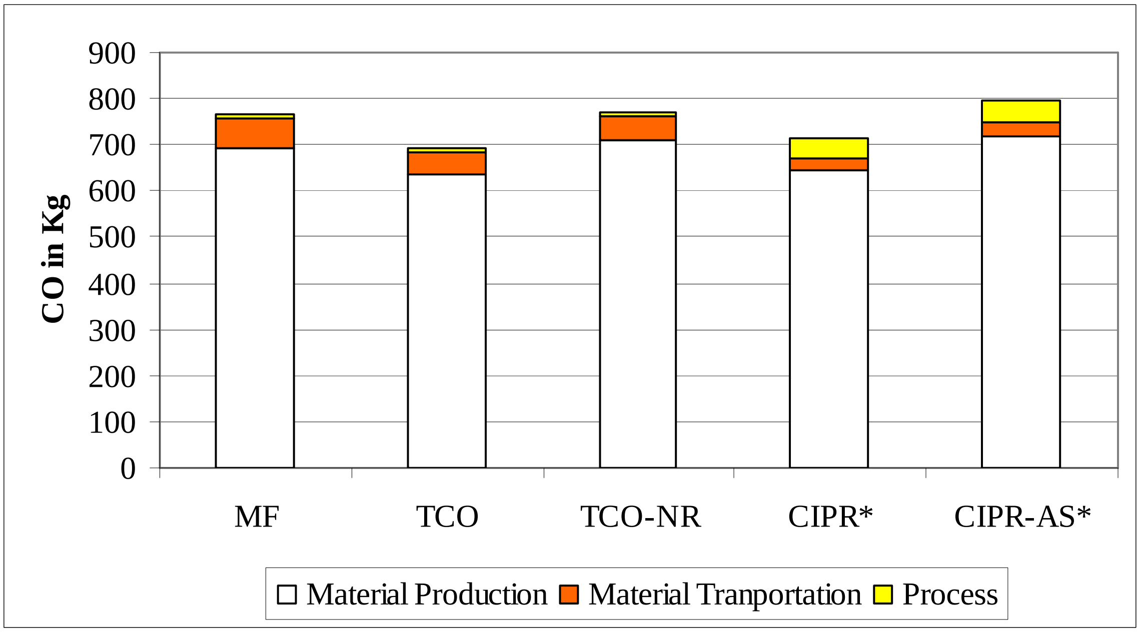
Carbon monoxide (CO) ***emissions***

The chief producer of carbon monoxide is the burning of fuel. Fuel is burnt during aggregate, AC and EAC production. Hauling, paving and milling equipment all burn fuel so carbon monoxide emissions are present during each phase and for each maintenance technique. The results are tabulated in table 18 and figure 9

TABLE 18 CO Emissions from Each Maintenance Technique

	CO in Kg				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	692	638	711	643	717
Transport.	67	47	52	27	33
Process.	8	8	9	45	45
Total	767	693	772	715	795
AC and EAC production	608	608	676	628	693
Mat. Prod as % of total	90	92	92	90	90
AC and EAC % of Material prod.	88	95	95	98	97

*includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 9 Carbon-monoxide emissions for maintenance techniques

Ninety to 92 percent of total CO emissions are due to material production. Out of that, about 88 to 98 percent is due to production of AC and EAC. Due to the milling involved in MF, CO emissions are more for MF than that for TCO. CIPR trains burn more fuel and process more material resulting in more process CO emissions for CIPR and CIPR-AS than that for the others. TCO produces the least amount of CO followed by CIPR, MF, TCO-NR and CIPR-AS.

Other Factors

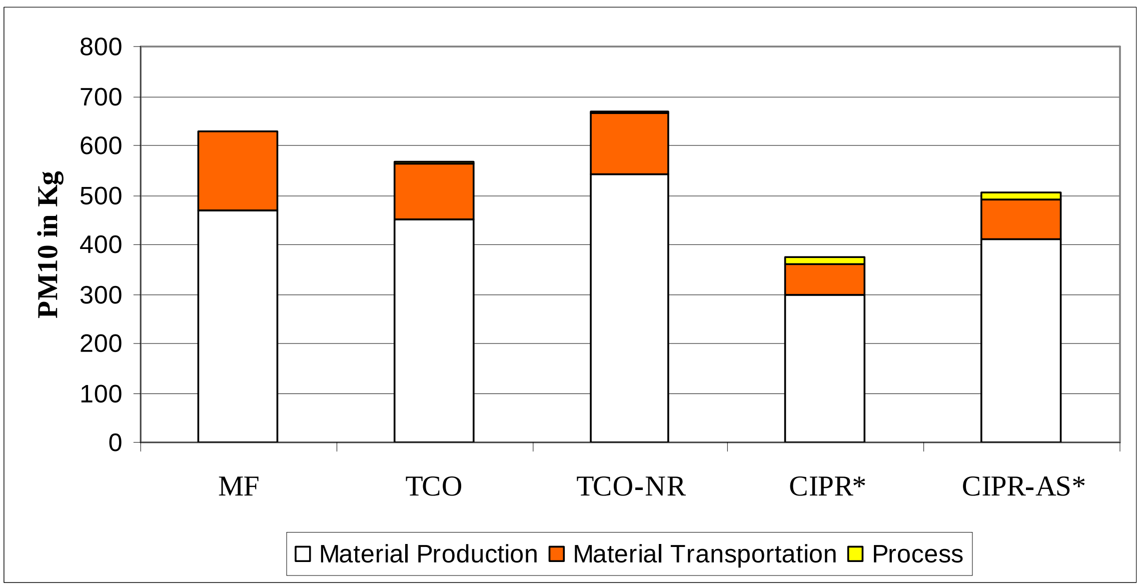
PM_{10} Production

Particulate matter less than ten microns are called $PM_{10.}$ Table 19 presents the emissions and figure 10 presents result graphically.

TABLE 19 PM_{10} Production for Each Maintenance Technique

PM10 in Kg	MF	TCO	TCO-NR	CIPR*	CIPR-AS*
Mat. Prod	470	452	541	298	412
Transport.	158	112	125	63	78
Process.	3	3	3	15	15
Total	630	567	669	376	504
AC and EAC production	136	136	150	140	155
Mat. Prod as % of total	75	80	81	79	82
AC and EAC % of Material prod.	29	30	28	47	38

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 10 PM_{10} production for maintenance techniques.

Particulate material less than ten micron are called PM_{10}. They are produced during each stage and each process. Most PM_{10} is produced during material production, 75 to 82 percent and 62-72 percent during material production is during production of aggregates rather than AC and EAC as with the other outputs. The contribution of material transportation is also significant, with TCO-NR producing the most PM_{10} followed by MF, TCO, CIPR AS and CIPR. Production of PM_{10} during process is minimal with CIPR and CIPR-AS producing more than MF, TCO and TCO-NR. TCO-NR produces the highest amount followed by MF, TCO, CIPR-AS and CIPR. Thus, CIPR is the best one regarding PM_{10} production.

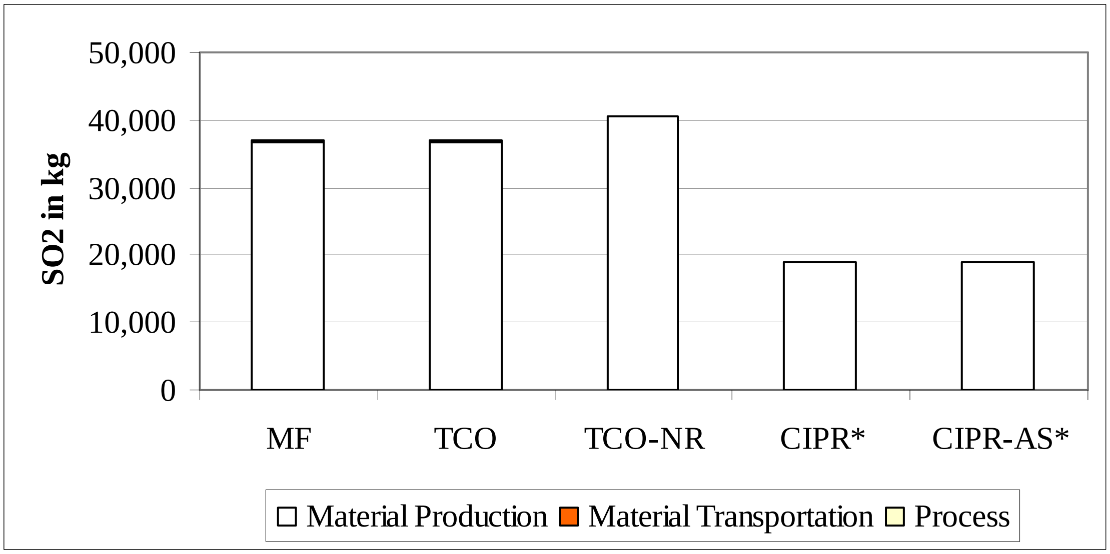
SO_2 emissions

SO_2 is produced during each phase; material production, transportation of constituent materials, RAP and HMA, and during each process. Table 20 summarizes SO_2 emissions and figure 11 presents the results graphically for each maintenance technique.

TABLE 20 Sulfur-dioxide Emissions for Maintenance Techniques

			SO_2 in Kg		
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	36,823	36,806	40,607	18,790	18,874
Transport.	48	34	38	19	24
Process.	2	2	3	14	14
Total	36,874	36,843	40,647	18,823	18,912
AC and EAC production	726	726	806	749	827
Mat. Prod as % of total	100	100	100	100	100
AC and EAC % of Material prod.	2	2	2	4	4

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 11 Sulfur-dioxide emissions of maintenance techniques.

SO_2 emissions during transportation and process are negligible compared to emission during material production. Production accounts for virtually all SO_2 emissions. Unlike other outputs, most SO_2 emissions are from the production of HMA in the HMA plant. SO_2 emissions are the highest for TCO-NR followed by MF, TCO, CIPR-AS and CIPR.

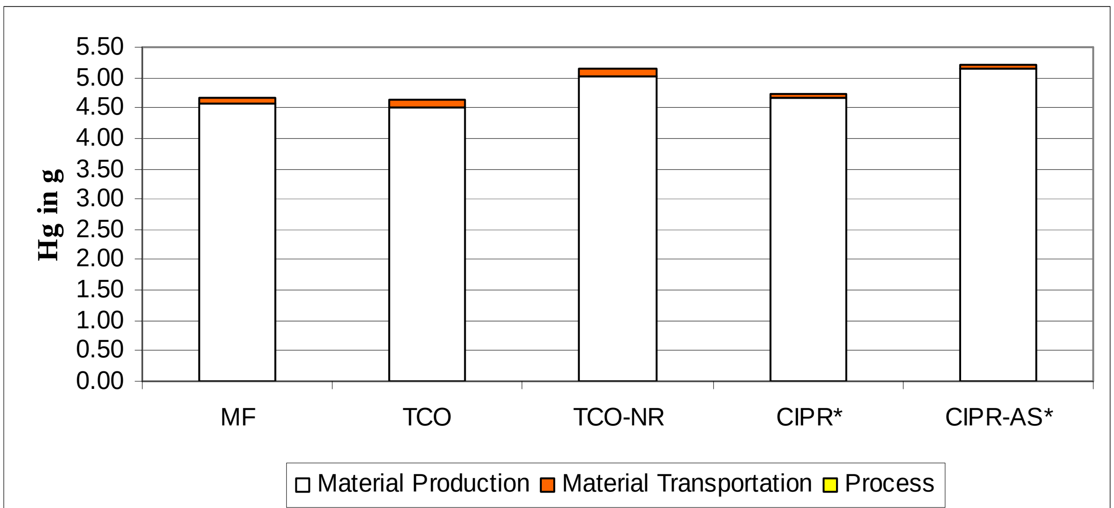
Hg Production

According to PaLATE, no Hg is produced during the material processing stage. A small amount is produced during transportation but it is negligible when compared to that which is produced during material production. The results are summarized in table 21 below and presented graphically in figure 12. From table 21 and figure 12 below, it is clear that almost all of the mercury production is due to AC and EAC production. Hg production is the highest for TCO-NR followed by CIPR-AS, CIPR, MF and TCO.

TABLE 21 Hg Production For Different Maintenance Techniques

	Hg in g				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	4.57	4.52	5.02	4.67	5.15
Transport.	0.10	0.10	0.11	0.06	0.07
Process.	0.00	0.00	0.00	0.00	0.00
Total	4.67	4.62	5.13	4.73	5.22
AC and EAC prod	4.52	4.52	5.00	4.41	4.89
Mat. Prod as % of total	98	98	98	99	99
AC and EAC % of Material prod.	99	100	100	94	95

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 12 Mercury production for maintenance techniques.

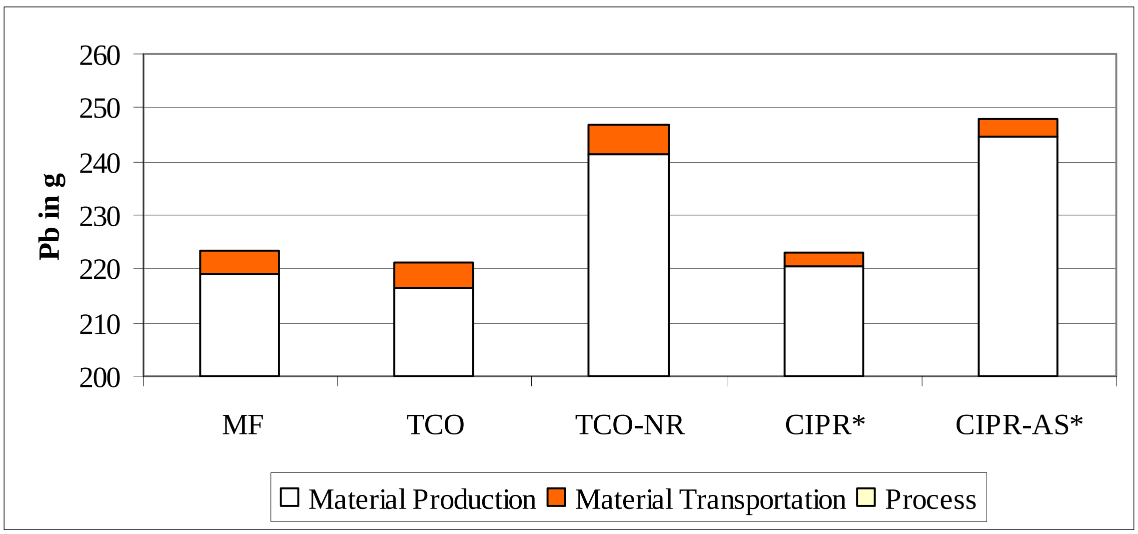
Pb Production

Like mercury, no lead is produced during the processing stage. Most of it is produced during AC and EAC production. Table 22 and figure 13 summarize the results. Material production accounts for 98 to 99 percent of total Pb production and during out of it 96 to 98 percent is due to AC and EAC production. Pb production is the highest for CIPR-AS, followed by TCO-NR, CIPR, MF and TCO.

TABLE 22 Lead Production for Maintenance Techniques

	Pb in g				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	219	217	241	220	245
Transport.	5	5	5	3	3
Process.	0	0	0	0	0
Total	223	221	247	223	248
AC and EAC production	210	210	234	217	239
Mat. Prod as % of total	98	98	98	99	99
AC and EAC % of Material prod.	96	97	97	98	98

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 13 Lead production for maintenance techniques.

RCRA hazardous waste generation

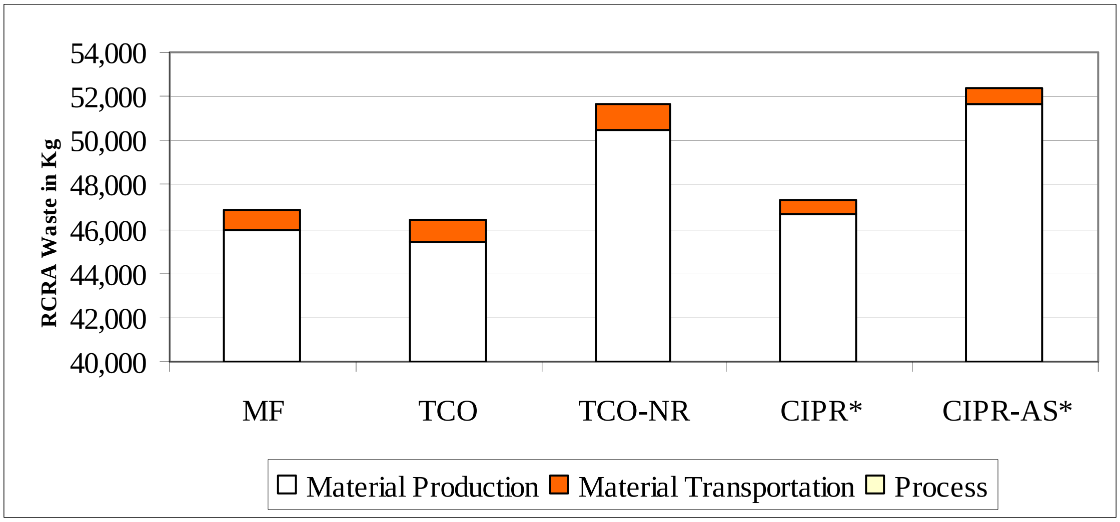
RCRA hazardous waste is generated during material production and transportation of constituent materials, RAP and HMA. Table 23 summarizes the RCRA Hazardous Waste production for each maintenance technique and figure 14 presents the results graphically. Almost all of the RCRA hazardous waste generation is due to AC and EAC production.

RCRA hazardous waste generation is the highest for CIPR-AS followed by TCO-NR, MF, TCO and CIPR.

TABLE 23 RCRA Hazardous Waste Generation for Maintenance Techniques

	RCRA Hazardous waste generated in Kg				
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	45,918	45,423	50,502	46,726	51,640
Transport.	978	1,025	1,133	575	713
Process.	0	0	0	0	0
Total	46,897	46,449	51,636	47,301	52,353
AC and EAC production	45,044	45,044	50,055	46,536	51,337
Mat. Prod as % of total	98	98	98	99	99
AC and EAC % of Material prod.	98	99	99	100	99

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 14 RCRA Hazardous waste for maintenance techniques.

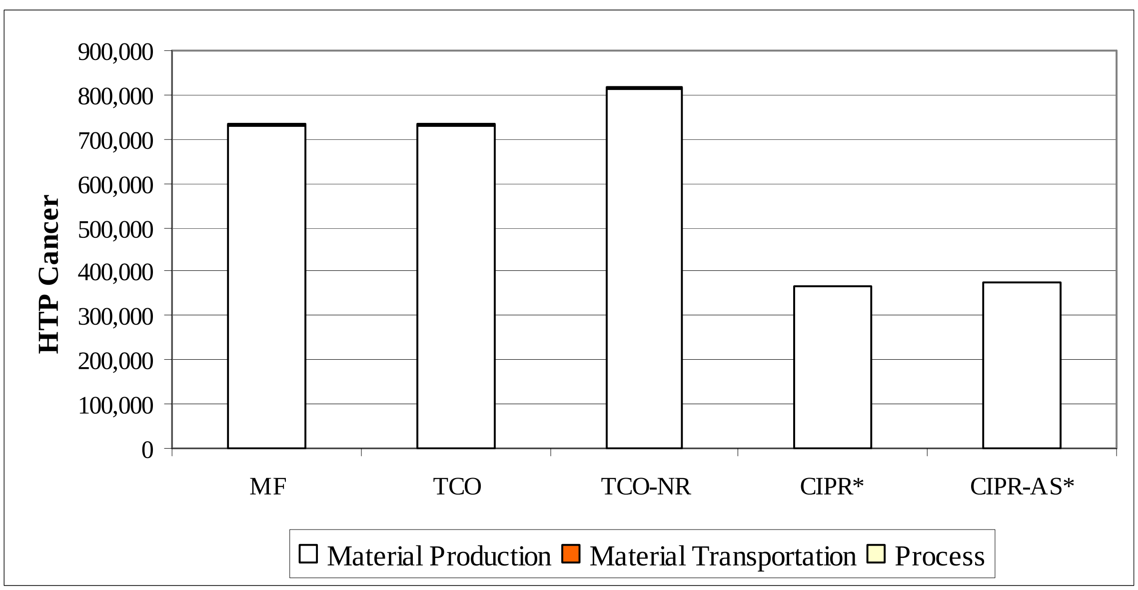
Human toxicity potential (Cancer)

Material production and transportation are responsible for cancerous toxicity potentiality. Table 24 below summarizes the HTP (cancer) for the different maintenance techniques and breaks down outputs for production during AC and EAC production. Figure 15 presents the results graphically.

TABLE 24 HTP (cancer) for Maintenance Techniques

Human Toxicity Potential (Cancer)					
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	730,545	730,545	811,654	365,272	374,530
Transport.	4,310	3,050	3,371	1,712	2,122
Process.	0	0	0	0	0
Total	734,854	733,594	815,024	366,984	376,652
AC and EAC production	697,559	697,559	775,167	348,779	348,779
Mat. Prod as % of total	99	100	100	100	99
AC and EAC % of Material prod.	95	95	96	95	93

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 15 HTP (cancer) for maintenance techniques.

Tables 24 and figure 15 above show that almost all of the HTP (cancer) is during the production stage and AC production accounts for 93-96 percent out of it. However, total HTP (cancer) is the highest for TCO-NR followed by MF, TCO, CIPR-AS and CIPR which is unusual. According to PaLATE, EAC production is not responsible for HTP (cancer).

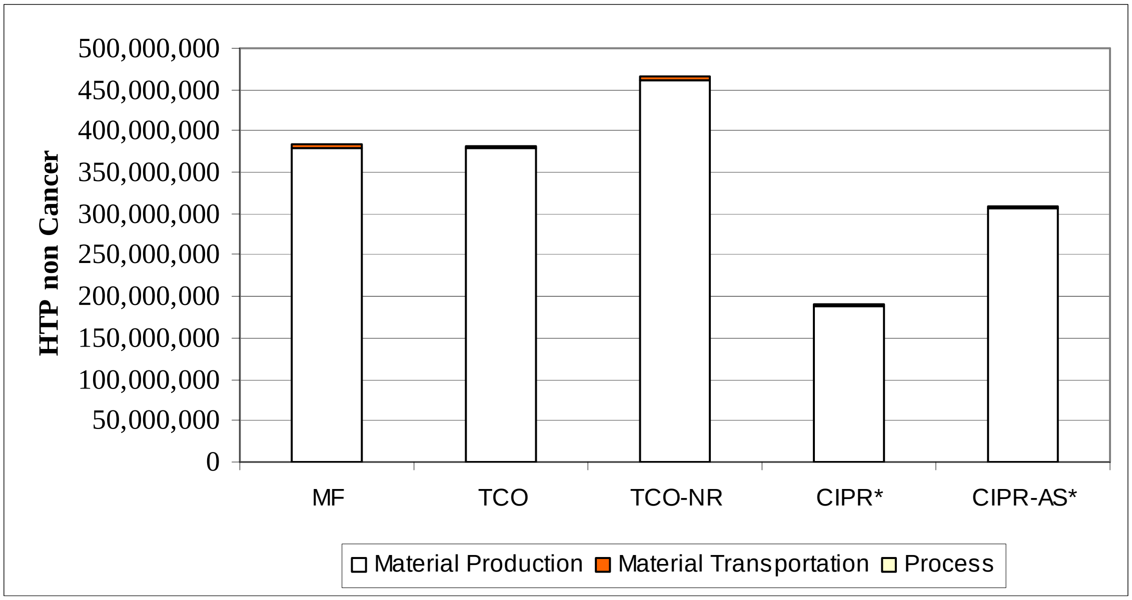
Human toxicity potential (non-Cancer)

Just like HTP (cancer), HTP (non-Cancer) is due to production and transportation of constituent materials, RAP and HMA. Table 25 summarizes the HTP (non-Cancer) for each maintenance technique and figure 16 presents the results graphically. Unlike HTP (cancer), PaLATE attributes almost all of the HTP (non-cancer) due to the production of new aggregate with a minor amount attributed to transportation. HTP (non-cancer) is the highest for TCO-NR followed by MF, TCO, CIPR-AS and CIPR.

TABLE 25 HTP (Non-Cancer) for Maintenance Techniques

Human Toxicity Potential (non-Cancer)					
	MF	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
Mat. Prod	378,982,282	378,982,282	460,936,194	189,491,141	306,365,831
Transport.	5,287,683	3,741,526	4,135,286	2,099,834	2,603,176
Process.	0	0	0	0	0
Total	384,269,965	382,723,808	465,071,479	191,590,975	308,969,007
AC and EAC production	288,783	288,783	320,912	144,391	134,715
Mat. Prod as % of total	99	99	99	99	99
AC and EAC % of Material prod.	0	0	0	0	0

* includes 1.5 inch HMA



* includes 1.5 inch HMA overlay

FIGURE 16 HTP (non-cancer) for maintenance techniques.

PaLATE RESULTS COMPARISION

Environmental effects are a function of materials consumed, transportation and construction processes. However, materials production accounts for most of the environmental effects . Haul distances and processing have very little contribution to total environmental effects. This is finding is supported by the figures in table 26 below.

TABLE 26 Contribution of Materials Production In Total Effects And Contribution AC and EAC Production In Material Production

Effect	Materials production as percentage of total	AC and EAC production as percentage of materials production
Energy consumption	94-96	74-87
Water consumption	98	96-98
Carbon dioxide	92-94	75-93
NOx	60-64	64-89
CO	90-92	88-98
PM_{10}	75-82	29-47
SO_2	100	2-4
Hg	80-100	80-100
Pb	98-99	96-98
RCRA Hazardous Waste Generated	98-99	98-100
HTP (Cancer)	99-100	93-96
HTP (Non-cancer)	99	0

As seen in table 26 above, except for NOx, PM_{10} and Hg, effects due to material production is more than 90 percent of total. Furthermore, AC and EAC production contribute more than 64 percent during the production stage except $PM_{10,}$ $SO_{2,}$ and HTP (non-cancer). Thus, according to PaLATE, the amount of AC and EAC used is the determining factor in the amount emissions and environmental suitability. PaLATE is a global model and it is not a site specific model. Emissions during AC and EAC production determine the environmental effects and PaLATE includes them in calculation of total emissions. The AC and EAC production facility could be miles away and emissions there may not be a concern for a site specific study. Because PaLATE is a global model, it does not exclude them. Thus, the amount of AC and EAC is the major factor and project locations and haul distances are minor factors in determining environmental effects.

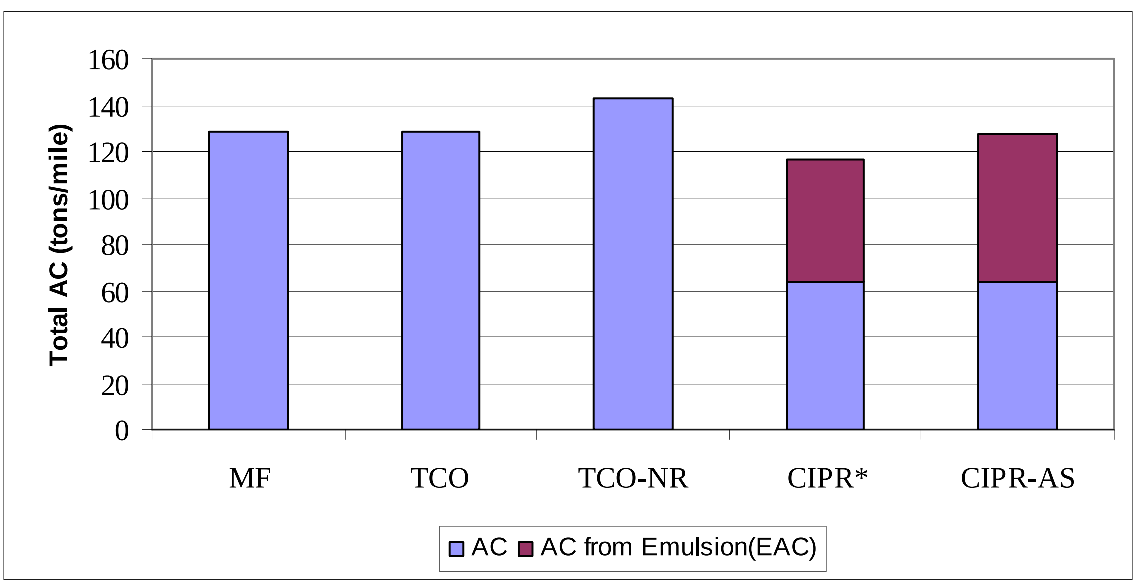
AC and EAC Production and Usage Trend

Materials production accounts for the majority of outputs in PaLATE and AC and EAC production accounts for most of it. Table 27 presents the amount of AC and EAC plus the amount of asphalt in the EAC used during each technique. For calculations in the table below, it has been assumed that asphalt emulsion contains two thirds of asphalt cement and one third of water. CIP.R and CIPR-AS contain 2.5% and 3% EAC respectively. Figure 17 presents the amounts used in each technique graphically.

TABLE 27 Asphalt Cement Usage For Maintenance Techniques

	Treatments				
Materials	**MF**	**TCO**	**TCO-NR**	**CIPR***	**CIPR-AS***
AC (tons/mile)	128.4	128.4	142.6	64.2	64.2
EAC (tons/mile)	-	-	-	79.2	95.0
AC and AC in EAC (tons/mile)	128.4	128.4	142.6	52.8	63.3
Total AC (tons/mile)	128.4	128.4	142.6	117.0	127.5

* includes 1.5 inch HMA overlay



* includes 1.5 inch HMA overlay

FIGURE 17 Amount of asphalt cement used for each maintenance technique.

From table 26 and figure 17, CIPR uses the least amount of total asphalt cement followed by CIPR-AS, MF and TCO, and TCO-NR. CIPR-AS consumes less than a ton of asphalt cement per mile consumed by MF and TCO.

Water consumption, SO_2 emissions and RCRA hazardous waste generation, HTP (cancer) and HTP (non-cancer) follow the AC usage trend in figure 17, meaning that the maintenance technique which uses the least amount of total AC has least environmental effect. For most environmental effects, CIPR has the least effect and TCO-NR has the most effect other techniques lying somewhere between them. Thus, it can be concluded that according to PaLATE, the amount of AC used in the technique determines the environmental effects.

RANKING MAINTENANCE TECHNIQUES BASED ON ENVIRONMENTAL EFFECTS

Due to the lack of sufficient data for statistical analysis, maintenance techniques have been ranked according to their effects using a subjective approach. Each effect was ranked from 1 to 5 based on total output with the one ranked 1 having less emissions of the environmental factors/effects and 5 the highest. If two techniques have same amount of emissions, they are assigned the same rank. The total score gives an indication of overall environmental impact. Ranking of maintenance techniques according to environmental effects has been tabulated in table 28.

TABLE 28 Ranking of Maintenance Techniques Based on Environmental Effects

Factors/Effects	MF	TCO	TCO-NR	CIPR	CIPR-AS
Energy consumption	3	2	5	1	4
Water consumption	1	1	3	2	4
CO_2	4	2	5	1	3
NOx	5	2	4	1	3
CO	3	1	4	2	5
PM_{10}	4	3	5	1	2
SO_2	4	3	5	1	2
Hg	2	1	5	3	4
Pb	2	1	3	2	4
RCRA Hazardous Waste Generated	2	1	4	3	5
HTP (Cancer)	4	3	5	1	2
HTP (Non-cancer)	4	3	5	1	2
Total	38	23	53	19	40
Overall Ranking	3	2	5	1	4

From table 28 it is clear that CIPR consumes less energy and emits the least amount of environmental effects. CIPR is followed by TCO, MF, CIPR-AS and TCO-NR. The rankings follow the general trend of AC usage shown in table 27 and figure 17. However, above ranking is a subjective one, giving equal weight to each factor.

CHAPTER 5

PCI RESULTS AND ANALYSIS

PCI RESULT

Field survey from New York, sent by the CIPR study team (X), were analyzed according to ASTM D 6433-07. The PCI was determined for each survey unit (sample unit) of each route then the average PCI for each route was calculated. After that, the average PCI for each maintenance technique was calculated. The results, by maintenance technique, are shown in table 29.

TABLE 29 Summary of PCI of Treatment Techniques

CIPR		**TCO**		**MF**	
RT	PCI	RT	PCI	RT	PCI
7	80.7	11.0	85.4	12.0	73.7
9	60.5	22.0	66.3	11.0	74.6
12	80.9	37.0	62.3	9L	72.4
23	43.2	126.0	90.9	3.0	68.4
26	72.1	197.0	60.2		
30	56.8	9N	72.0		
67	85.8	81.0	50.1		
342	78.0	86.0	48.5		
346	62.2				
349	62.4				
920V	53.8				
9N	75.8				
Avg.	67.7	Avg.	67.0	Avg.	72.3
Std. Dev	13.1	Std. Dev	15.3	Std. Dev	2.8

STATISTICAL ANALYSIS AND SIGNIFICANCE

ANOVA (Analysis of variance) was the statistical model used for statistical analysis. ANOVA provides a simple test whether or not means of several groups are all equal. It was used to determine whether there was a significant difference in the performance of the three maintenance techniques . Since the calculation of PCI was based on field data, a confidence level of 90% (alpha=0.1) was used. SAS was used to determine a statistical difference.

Below is the box plot obtained by SAS which depicts the mean value and the spread of the data (PCI) for each maintenance technique.

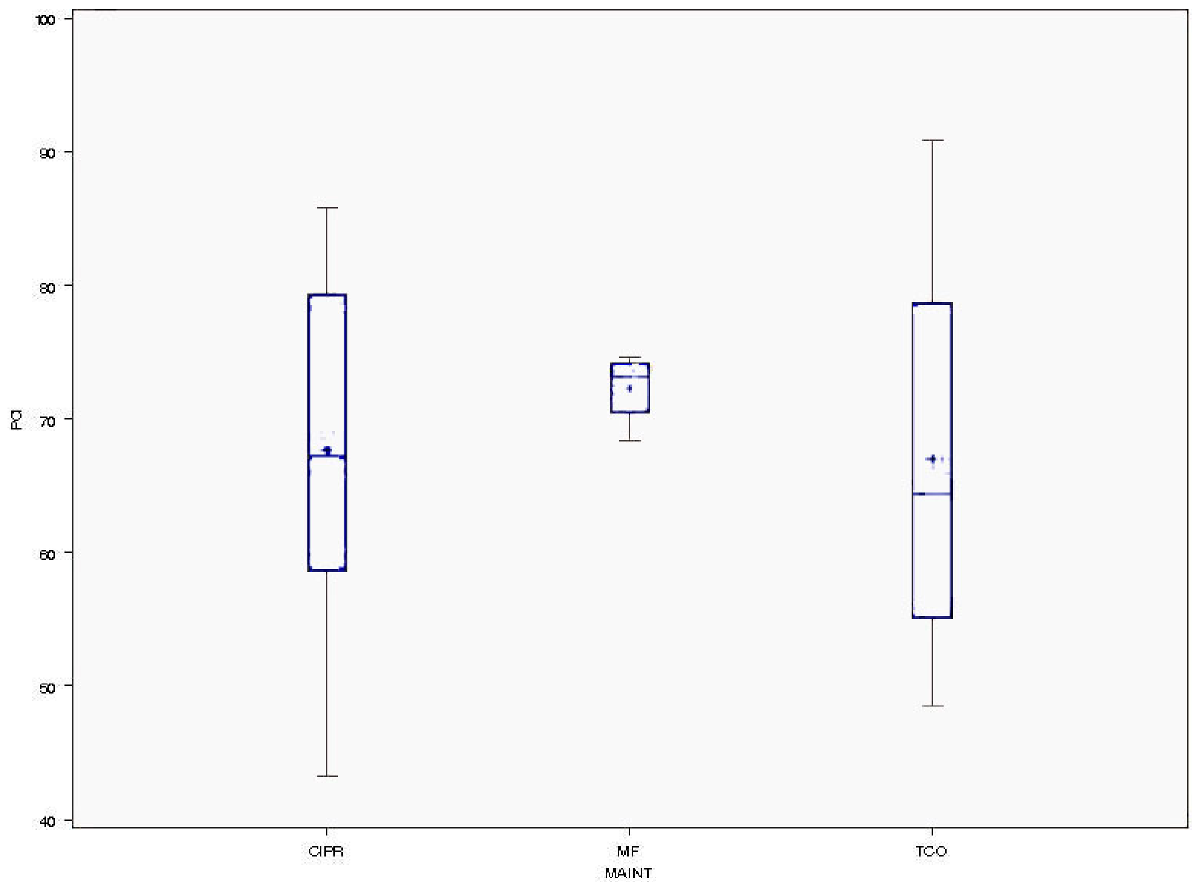


FIGURE 18 Box plot of PCI for maintenance techniques from SAS.

The figure above shows that the average PCI for CIPR, MF and TCO are 68, 72 and 67 respectively and that the standard deviation is the highest for TCO followed by CIPR and MF. From table 31 the p value (Pr), is greater than Alpha. Thus, there is no significant difference ($p>0.1$) between the three maintenance techniques.

Tables 30 below summarize the outputs of the ANOVA by SAS.

TABLE 30 Calculation of F Value and P Value

Sources	DF	Sum of squares	Mean square	F value	Pr>F
Model	2	87.875	40.938	0.24	0.7865
Error	21	3538.263	168.489		

CHAPTER 6

LIFE CYCLE COST RESULTS AND ANALYSIS

LIFE CYCLE COST RESULTS

Life cycle cost analysis was performed for the treatments by using typical maintenance costs and by varying the service lives because the average service lives was unknown. Discount rates used were 3% and 6%. Each pavement was assumed to be 1 mile long and 24 feet wide. Shoulders were excluded from the analysis and the pavement cross-section is dependent on the type of treatment, as discussed in previous chapters.

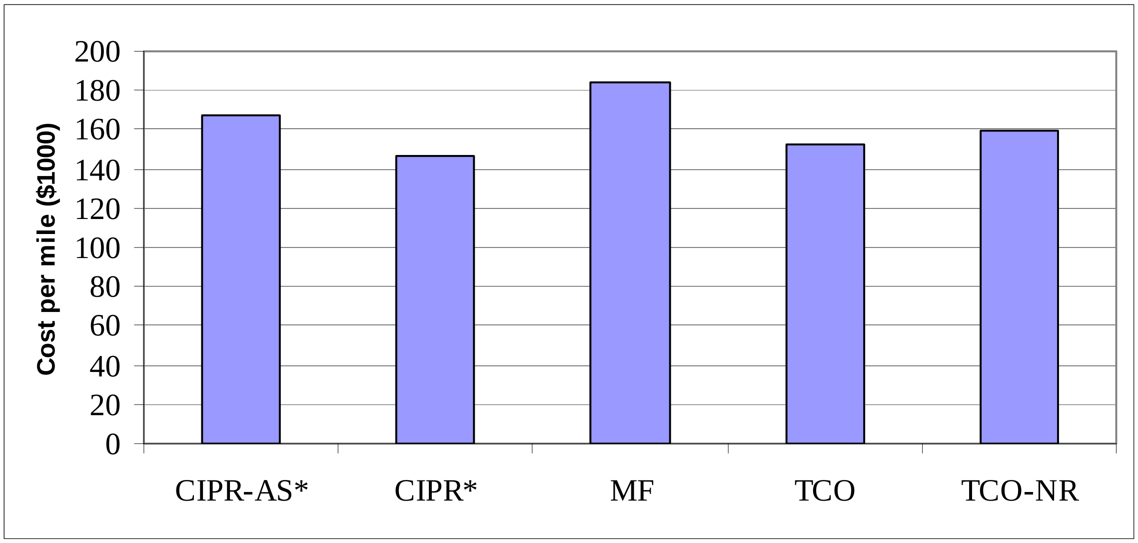
Initial Cost

Initial maintenance cost is a component of agency cost. Initial costs vary for different maintenance techniques due to amount of aggregates, RAP and asphalt cement used and the construction process involved. Table 31 summarizes the initial cost of each maintenance technique. The results are presented graphically in figure 19.

TABLE 31 Initial Cost of Maintenance Techniques

Treatment	Cost per mile ($1000)
CIPR-AS*	166.85
CIPR*	146.57
MF	183.74
TCO	152.06
TCO-NR	159.19

* includes 1.5" HMA overlay



* includes 1.5” HMA overlay

FIGURE 19 Initial construction cost for single time application of maintenance. techniques.

The initial cost is the lowest for CIPR followed by TCO, TCO-NR, CIPR-AS and MF. Further analysis was performed to see the effects of service life and discount rate on NPV of the different maintenance techniques.

LCCA

A sensitivity analysis was performed by varying the treatment life and discount rate because CIPR life was shown to vary from 4 to 30 years (22) and lives of MF and TCO were unknown and would be expected to vary as well. Discount rates are not constant with time either, therefore 3% and 6% discount rate was used. Each maintenance technique was assumed to last for 8 to 20 years in 3 years increments. The analysis was performed to see how long another treatment should last to have the same net present value. The results are presented in table 32 and 33 below for a 3% and 6% discount rate, respectively.

TABLE 32 Sensitivity Analysis For 3% Discount and 20 Year Analysis Period

Treatment life (yrs)	Net Present Value($1000)				
	CIPR-AS*	CIPR*	MF	TCO	TCO-NR
8	356.35	313.04	392.42	324.76	339.99
11	270.59	237.70	297.98	246.60	258.17
14	224.37	197.10	247.08	204.48	214.07
17	191.72	168.42	211.13	174.72	182.92
20	166.85	146.57	183.74	152.06	159.19

* includes1.5" HMA overlay

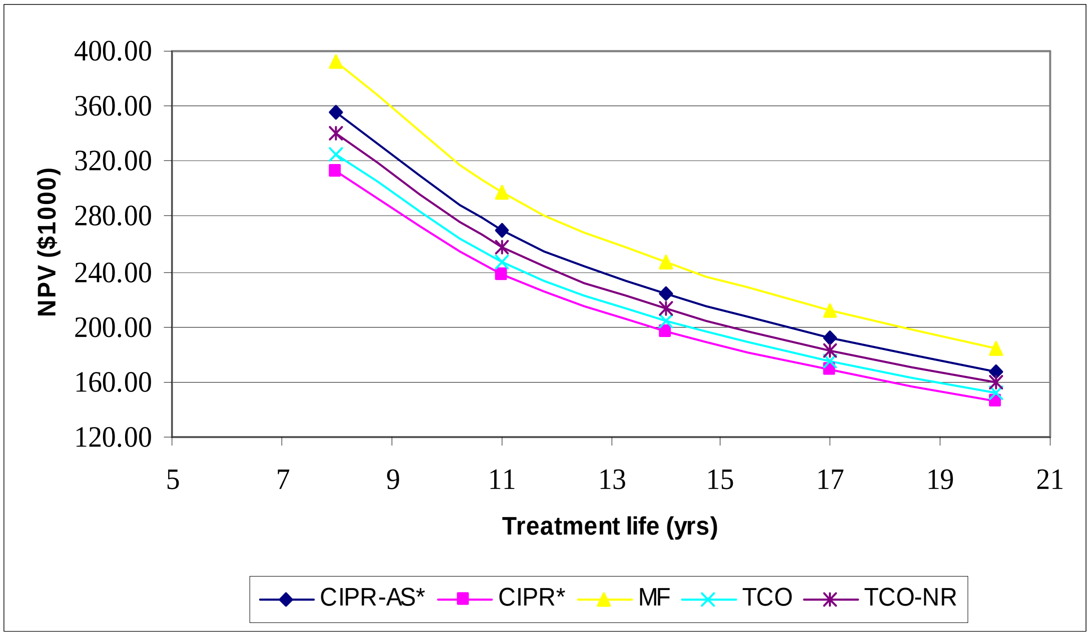
TABLE 33 Sensitivity Analysis For 6% Discount and 20 Year Analysis Period

Treatment life (yrs)	Net Present Value($1000)				
	CIPR-AS*	CIPR*	MF	TCO	TCO-NR
8	311.20	273.38	342.70	283.62	296.91
11	245.29	215.47	270.12	223.54	234.02
14	210.92	185.28	232.17	192.22	201.24
17	185.97	163.36	204.79	169.48	177.43
20	166.85	146.57	183.74	152.06	159.19

* includes 1.5" HMA overlay

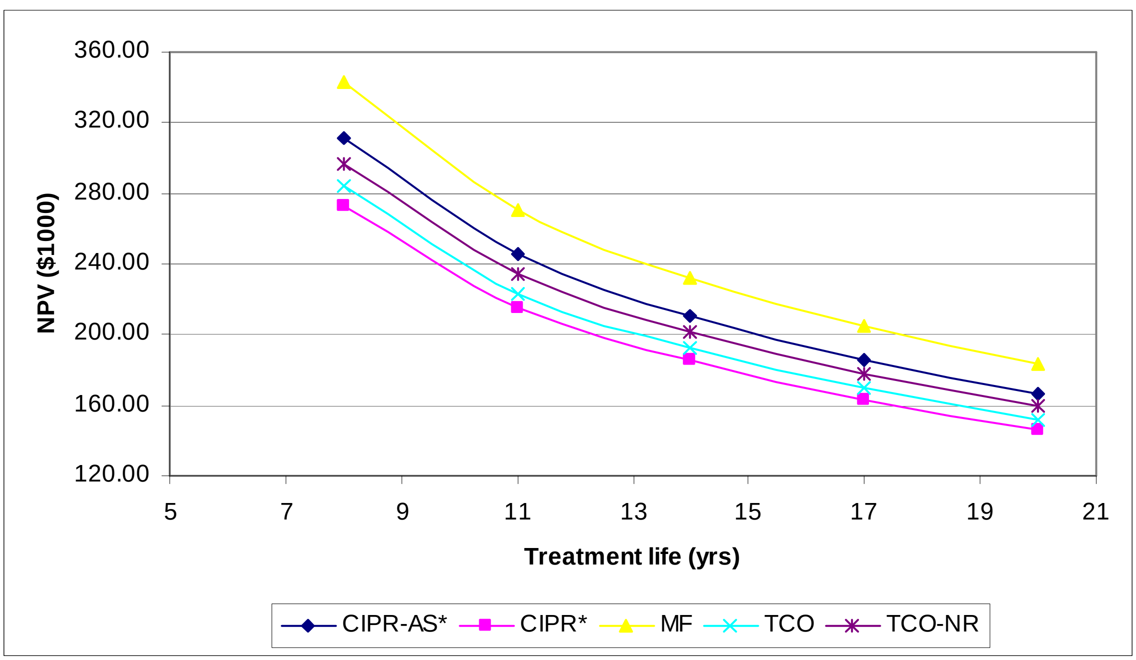
If each treatment lasts the same number of years, then the trend follows the initial cost trend. CIPR has the lowest NPV followed by TCO, TCO-NR, CIPR-AS and MF, regardless of discount rate.

Figures 20 and 21 show the variation in NPV with treatment life for the maintenance techniques evaluated. Fig. 20 is for a discount rate of 3% and fig. 21 is for a discount rate of 6%. From these figures one can determine the number of years for which a particular maintenance technique should last in order to have the same NPV as the others. For example, let us take CIPR as reference because its life is known but the service lives of other techniques are estimated.



* includes 1.5” HMA overlay

FIGURE 20 Sensitivity analysis curves for 3% discount and 20 years analysis.



* includes 1.5” HMA overlay

FIGURE 21 Sensitivity analysis curves for 6% discount and 20 years analysis.

The service life of CIPR is 11 years (22). At 3% and 6% discount rate the NPV is $237,700 and $215,470 respectively. Using the NPV for CIPR above, one can enter the graph and determine the required treatment life for each option to have the same NPV. Table 59 shows how long each technique must last to have the same NPV as CIPR with an 11 year service life.

TABLE 34 Treatment Life Required To Have Same NPV As of Year CIPR

Treatment	3% discount	6% discount
CIPR-AS*	13.0 yrs	13.5 yrs
MF	14.7 yrs	15.7 yrs
TCO	11.5 yrs	11.7 yrs
TCO-NR	12.3 yrs	12.6 yrs

* includes 1.5” HMA overlay

Table 34 shows that for 3% discount rate CIPR-AS, MF, TCO and TCO-NR should have the service life of 13, 14.7, 11.5 and 12.3 years respectively to have the same NPV as CIPR lasting 11 years. Similarly for 6% discount rate they should last for 13.5, 15.7, 11.7 and 12.6 years to have same NPV as CIPR lasting 11 years. Furthermore, it can be seen from the table that if the discount rate is increased, the service life of the maintenance techniques must increase to have the same NPV as CIPR.

CHAPTER 7

CONCLUSIONS AND RECOMMEDDATIONS

CONCLUSIONS

Based on the results obtained for the pavement sections analyzed, the following conclusions are warranted.

PaLATE

1. Based on the subjective rankings of the environmental effects, CIPR has the least environmental impact followed by TCO, MF, CIPR-AS and TCO-NR.
2. CIPR emits the least amount of green house gases followed by TCO, CIPR-AS, MF, and TCO-NR.
3. Energy consumption is the least for CIPR followed by TCO, MF, CIPR-AS and TCO- NR
4. The amount of AC and EAC had a major impact on environmental outputs.
5. The use of add-stone in CIPR had an adverse effect on environmental effects. Add-stone resulted in use of more aggregates and more AC which increased emissions and consumptions above those of TCO.
6. The use of RAP had positive effects on environmental outputs. TCO with RAP is ranked second in terms of environmental impact but if no RAP is used it is ranked last among all the maintenance techniques.

PCI

1. There was no statistical significance on the performance of the maintenance techniques.

LCCA

1. Based on data maintenance technique with least initial cost has least life cycle cost and vice versa.
2. The use of add-stone to CIPR had an adverse effect on LCC. When add-stone is not added CIPR has the lowest initial cost.
3. Use of RAP had positive effect on TCO as it reduced the initial cost LCC.
4. MF is the costliest maintenance technique and would require the longest service life to have an equivalent LCA.

RECOMMENDATIONS

Based on the limits of study and data analyzed, following recommendations are made.

1. The use of add-stone with CIPR had an adverse effect on environmental impacts and LCCA , further studies are needed to evaluate benefits of its use.
2. The use of RAP in TCO had positive impacts on environmental effects and LCCA. Thus, use of RAP is beneficial.
3. At the significance level used in the analysis there was no significant difference in the performance of maintenance techniques. Therefore, the decision of which maintenance technique to use should be based on environmental effects and cost.

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APPENDIX A

PAVEMENT DISTRESS

Nineteen pavement distresses enlisted in ASTM D 6433-07 are described below along with their causes and the problems they create.

Fatigue cracking / Alligator cracking

Alligator cracking is series of interconnecting cracks which resembles the pattern of the back of an alligator/crocodile. It is a load associated distress and is caused by the fatigue failure of the asphalt pavement under repeated loading and is usually bottom up cracking. The causes for this distress are inadequate structural support, poor construction, heavy loads and stripping on bottom layer. The problems that arise due to this distress are structural failure, moisture infiltration from cracks, roughness and development of potholes. Repair strategy is removal and replacement. (5, 8, 18)

Bleeding

Bleeding is a film of asphalt binder on the surface which creates shiny, glass like reflecting surface. The surface is sticky. The causes of bleeding are excessive asphalt binder during design or construction from low voids total mix (VTM) or excessive asphalt binder from bituminous surface treatments. Due to the excess asphalt aggregate texture cannot be seen. Problems that arise due to bleeding are slipping of tires and sticky surface during hot weather. Repair strategy for minor bleeding is by applying blotter sand and removal for major bleeding using grader or heater planer. (5, 8, 18)

Block Cracking

Block cracks are interconnected cracks that divide the pavement into rectangular pieces of size approximately 1ft by 1ft to 10ft by 10 ft. They are not load associated. The cause of block cracking is shrinkage of HMA due to daily temperature cycle because of asphalt binder aging or poor choice of asphalt binder in mix design. Problems that arise due to block cracking are moisture infiltration and roughness. Repair strategy for low severity cracks, less than 0.5 inch wide, is crack sealing and for high severity cracks, more than 0.5 inch wide, by removal and replacement with HMA overlay. (5, 8, 18)

Bumps and Sags

Bumps and sags occur due to small, localized upward displacement of the pavement surface. Causes for these are buckling and bulging of underlying concrete cement slabs frost heave, infiltration of water causing different subgrade movement. Bumps and sags cause roughness and poor ride quality. Repair is by removal and replacement for minor areas and overlay for severe areas. (5, 8, 18)

Corrugations

Corrugations are characterized by formation of ridges and valleys perpendicular to the flow of traffic. Corrugations are plastic movement of the HMA due to shear loads. Corrugations are also called wash boarding and they cause roughness. Causes are traffic starting and stopping on unstable HMA layers, excessive moisture in the subgrade. Small corrugations are repaired by removing and patching and large corrugation damage repaired by removal and overlay. (5, 8, 18)

Depressions

Depressions are localized pavement surface areas with elevation slightly lower than those of the surrounding pavement. Depressions can be noticed by localized ponding of water. The causes for depressions are frost heave, subgrade settlement, and poor construction. Depressions cause roughness and vehicle hydroplaning. Repairs for depressions caused by subgrade consist of distress patching after removal and replacement of the poor subgrade. (5, 8, 18)

Edge Cracking

Edge cracks are parallel to the outer edge of the pavement and are within 1 to 1.5 ft of the outer edge. The causes for edge cracking are frost weakened base, weakened subbase and lack of edge support. They are increased further by traffic load. They cause moisture infiltration. Repair can be done by crack sealing for minor ones and subgrade or base removal and replacement followed by overlay for major ones. (5, 8,18)

Reflection Cracking at Joints

Reflection cracks at joints occur on asphalt pavement surfaces which are laid over concrete slabs. They are not load associated distress. They are caused by movement of concrete slabs due to thermal and moisture variations. Reflection cracking resulting from cracks in underlying joint from any other type of base is different from joint reflection cracking. Problems that arise due to it are moisture infiltration and roughness. Repair consists of crack sealing for low severity cracks, less than 0.5 inch, and removal and replacement with an overlay for high severity crack or by seating the underlying concrete slabs. (5, 8, 18)

Lane-shoulder drop-off

Lane Shoulder drop-off is a difference in elevation between the pavement edge and shoulder. The causes for this distress are shoulder settlement as a result of pavement material differences, shoulder erosion and settlement, and building without adjusting the shoulder level. Lane shoulder dropoff results in an abrupt change elevation causing discomfort. Repair consists of adequate compaction and quality control of shoulder material and paving shoulder after rectifying drop off. (5, 8, 18)

Longitudinal Cracking

Longitudinal cracking are cracks that are mainly parallel to the centerline or lay-down direction of the pavement. Causes are poor joint construction and reflective cracking from an underlying layer which reflects up on the top layer. Top down fatigue cracking in wheelpaths first appear as longitudinal cracking. Problems caused are moisture infiltration roughness and it triggers alligator cracking and structural failure. Low severity cracks less than 0.5”, can be repaired by crack sealing and high severity crack, more than 0.5” wide, can be repaired by removal and replacement with overlay. (5, 8, 18)

Transverse Cracking

Transverse cracks are non load associated thermal cracks which extend approximately perpendicular to the lay-down direction or centerline of the pavement. Causes are shrinkage due to low temperature and binder hardening and reflective cracking. They cause moisture infiltration and roughness.. Repairs can be done in the same way as longitudinal cracking. (5, 8, 18)

Patching

Patches are areas of pavement that have been removed and replaced with new material for maintenance after original construction. Causes of patches are replacement of deteriorated pavement by patching and utility cuts. Patches cause roughness. Repair is done by overlay. (5, 8, 18)

Polished aggregates

When the aggregates extending above asphalt are negligible or there are no rough or angular aggregate particles and the surface aggregates are smooth to touch, the distress is considered polished aggregates. The causes are repeated traffic application, studded tires and aggregates susceptible to abrasion. Decreased skid resistance is caused by it. Repair can be done by application of skid resistance slurry seal, bituminous surface treatment, or HMA overlay. (5, 8, 18)

Potholes

Potholes are small bowl shaped depressions having minimum plan diameter of 150mm with sharp edges and vertical sides near the top of the hole. The causes for potholes are severe alligator cracking which cause dislodgement and piping (a phenomenon in which fine particles in layers underlying the top layer are washed away by flowing water). Potholes cause roughness, moisture infiltration and ponding of water. They are repaired by patching. (5, 8, 18)

Rutting

Depression in wheel paths is rutting. Shearing may occur along the sides of the rut. Lateral movement due to traffic loading, insufficient compaction, subgrade rutting, improper mix design can cause rutting. Problems caused by it are vehicle steering problems and hydroplaning. Rutting can occur in the HMA mix or the other layers. Repair is by leveling and overlaying for mix rutting and subgrade improvement for subgrade rutting. Severe subgrade rutting usually requires reconstruction.
(5, 8, 18)

Shoving

Shoving occurs when applied forces exceed the shear strength of HMA layer. It is longitudinal displacement of a small area of pavement. Causes are braking and accelerating of vehicles, shear flow of mixture or slippage between layers. Shoving causes roughness and ponding of water. Repair is by repair and replacement. (5, 8, 18)

Slippage cracking

Slippage cracks are half moon or crescent shaped cracks which are transverse to the direction of travel with the two ends pointed into the direction of travel. Contributing factors are braking and turning forces and poor bond between the pavement layers. Slippage cracks allow moisture infiltration and causes roughness. Repair is by removal and replacement of affected area. (5, 8, 18)

Swell

Gradual upward wave bulging for a length of more than 10 ft in length is termed swell. Causes are swelling of soil and frost action. There are roughness and resulting cracks which cause moisture infiltration. Swells are repaired by subgrade stabilization. (5, 8, 18)

Raveling/weathering

Due to loss of binder, aggregate particles are dislodged which is termed weathering and raveling. It is a top-down distress and is indicative of hardened binder or poor quality mix.

Causes are dust coatings on aggregate particles, segregation of aggregate and inadequate compaction. Raveling/weathering cause roughness, loss of materials, water ponding and loss of skid resistance. Small localized raveling is repaired by removal and patching and large are removed and overlaid. (5, 8, 18)

APPENDIX B

Results of PCI for CIPR Routes

The PCI calculated for each sample unit of each CIPR route is shown in tables B1, B2 and B3.

TABLE B1 PCI of CIPR Route 9N

CIPR RT 9N											
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	86	11	71	19	82	27	58	35	81	43	78
2	76	12	71	20	76	28	71	36	84	44	80
3	69	13	69	21	74	29	81	37	92	45	79
4	72	14	76	22	73	30	78	38	74	46	80
5	82	15	75	23	75	31	77	39	75	47	82
6	85	16	78	24	80	32	71	40	42	48	80
7	73	17	74.5	25	74	33	76	41	83	49	80
8	78	18	59	26	70	34	81	42	77	50	90
9	71										
10	68										
Avg.75.25											

TABLE B2 PCI of Different CIPR Routes

CIPR											
Route 23		Route 26		Route 9		Route 7		Route 12		Route 349	
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	45	1	41	1	45		89	1	77	1	59
2	37	2	93.5	2	57	2	79	2	76	2	80
3	57	3	66	3	49	3	85	3	69	3	72
4	34	4	48	4	42	4	82	4	81	4	32
5	25	5	51	5	65	5	76	5	74.5	5	35
6	35.6	6	34	6	63	6	83	6	85	6	71
7	16	7	43	7	70	7	82	7	75	7	67
8	41.5	8	86	8	59	8	81	8	87	8	73
9	36	9	69	9	70	9	81.5	9	83	9	67
10	53	10	80	10	70	10	83.5	10	89	10	78
11	32	11	87	11	70	11	67	11	82.5	11	67
12	64	12	78	12	66	12	80.5	12	90	12	50
13	35	13	63	13	60	13	75	13	82	13	51
14	59.8	14	92	14	40	14	88.5	14	82	14	71
15	84.5	15	89	15	66	15	72				
16	40	16	80	16	41	16	82				
17	58	17	70	17	62	17	78				
18	15	18	79	18	73	18	87.5				
19	48	19	89.5	19	65	19	81				
20	27	20	92	20	72	20	80				
21	40	21	93	21	66						
22	38	22	78								
23	54	23	57								
24	52	24	63								
25	52	25	80								
Avg.	43.2		72.1		60.5		80.7		80.9		62.4

TABLE B3 PCI of Different CIPR Routes

CIPR									
Route 67		Route 346		Route 30		Route 920V		Route 342	
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	88	1	87	1	63	1	76	1	82
2	100	2	82	2	33	2	32	2	90
3	55	3	90	3	45	3	47	3	82
4	97.5	4	57	4	28	4	61	4	71
5	88	5	60	5	65	5	21	5	73
6	47	6	42	6	50	6	77	6	70
7	93	7	60	7	76	7	38		
8	92	8	44	8	70	8	69		
9	96.5	9	57	9	68	9	62		
10	98.5	10	90	10	73	10	55		
11	81	11	45	11	54				
12	93.5	12	32						
Avg.	85.8	Avg.	62.2	Avg.	56.8	Avg.	53.8	Avg.	78.0

Results of PCI for TCO Routes

The PCI calculated for each sample unit of each TCO route was done is shown in tables B4 and B5.

TABLE B4 PCI of Different TCO Routes

TCO					
Route 22		Route 81		Route 86	
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	78	1	63	1	44
2	100	2	17	2	66
3	54.5	3	56	3	42
4	54	4	28	4	43
5	70	5	70	5	45
6	67	6	57	6	71
7	68	7	74	7	40
8	63	8	67	8	37
9	48	9	66		
10	38	10	40		
11	66	11	13		
12	87				
13	68				
Avg:	66.27	Avg:	50.09	Avg:	48.5

TABLE B5 PCI of Different TCO Routes

TCO									
Route 11		Route 9N		Route 37		Route 126		Route 197	
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	90	1	80	1	46	1	100	1	67
2	86	2	80	2	72	2	98	2	59.5
3	88.5	3	74	3	37	3	91	3	81
4	82	4	77	4	74	4	97	4	74
5	81	5	84	5	74	5	98	5	65
6	80	6	82	6	65	6	97	6	43
7	85	7	71	7	62	7	89	7	13
8	86	8	71	8	60	8	98	8	58
9	84	9	75	9	64	9	92	9	73.5
10	93	10	53	10	65	10	98	10	39
11	87	11	72	11	65	11	82	11	55.5
12	88.5	12	54	12	65	12	83	12	80
13	89	13	81	13	82	13	76	13	65
14	73	14	65	14	83	14	74	14	69
15	68	15	81	15	55				
16	90	16	54	16	14				
17	84	17	67	17	76				
18	68	18	98						
19	74	19	64						
20	92	20	94.5						
21	94.5	21	82						
22	94	22	78						
23	100	23	81						
24	88.5	24	76						
25	90	25	50						
		26	27						
Avg.	85.44	Avg:	71.98	Avg:	62.29	Avg:	90.93	Avg:	60.18

Results of PCI for MF Routes

The PCI for each sample unit of each MF route is presented in table B6.

TABLE B6 PCI of Different MF Routes

MF							
Route 12		Route 11		Route 9L		Route 3	
Unit no.	PCI	Unit no.	PCI	Unit no.	PCI	Unit no.	PCI
1	75	1	65	1	43	1	79
2	71	2	64	2	55	2	63
3	73	3	62	3	79	3	82
4	69	4	77	4	77	4	58
5	73	5	76	5	85	5	47
6	70	6	82	6	28	6	51
7	63	7	70	7	99	7	82
8	65	8	78	8	28	8	69
9	70	9	57	9	77	9	77
10	84	10	91	10	45	10	72
11	76	11	58	11	81.5	11	64
12	79	12	63	12	72	12	70
13	66	13	88	13	79	13	69
14	76	14	75	14	54	14	74
15	80	15	69	15	78		
16	48	16	92	16	93		
17	76	17	73	17	95.5		
18	79	18	75	18	90		
19	66	19	75	19	94		
20	82	20	78	20	95.5		
21	80	21	67	21	66		
22	82	22	70	22	78		
23	75	23	88				
24	71	24	88				
25	84	25	84				
26	80						
27	72						
28	78						
Avg.	73.68	Avg.	74.6	Avg.	72.39	Avg.	68.36

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Scope and Method of Study: Environmental, performance and life cycle cost analysis of maintenance techniques of asphalt pavements were done. Environmental effects of those techniques were evaluated using PaLATE. A typical section was chosen for each maintenance technique and environmental effects were quantified using PaLATE. For performance evaluation, pavement sections repaired using different maintenance techniques were surveyed and PCI was calculated according to ASTM D 6433-07. ANOVA was used to analyze if there was difference in performance. Life cycle cost analysis was performed using Real Cost, a Excel based program. Inputs used in the program were obtained for the New York CIPR study (22).

Findings and Conclusions: Based on subjective rankings and input used in our study, CIPR has the least environmental effects followed by TCO, MF, CIPR-AS and TCO-NR. The use of RAP had positive effects on environmental effects and the use of add stone had adverse effects. Performance of the maintenance techniques was not statistically significant. Maintenance technique with least initial cost had least life cycle cost. For LCCA also, the use of add-stone to CIPR had an adverse effect on LCC and addition of RAP to TCO had positive effect. MF was the costliest maintenance technique and would require the longest service lfie to have and equivalent LCC. Further studies are needed to evaluate the positive and adverse effect of use of RAP and add-stone to TCO and CIPR respectively. For our study the performance was not significantly different for maintenance techniques, so the decision was based on environmental effects and LCC. CIPR without add-stone was the best maintenance technique based on those two.

ADVISER’S APPROVAL: Dr. Stephen A. Cross