COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Final Summary Report

Prepared for

THE NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

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Abstract

Cold in-place recycling (CIPR) is a continuous multi-step process in which the existing asphalt pavement is recycled using specialized equipment that cold mills the asphaltic pavement and blends asphalt emulsion and aggregate (if necessary) with the reclaimed material. The blended mix is then redeposited and compacted in-place. Once cured, all CIPR projects are overlaid with a wearing surface. Although CIPR has been used in many regions of New York, the comparative performance and life cycle costs of CIPR versus other maintenance options have not been well established. This report presents a summary of the findings, conclusions and recommendations of a comprehensive examination of CIPR use, field performance, comparative life cycle costs and the life cycle environmental burden of CIPR versus alternative maintenance options currently used in New York State. It includes a Best Practice Guideline and recommended mix design and construction specifications. Supporting attachments are provided to support the summarized findings and conclusions presented herein.

Key Words cold in-place recycling, CIPR, asphalt emulsion, pavement recycling, pavement maintenance, pavement rehabilitation, life cycle cost analysis, life cycle environmental analysis, pavement service life, pavement condition indices, pavement distress.	Distribution Statement

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ABSTRACT

Cold in-place recycling (CIPR) is a continuous multi-step process in which the existing asphalt pavement is recycled using specialized equipment that cold mills the asphaltic pavement and blends asphalt emulsion and aggregate (if necessary) with the reclaimed material. The blended mix is then redeposited and compacted in-place. Once cured, all CIPR projects are overlaid with a wearing surface. Although CIPR has been used in many regions of New York, the comparative performance and life cycle costs of CIPR versus other maintenance options have not been well established. This report presents a summary of the findings, conclusions and recommendations of a comprehensive examination of CIPR use, field performance, comparative life cycle costs and the life cycle environmental burden of CIPR versus alternative maintenance options currently used in New York State. It includes a Best Practice Guideline and recommended mix design and construction specifications. Supporting attachments are provided to support the summarized findings and conclusions presented herein.

ACKNOWLEDGMENTS

The members of the research team gratefully acknowledge sponsorship of this project by the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Transportation (NYSDOT), under the direction of Joseph D. Tario of NYSERDA and Michael A. Rossi of NYSDOT. We also acknowledge the very helpful input and technical support throughout the course of the project provided by Thomas Kane, NYSDOT Materials Engineer, Dennis Pawlicki, NYSDOT Region 7 Maintenance, Dave Fisher, NYSDOT Region 5 Materials, Jim Jordan, Region 4 Materials, Frank Komoroske, NYSDOT Warren Co. Resident Engineer and Gary Frederick, NYSDOT Director of Transportation Research and Development. A special thanks is conveyed to Gary Foux, Suit-Kote and Tony and Mark Gorman, Gorman Brothers Inc. for sharing their experiences and knowledge on CIPR projects that they have respectively undertaken in New York State.

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Summary

Objectives

Cold in-place recycling (CIPR) is a continuous multi-step process in which the existing asphalt pavement is cold-milled and blended with asphalt emulsion and aggregate (if necessary). Adding emulsion and aggregate improves the strength and durability of the reclaimed material. The recycled asphalt mix is then placed onto the existing milled roadway using conventional paving equipment and compacted using vibratory and pneumatic tire rollers. Once cured, all CIPR projects are overlaid with a wearing surface. Recycling pavements using CIPR has the potential to decrease energy consumption, the environmental burden and the cost associated with asphalt pavement rehabilitation.

The objective of this study was to evaluate and compare the relative performance of CIPR with other asphalt pavement rehabilitation practices currently employed in New York State, and to recommend improvements to current New York State Department of Transportation (NYSDOT) practices and standards for the design and construction of CIPR projects.

Research Approach

To achieve the aforementioned objectives, the Research Team undertook several tasks:

1. A review of relevant CIPR literature.
2. A survey of other State transportation agency's usage of CIPR.
3. The development of a database of NYSDOT CIPR projects.
4. A comparative assessment of
    a. CIPR field performance relative to other maintenance options, and
    b. CIPR life cycle cost, energy and environmental emissions relative to other maintenance options.
5. An analysis of the anticipated CIPR service life, and the
6. Preparation of a draft and final report.

Analyses and Results

The comprehensive analysis of field performance, life cycle costs, energy and environmental modeling, and projections of anticipated CIPR service life yielded the following findings:

- CIPR rehabilitated pavements can be expected to perform as well as alternative pavement maintenance options.

- CIPR pavements have the lowest initial cost and if properly planned, designed and constructed can be expected to exhibit life cycle costs equal to or lower than other rehabilitation options.

- CIPR rehabilitation consumes the least amount of energy, emits the lowest quantity of greenhouse gas emissions and exhibits the lowest life-cycle environmental burden.

- The use of add-stone can negatively impact the life cycle cost and environmental burden of CIPR.

Conclusions and Recommendations

NYSDOT currently supports the use of CIPR on its roadway network. During this investigation it was determined that CIPR rehabilitated pavements can be expected to perform as well or better than alternative pavement maintenance options if the proper pavements are selected for rehabilitation. In addition, CIPR application on properly selected pavements could result in energy and cost savings and a reduction in greenhouse gas and other polluting emissions.

Based on the findings of this study it is suggested that the following recommendations be considered by NYSDOT:

- Establish formal screening criteria as presented in the Best Practice Guidelines for the investigation of pavements to determine if they are eligible for CIPR application.

- Evaluate the traffic limitations of CIPR and establish eligible pavements based on existing pavement condition and distresses.

- Continue to track the performance of CIPR projects through the Pavement Management Group database system.

- Consider modification of the Sufficiency Rating (SR) condition index that is currently used to determine maintenance requirements on roadways.

- Update current specifications as presented in the Recommended Specifications (see Attachment A, Appendix B) and in particular include mix design requirements to improve the quality and performance of CIPR pavements.

- Evaluate the cost effectiveness and performance benefits of using add-stone with CIPR.

Introduction

Cold In-Place Recycling (CIPR) is an asphalt pavement rehabilitation technique that processes the existing in-situ pavement materials, by cold-milling the pavement and supplementing the milled material with asphalt emulsion and aggregate (if necessary). All work is completed on site and the transportation of materials, except for the additives being used, is normally not required. The depth of processing is typically 3 to 4 inches. The process is sometimes referred to as partial depth recycling because the base and or some of the bituminous materials are left intact. Once cured, all CIPR projects are overlaid with a wearing course. While CIPR is presently employed as a maintenance option on asphalt pavements in New York State, its use tends to be limited to select regions of the state and to specific pavement types. Decisions on whether to employ CIPR are in most cases determined by the Regional Maintenance Engineer. As a result, the decision-making process is in great part based on the Engineer's preference and experience with CIPR.

This report presents the results of a multi-year investigation of CIPR application and performance in New York State. Its primary goals were to establish the comparative field performance, economic, energy and environmental implications of using CIPR versus other rehabilitation approaches and to develop a Best Practice Guideline Document to facilitate CIPR planning and use in the State.

This report presents a summary of the research approach findings and conclusions of the investigation. It is divided into three subsequent sections: 1) Research Method, 2) Findings and Conclusions, 3) Statement of Implementation and Recommendations.

More detailed supporting information is presented in a series of Attachments to this report that include:

- Attachment A: CIPR Best Practice Guidelines,
- Attachment B: Transportation Agency Survey,
- Attachment C: Indices and Models,
- Attachment D: Comparative Performance Analysis,
- Attachment E: CIPR Life Cycle Modeling, and
- Attachment F: CIPR Service Life Projections.

Research Method

The overall effort included six primary activities:

1. Transportation Agency Survey,
2. NYS CIPR Database,
3. Comparative Performance Analysis,
4. CIPR Service Life Projections,
5. Life Cycle Modeling, and
6. Best Practices Guideline Preparation.

A summary of the general Research Method associated with each primary activity is outlined below.

Transportation Agency Survey[1]

State transportation agencies with significant experience with CIPR were contacted and sent a questionnaire form to obtain information on past and present CIPR experience. The survey focused on the use of formal specifications, mix design procedures, recycling additives in use, field monitoring procedures, project selection criteria and performance evaluations that might have been conducted to assess CIPR performance.

NYS CIPR Database

A computerized database was developed to compile information on all existing NYS CIPR pavements constructed through 2007. Relevant data were collected through surveys and meetings with NYSDOT regional materials engineers, maintenance engineers, resident engineers and contractors to identify existing CIPR sites. The primary source of data, however, was provided by the NYSDOT Pavement Management Group. The final database was submitted to NYSDOT.

CIPR Service Life Projections[2]

The service life of CIPR pavements was projected by developing a model to describe the relationship between NYSDOT Sufficiency Ratings (SR) and Pavement Age (Age). NYSDOT tracks the condition of State pavements and defines maintenance and rehabilitation needs by use of a pavement rating scale known as the NYSDOT Sufficiency Rating (SR). The SR scale is a 10 to 1 point scale (10 being the best condition) based on the prevalence of surface related pavement distresses. An SR value of six (6) is used to indicate that corrective action is required. The model was developed by analyzing scatter plots of NYSDOT Sufficiency Ratings (SR) versus Pavement Age (PA) for CIPR pavements, and determining from these data the best-fit model. The Age at which the pavement SR value dropped to six (6) was used to define the extended service life of the pavement. The analysis included an evaluation of the affect of

[1] See Attachment B, Transportation Agency Survey, June 2008
[2] See Attachment F, CIPR Service Life Projections, August 2009

AADT, truck traffic, base and sub-base thickness, environment (climate) and the extent of pavement deterioration at the time of CIPR application on service life projections.

Comparative Performance Analysis[1]

Field Pavement Distress Surveys were performed on representative roadway sections of cold-in-place recycling (CIPR), mill and fill (MF) and two-course overlay (TCO) pavements. The surveys were performed in accordance with ASTM 6433-07. Data from the distress surveys were used to undertake a comparative performance analysis to assess whether differences in relative field performance of CIPR, MF and TCO pavements could be derived from the field pavement distress surveys. CIPR, MF and TCO pavements of similar age, traffic and climatic conditions were surveyed and included in the analysis. Three pavement indices were used to compare the CIPR, MF and TCO pavement groupings.[2] These indices included: 1) ASTM D 6433-07[3], 2) RSMS01[4] and 3) IS-169[5]. Each of the indices was also compared to the NYSDOT Sufficiency Rating (SR) index, which as noted above is used by NYSDOT to assess the NYS road network. This latter effort was undertaken to determine how well the SR index correlates with other standard distress indices.

Life Cycle Modeling[6]

The computer program "Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects" (PaLATE)[7] was used to compare the costs, energy and environmental burden of employing cold in-place recycling (CIPR), mill and fill (MF) and two course overlay (TCO) maintenance options. To undertake this analysis a mainline pavement model roadway (24 feet in width and one mile long without shoulders) was used in the assessment. Modeling was conducted on this model pavement using eight different rehabilitation options. These options included: 1) CIPR with four inch mill depth, 2) CIPR with three inch mill depth, 3) CIPR with four inch mill depth and 20% add-stone, 4) CIPR with three inch mill depth and 20% add-stone, 5) MF with 1.5 inch mill depth, 6) MF with 2 inch mill depth, 7) MF with 3 inch mill depth, and 8) Two Course Overlay (TCO). HMA overlays for each treatment were assumed as follows: 1) TCO - two 1.5 inch lifts, 2) MF- two 1.5 inch lifts, and 3) CIPR – one 1.5 inch lift.

Best Practice Guidelines[8]

On the basis of the information gathered and the analyses conducted during the investigation a Best Practice Guideline was prepared that included: 1) Recommended Project Selection

[1] See Attachment D: Comparative Performance Analysis, May 2010.
[2] See Attachment C: Indices and Models, November 2008.
[3] ASTM D 6433-07 Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. Volume 04.03, American Society for Testing and Materials, West Conshohocken, PA., 2008.
[4] RSMS01, Recycled Materials Resource Center, University of New Hampshire, Durham, NH, March 2004.
[5] IS-169, A Pavement Rating System for Low-Volume Roads. The Asphalt Institute, Lexington, KY.
[6] See Attachment E: CIPR Life Cycle Modeling, May 2010.
[7] Horvath, Arpad. A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications. Final Report, Research Project No. 23, Recycled Materials Resource Center, University of New Hampshire, Durham, NH, March 2004.
[8] See Attachment A: CIPR Best Practice Guidelines, June 2008.

Practices, 2) Recommended Mix Design Practices, and 3) Recommended Construction Practices. Recommended modifications to the existing NYSDOT CIPR specification and a proposed CIPR mix design method are included with the Best Practice Guideline in Attachment A.

Findings and Conclusions

Transportation Agency Survey Findings[1]

A formal survey of 13 participating Transportation Agencies was conducted, which included Arizona, Delaware, Iowa, Kansas, Montana, Nebraska, Nevada, New Hampshire, Ohio, South Dakota, Utah, Washington and FHWA's Central Federal Lands Highway Division. This survey focused on the availability of formal specifications, mix design procedures, recycling additives in use, field monitoring procedures, project selection criteria and prior performance evaluations. The following is a summarized listing of some of the more relevant findings:[2]

- Six agencies have specifications for CIPR in their standard specifications with the other seven using special provisions or supplemental specifications.
- Nine agencies require a mix design with seven of these agencies requiring the contractor provide the mix design.
- Types of recycling additives vary from cationic slow and medium set emulsions to high float emulsions, with and without polymer modification, to engineered emulsions. Two agencies reported preferring expanded asphalt (foam) to asphalt emulsions. Only two agencies indicated they occasionally added virgin aggregates.
- All 13 agencies reported the use of density or compaction monitoring.
- Ten agencies indicated that they have no official traffic restrictions on the use of CIPR. Nevada, Kansas, Iowa, New Hampshire and New Mexico have all reported using CIPR on Interstate pavements. Two agencies indicated they have traffic restrictions and reserved CIPR for low to moderate traffic (less than 4,000 ADT).
- All agencies indicated overlay thicknesses are designed based on traffic with chip seals being used for low volume roads and 1.5 to 3 inch HMA overlays reported as typical.

Transportation Agency Survey Conclusion

CIPR is being practiced in many States; however, there are significant differences in the respective planning, design and specifications associated with CIPR use.

NYS CIPR Database Findings

A database of New York State (NYS) CIPR projects was compiled and designed using a Microsoft Access 2000 Platform. The database contains a listing of 169 CIPR sites and includes

[1] See Attachment B, Transportation Agency Survey, June 2008
[2] Task 2 State Agency Survey, June 25, 2008

information on: 1) Route, 2) Beginning Mile Post, 3) End Mile Post, 4) Length, 5) Reference Marker, 6) Dominant Distress, 7) Region, 8) County, 9) Surface Type, 10) Base Type, 11) Subbase Type, 12) Year Last Worked, 13) Number of Lanes, 14) Work Type, 15) Average Annual Daily Traffic (VPD) and 16) Percent Truck Traffic. Additional information where available included: 1) the Recycling Contractor, 2) the Depth of Cut, 3) the Addition of Stone, and 4) the Emulsion Rate.

CIPR Service Life Projection Findings[1]

It was determined that a logarithmic model is the best representation of the relationship between Pavement Age and the NYSDOT SR condition index. The results of projections using this model were as follows:

- On average CIPR can be expected to increase the service life of rehabilitated pavements by approximately 11 years.
- Pavements constructed with thicker pavement base, base plus sub-base and total pavement thickness exhibit longer pavement service lives.
- Pavements subjected to higher AADT and higher truck traffic (due in great part to the thicker pavement base associated with higher trafficked pavements) exhibit longer service lives than pavements with lower AADT and lower truck traffic.
- The environment and climate for CIPR rehabilitated pavements examined in this study did not significantly affect the expected service life of the pavement.
- The service life of pavements that were rehabilitated with CIPR prior to severe pavement deterioration were approximately 50 percent longer than those pavements rehabilitated with CIPR after severe pavement deterioration.

CIPR Service Life Projection Conclusions

On the basis of the CIPR service life projection analysis, it is concluded that CIPR rehabilitated pavements can be expected to increase the service life of pavements on average approximately 11 years; however

- When CIPR is used on better-designed pavements that have thicker supporting bases and sub-bases, CIPR performance will benefit and the service life of the pavement will be extended. This could significantly expand the locations that CIPR can be employed.

[1] See Attachment F, CIPR Service Life Projections, August 2009

- When CIPR is used on poorly supported pavements the service life of the pavement can be expected to decrease.
- When pavement rehabilitation is implemented prior to severe pavement deterioration the service life of the pavement can be expected to increase.

It is also concluded that a general policy of employing CIPR as a rehabilitation strategy on low AADT and lightly traveled pavements with low truck traffic may be misleading. The data generated in the CIPR service life projection analysis tends to support the opposite conclusion. CIPR pavements last longer if applied on pavements with higher AADT and higher levels of truck traffic. It is concluded however that the primary factor is not traffic but the pavement support structure. Higher trafficked pavements tend to be designed with greater base and subbase thickness, thereby providing enhanced support to the CIPR section, which increases the service life of the pavement.

Comparative Performance Analysis Findings

The comparative field distress surveys of CIPR, MF and TCO pavements conducted during the investigation yield the following:

- There was no statistical difference in performance between CIPR, MF and TCO pavements, as measured by ASTM, RSMS or AI CR condition indices.
- There was poor correlation between SR and the ASTM, RSMS or AI CR methods.
- The three field evaluation methods, ASTM, RSMS and AI CR, correlated well to each other.

Comparative Performance Analysis Conclusions

- CIPR, MF and TCO pavements exhibit similar field performance characteristics.
- The NYSDOT SR rating methodology, unlike the ASTM, RSMS and AI CR rating system methodologies, generates ratings that decrease rapidly during the initial years of pavement life and asymptotically plateau during the latter years of pavement life. Such a rating system is less sensitive to end of life identification than the ASTM, RSMS and AI CR rating systems.

Life Cycle Modeling Findings[1]

Findings for both the life cycle cost analyses (LCCA) and life cycle environmental analysis (LCEA) are presented below.

Life Cycle Cost Analysis (LCCA) Findings

Life cycle cost analyses (LCCA) modeling results using a 20-year analysis period and a 3.0 percent discount rate, with an 11-year treatment life for CIPR and MF and 14 years for TCO showed the following:

- TCO, followed closely by the CIPR options without add-stone, exhibit the lowest life cycle costs.
- The addition of 20% add-stone measurably increases the life cycle costs of CIPR.
- The MF options have the highest life cycle costs.

Life Cycle Environmental Analysis (LCEA) Findings

Life cycle environmental analyses (LCEA) energy, greenhouse gas emissions and USEPA criteria pollutant emissions modeling results yield the following:

- The CIPR options consume the least energy and emit the lowest quantities of greenhouse gas.
- The CIPR options emit the least quantity of USEPA criteria pollutant emissions.
- The addition of add-stone to 4-inch CIPR reduces the environmental advantage of CIPR as a maintenance option over TCO.

Life Cycle Modeling Conclusions

Life Cycle Cost Analysis (LCCA) Conclusions

While in general the CIPR options exhibit the lowest initial cost, TCO and CIPR without add-stone exhibit the lowest life cycle costs. The lower TCO life cycle cost was attributed to the longer projected treatment life used for TCO (14 years) compared to the 11year life used for both the CIPR and MF options. The MF options exhibit the highest initial and highest life cycle cost.

Based on the LCCA findings it is concluded that:

[1] See Attachment E: CIPR Life Cycle Modeling, May 2010.

- Three-inch CIPR and TCO are comparable life cycle cost options.
- Treatment life is a critical parameter when comparing the CIPR and TCO options.
- When deciding between TCO and CIPR as treatment options, the deciding factor should be based on structural requirements and functional distresses exhibited by the pavement.
- The MF options are the least cost effective of the treatments evaluated.

Life Cycle Environmental Analysis (LCEA) Conclusions

The use of CIPR is the most energy efficient and least polluting of the three maintenance options (CIPR, MF and TCO) examined during the study. This advantage is reduced somewhat when add-stone is incorporated into the mix. This is primarily due to the need for additional asphalt emulsion in the CIPR treatment.

Based on the LCEA findings it is concluded that:

- The CIPR option, from a life cycle environmental perspective, is the most favorable treatment option.
- The TCO maintenance option is similar to 4-inch CIPR if add-stone is included in the mix.
- The MF options exhibit the highest life cycle environmental burden, when compared to the CIPR and TCO options.

CIPR and TCO

Although the TCO option exhibited the lowest life cycle cost and a similar environmental burden when compared to CIPR with add-stone, the PaLATE analysis was limited to the mainline pavement only. Shoulders were excluded from the analysis. Treating shoulders will result in higher costs and increased environmental outputs for all the options examined. However, since the TCO option is a surface treatment option only, it is likely that additional TCO shoulder treatment, which may not be needed with CIPR and MF, may be required to ensure that the grade and elevation of the mainline pavement and the shoulder conform to specifications. If such is the case, then it is likely that the CIPR option will exhibit more favorable relative costs and environmental outputs compared to TCO.

Statement of Implementation and Recommendations

NYSDOT currently supports the use of CIPR on its roadway network. During this investigation it was determined that CIPR application on properly selected pavements could result in energy and cost savings and a reduction in greenhouse gas and other polluting emissions.

Based on the findings of this study it is suggested that the following recommendations be considered by NYSDOT:

- Establish formal screening criteria as presented in the Best Practice Guidelines for the investigation of pavements to determine if they are eligible for CIPR application.

- Evaluate the traffic limitations of CIPR and establish eligible pavements based on existing pavement condition and distresses.

- Continue to track the performance of CIPR projects through the Pavement Management Group database system.

- Consider modification of the Sufficiency Rating (SR) condition index that is currently used to determine maintenance requirements on roadways.

- Update current specifications as presented in the Recommended Specifications, and in particular include mix design requirements to improve the quality and performance of CIPR pavements.

- Evaluate the cost effectiveness and performance benefits of using add-stone with CIPR.

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment A: Best Practice Guidelines

Prepared for

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Scope and Information Sources

Cold in-place recycling (CIPR) is a process where the existing bituminous pavement is recycled in-place without application of heat. The depth of treatment is typically 3-4 inches. In the CIPR process, scarified material from the existing pavement is crushed to the required gradation and binder is added. The most common binders are asphalt emulsions and expanded (foamed) asphalt but additives such as fly ash and rejuvenating agents have been successfully utilized as well. Portland cement or lime have also been used to enhance mix properties and curing. Externally acquired reclaimed asphalt pavement (RAP) or virgin aggregates (add-stone) are sometimes added depending on mix design and project requirements. The milled material is mixed in-situ, placed, and compacted using conventional paving equipment. After a curing period a wearing surface, typically hot mix asphalt or chip seal, is added for traffic and to prevent moisture penetration into the CIPR material.

Implementing a successful CIPR rehabilitation project requires the selection of suitable pavements for CIPR rehabilitation, mix design analysis and the implementation of appropriate construction procedures. This Best Practices Guidelines is divided into three sections and is designed to assist the design and construction engineer in understanding how CIPR works and how to successfully implement a CIPR project. The three sections respectively include:

1. **Project Selection Practices**
   Presents recommendations for determining when and where CIPR should be used and factors to consider when determining if CIPR is the best rehabilitation option,

2. **Mix Design Practices**
   Describes the steps and recommended practices to successfully undertake a CIPR mix design, and

3. **Construction Practices**
   Addresses recommended practices, equipment, and quality control procedures for the construction of CIPR pavements.

In addition, supporting appendices are provided that include a detailed description of the recommended mix design procedure (Appendix A) and proposed revisions to the current NYSDOT CIPR construction specification (Appendix B).

Much of the information used in preparation of these guidelines was derived from several major sources. These included the Basic Asphalt Recycling Manual (1), the Asphalt Recycling and Reclaiming Association (ARRA) web site (2), Pacific Coast Conference on Asphalt Specifications[1] (PCCAS) documents (3,4) along with existing specifications

[1] PCCAS is a user-producer group that works to standardize asphalt specifications across the states of Alaska, Arizona, California, Hawaii, Nevada, Oregon, and Washington.

and practices employed by State DOTs, including information in the NYSDOT Comprehensive Pavement Design Manual (5) and the NYSDOT CIPR Specification (6) and 2003 Draft Inspector Guidelines (7).

The aforementioned data sources were supplemented with the results of the effort undertaken by the authors in fulfilling the requirements of Contract No. 6764F-2. This included, in addition to the preparation of these Best Practices Guidelines (presented as Attachment 1), a survey of practices currently used in States employing CIPR on a regular basis. The effort also included a field survey and comparative analysis of pavement distresses in CIPR rehabilitated pavements versus two course overlay and mill and fill rehabilitation approaches, projections of the expected service life of CIPR, and life cycle cost and environmental analyses of CIPR versus two course overlay and mill and fill options.

Project Selection

The successful employment of CIPR as a pavement rehabilitation strategy is dependent on the selection of good candidate pavements. This section presents recommendations for screening pavements for CIPR application. The recommended screening procedure is divided into two stages: a pre-screening and final screening stage. The stages and steps in the procedure are outlined in Table 1. Pre-screening steps include a series of evaluation criteria used to determine if CIPR is a viable rehabilitation option. Final screening steps comprise a series of evaluation criteria used to help determine if CIPR is the best rehabilitation option.

Table 1. Project Selection Screening Procedure

Screening Stages	Screening Criteria	Recommended Action
Stage 1 **Pre-Screening Steps**	**Is CIPR a viable rehabilitation option?**	
Distress Identification	Distress type suitable for CIPR?	Condition survey
Traffic Assessment	Traffic acceptable?	Evaluate supporting base
Structural Capacity	Adequate support for CIPR train?	Coring and assessment
Constructability	Roadway suitable for CIPR construction?	Roadway geometry evaluation.
Stage 2 **Final Screening Steps**	**Is CIPR the best rehabilitation option?**	
Traffic Load	Adequate pavement thickness with CIPR?	Deflection tests, Load analysis
Grades	Long steep grades?	Evaluate effect on productivity
Traffic Control	Will CIPR train size interfere with traffic?	Traffic analysis
CIPR Mixture Curing	Will curing significantly impact pavement performance or traffic?	Mix design assessment

PRE-SCREENING STEPS

Four steps are included in the prescreening analysis. These include: 1) Distress Identification, 2) Traffic Assessment, 3) Structural Capacity, and 4) Constructability.

Distress Identification

CIPR will not address pavement thickness design, or subbase and subgrade issues. As a result, most transportation agencies limit CIPR to the rehabilitation of pavements with functional failures, not structural failures. Functional failures include distresses such as non-wheel path longitudinal cracking, transverse cracking, block cracking, and poor rideability, flushing, and raveling. Fatigue or alligator cracking located in wheel paths, rutting and patching can be indicative of structural inadequacy. If the distresses present are caused by inadequate pavement structure, poor road base material, soft subgrades or lack of proper drainage, CIPR would not be an appropriate rehabilitation treatment without prior corrective action. In such cases, other methods of rehabilitation or reconstruction, such as full depth reclamation (FDR), should be considered. When small areas of failure are encountered, generally less than 10 percent, it may be possible to perform full depth repair for those areas and then proceed with a complete CIPR rehabilitation of the roadway.

A condition survey should be undertaken to assist in determining whether the cause of pavement deterioration is functional or structural. ASTM D 6433 (8) is one of the more effective methods for determining the extent and severity of pavement distress or the Distress Identification Manual for the Long-Term Pavement Performance Program (9) can be used.

Figures 1, 2, 3 and 4 show pavements that exhibit block cracking, transverse cracking, fatigue cracking and raveling, respectively. Each would be an excellent candidate for CIPR projects.

Figure 1. Block cracking (courtesy ARRA)

Figure 2. Transverse cracking (courtesy ARRA)

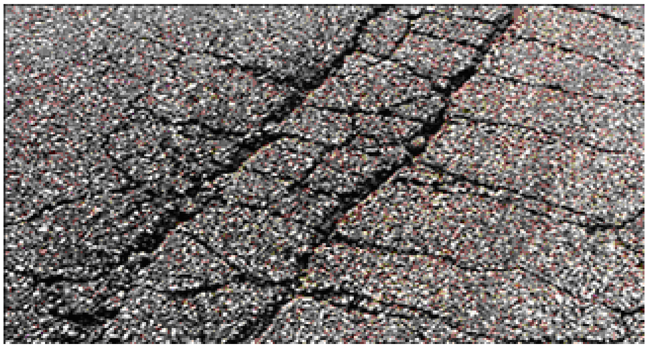

Figure 3. Fatigue cracking (courtesy ARRA)

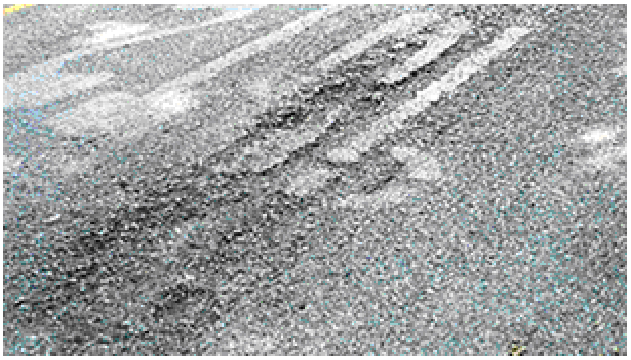

Figure 4. Pavement Raveling (courtesy ARRA)

Table 2, adopted from ARRA, is a listing of pavement distresses that can be used to screen eligible pavements (2).

Table 2. Applicability of CIPR to Pavement Distress

Pavement Conditions		
Distress	**Criteria**	**CIPR Applicability**
Ruts	< 3/8 inch	Yes
	> 3/8 inch	Possible[1]
Cracking	Fatigue	Possible[1]
	Longitudinal	Yes
	Transverse	Yes
Surface Defects	Dry	Yes
	Flushing	Yes
	Bleeding	Yes
	Variable	Yes
Raveling	All levels	Possible[1]
Potholes	All levels	Possible[1]
Stripping	High degree	Possible[1]
Ride	Poor	Possible[1]
Drainage	Poor	No

[1]Further investigation, described under each heading, would be necessary to determine CIPR applicability.

Rutting
Minor surface rutting, less than 3/8 inch, is most likely due to densification of pavement layers over time. It is not an indication of unstable pavement layers, making the project a good candidate for CIPR. Rut depths greater than 3/8 inch should be investigated to determine the cause. Rutting caused by plastic flow of a surface mix can be successfully rehabilitated using CIPR but consideration of additives to stiffen the mixture should be evaluated. Rutting caused by instability of base and/or subgrade layers are not good candidates for CIPR.

Cracking
Minor fatigue cracking can be successfully treated by CIPR if the distress is not caused by poor drainage or a softened base or subgrade. The thickness of the wearing surface must be properly designed to provide adequate structure to prevent return of fatigue cracking. Pavements with transverse and or longitudinal cracking are excellent choices for CIPR because transverse and longitudinal cracking are not generally load associated. Successful rehabilitation can be a function of how much of the existing crack is removed. CIPR economically treats 3-4 inches of the existing pavement.

Surface Defects
Pavements with surface defects, including a dry, flushed or bleeding surface, are good candidates for CIPR rehabilitation since CIPR completely removes the distressed surface. Pavements with variable surface conditions are also good candidates. More than one mix design may be required if variable surface conditions exist.

Raveling
Raveling, a progressive disintegration of the wearing surface from the top down, can be successfully rehabilitated by CIPR if the distress is confined to the depth of treatment. A mix design to evaluate moisture susceptibility of the CIPR layer should be performed and lime, Portland cement or other suitable anti-strip agents should be considered.

Pot Holes
Potholes occur more frequently on thin rather than thick HMA pavements. Potholes can be successfully treated by CIPR if the distress is not caused by poor drainage or a softened base or subgrade, and if the distress is confined to the depth of CIPR treatment. The thickness of the wearing surface must be properly designed to provide adequate structure to prevent return of potholes.

Stripping
Stripping is the loss of bond between aggregates and asphalt cement, usually in the presence of moisture. Stripping begins at the bottom of a layer and progresses upward. When stripping starts at the surface and progresses downward, it results in raveling. Stripping in an asphalt layer can be treated by CIPR if the distress is confined to the depth of CIPR treatment. A mix design to evaluate moisture susceptibility of the CIPR layer should be performed and lime, Portland cement or other suitable anti-strip agents should be considered.

Ride
Poor ride quality or roughness can be treated by CIPR by milling to a specified grade rather than a constant depth and using a ski on the CIPR paver. Pavement roughness caused by an unstable subgrade cannot be adequately treated by CIPR as CIPR does not address base and subgrade issues.

Drainage
Inadequate drainage is a common cause of pavement deterioration and a realistic rehabilitation regime must involve repair of the base and/or drainage deficiencies.

Traffic Assessment

Many agencies limit CIPR to roadways with low traffic volumes or little truck traffic. The NYSDOT currently recommends CIPR for pavements with less than 4,000 AADT per lane and less than 10% trucks (5). In the State transportation agency survey conducted by the authors (10) under Contract 6764F-2464-2, 10 of 13 States in the survey with a history of CIPR use reported no official traffic restrictions.[2] Two agencies with no restrictions reported applying CIPR to roadways with traffic volumes between 15,000 and 16,000 AADT [3] and several agencies reported using CIPR on Interstate pavements.[4]

Findings of the service life projections conducted under Contract 6764-F revealed that CIPR pavements on higher trafficked routes in New York State tend to exhibit longer service lives than those on lower trafficked routes (11). This apparent anomaly was attributed to better pavement structure and support for the higher trafficked pavements relative to the lower trafficked pavements. This suggests that traffic is not the major factor in CIPR performance, but that structural capacity of the subbase is.

The Nevada Department of Transportation (NDOT) recommends CIPR be limited to low to medium trafficked pavements initially until adequate experience is gained and then these traffic restrictions could be dropped (12). The NDOT approach appears to be a prudent approach; however, with an adequate base and sufficient overlay thickness design, traffic should not be a major factor in CIPR performance.

CIPR can be considered a viable option on all pavements with good supporting bases.

Structural Capacity

Structural capacity relates to the bearing capacity of the granular base and the remaining HMA after surface milling or cold planning has been performed. Sufficient structural capacity and adequate asphalt pavement thickness is required to accommodate the weight of the CIPR train and prevent contamination of the CIPR mixture with aggregate base during the CIPR process. Cores

[2] States surveyed with no official restrictions: DE, KS, MT, NE, NH, NV, OH, SD, UT, WA.
[3] States applying CIPR to pavements with 15,000-16000 AADT: NH, OH.
[4] States reporting using CIPR on Interstate pavements: KS, NM, NV, and UT.

are required (field testing) to ensure that there will be an adequate depth of HMA to support the CIPR process.

The NYSDOT recommends a minimum of 1 inch of HMA remain above the underlying subbase or PCC pavement (5). This should be sufficient except in areas of poor drainage and softened subgrades. Others have recommended 1.5 – 2 inches of HMA and at least 6 inches of granular base material to support the construction train (1).

Constructability

CIPR can be used to make minor improvements in the cross-slope of existing roadways, including shoulders. However, CIPR rehabilitates a pavement in-place. As a result, pavements that require major realignment, such as major widening, major cross-slope or fall corrections and longitudinal or grade corrections are not good candidates for CIPR and other rehabilitation methods should be considered. Pavements that lack proper drainage are not good candidates for CIPR without prior corrective action. Pavements with minor cross-slope deficiencies may be rehabilitated with CIPR plus an additional HMA leveling course prior to placing the wearing course.

It is recommended that HMA shoulders be recycled along with the mainline pavement to prevent existing cracks in the shoulder from propagating into the HMA overlay and CIPR mixture.

If shoulders with a supporting granular base will not be recycled, but will be overlaid (and not incorporated into the CIPR mixture), the existing granular base must be of sufficient thickness to support anticipated traffic loads. If not of sufficient thickness, incorporating the existing granular base into the CIPR can improve the load carrying capacity of the shoulder.

When granular shoulders are incorporated into the CIPR, it is recommended that the uncoated granular material should not exceed 25% of the resulting RAP.

Cores are required (field testing) at different locations across the width of a pavement to assess the cross slope and uniformity of the roadway. This is important on low volume roads because maintenance crews may have completed roadway widening and inconsistent structural sections may exist. Inconsistent structural sections could require separate mix designs, provide inadequate support for the recycling train and require different thicknesses of the wearing surface. Major structural inconsistencies could make CIPR an unviable option.

Existing structures are not treated with CIPR. Approach slabs and areas of transition adjacent to approach slabs should not be considered as candidate areas for CIPR application.

FINAL SCREENING STEPS

Final screening is intended to assist in assessing whether CIPR is the best (most cost-effective) alternative. Four steps and corresponding criteria are included in the final screening. These include: 1) Traffic Load, 2) Grades, 3) Traffic Control, and 4) CIPR Mixture Curing.

Traffic Load

The wearing surface placed over a CIPR mix must be designed to carry anticipated traffic over the projected design life. Anticipated traffic and existing pavement structure are required for thickness design. Since CIPR is designed to rehabilitate pavements with functional distress, not structural distress, thick structural sections are typically not employed with CIPR.

All transportation agencies surveyed under Contract 6746-F by the authors reported that the thickness of the required wearing surface is based on traffic with chip seals being used for low volume roads and 1.5 to 3 inch HMA overlays reported as being typical for moderate traffic levels. Double chip seals are often recommended for low volume pavements that are snow plowed.

There are several field methods available to evaluate structural capacity of an existing pavement. The Dynamic Cone Penetrometer (DCP***)*** (ASTM D 6951[5]) and Falling Weight Deflectometer (FWD) (ASTM D 4694[6]***)*** are two excellent tools that have been used by transportation agencies to evaluate structural capacity. The DCP is often used for evaluation of low volume roads because it is readily available to contractors and consultants. Most DOTs have access to FWDs. Another approach used by some agencies is to assign AASHTO “a” coefficients, based on condition surveys, to the existing HMA and CIPR materials. The information is used with the 1986 AASHTO Thickness Design Guide to assess structural capacity. The use of stabilizers such as Portland cement, lime and modified emulsifying agents can significantly improve the stability of the CIPR layer.

Grades

Grades are not a limiting factor in CIPR project selection but some consideration should be given to grades on the project and to the length of these grades. Steep grades and multi-train equipment should be investigated to assess whether CIPR production may be significantly reduced, affecting project economics.

Traffic Control

CIPR has been successfully completed on all types of roads, ranging from low volume rural county roads, to city streets, to Interstate highways with heavy truck traffic. Traffic control for CIPR projects is similar to mill and fill projects except mill and fill generally requires more

[5] ASTM D 6951 Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications
[6] ASTM D 4694 Deflections with a Falling-Weight-Type Impulse Load

trucks. However, the CIPR train is longer and maintaining traffic through and around the construction zone needs to be considered. This is especially true on roads with limited pavement and or shoulder widths and few alternate or bypass routes. On urban roads the numerous cross streets, business or residential access locations and utility manhole covers must be assessed to determine the degree to which traffic might be impacted.

A single unit train may be preferred over multi-unit trains in urban areas and on roads with short turning radius due to its shorter length and better turning radii (1). Utility manhole covers require the use of small milling machines to mill around steel covers and pavers with width extenders, or the areas must be bypassed. Roadway iron (drainage structures, manholes, etc) may also be lowered and patched over prior to the CIPR process.

Intersections with slowed or stopped traffic that carry heavy truck traffic can rut and shove excessively and are not recommended for CIPR by NYSDOT (5). It is recommended that such conditions be assessed on a case-by-case basis and evaluated based on the amount of heavy truck traffic.

CIPR Mixture Curing

CIPR mixes must adequately cure before placement of the next pavement course. Before placing the next pavement course the CIPR mixture should be allowed to cure for a minimum of at least 2 days and in addition, there must be less than 1.5 percent moisture remaining in the CIPR mixture. With conventional emulsions, curing of a new CIPR mix, at least in the initial time-period after placement, depends on the evaporation of water from the surface of the layer. Therefore, it is important to consider the effect of significant amounts of shaded areas can have on curing as the minimum 1.5% moisture content may not be achievable. Similar slow curing problems may also occur when work takes place in damp or cold weather conditions. A second curing criterion, less than 0.5% moisture remaining in the CIPR mixture above the residual moisture content of the pavement prior to recycling, is recommended to address these situations.

At the very least, possible delays in curing must be considered in regards to other aspects of the project such as traffic control, when the roadway may be reopened to traffic on the CIPR mat and placement of the final wearing surface. Difficult curing conditions can be mitigated somewhat by careful selection of recycling agents, use of additives (lime or Portland cement), and paying close attention to construction conditions.

Mix Design Practices

A mix design is a formulation that defines the percent and grade of recycling agent, recommended water content, and additives, for the planned CIPR mixture. The data is used to develop mix properties that will ensure that the mix will exhibit adequate initial strength, resistance to moisture-induced damage, resistance to thermal cracking and resistance to raveling.

A formal mix design and a mix design report documenting the design formulation introduces additional quality control that helps to ensure that the pavement will meet desired specifications and performance expectations. It is recommended for all CIPR applications.

This section of the Guideline presents general background information on mix design procedures, the steps undertaken during the mix design process, and core materials and optional additives that are commonly used to prepare the mix.

A recommended mix design procedure is described and presented in the form of a specification in Attachment A.

BACKGROUND

In 2001, ARRA published the Basic Asphalt Recycling Manual (BARM), which summarized the available mix design procedures and provided recommended mix design steps for CIPR mixtures. Two currently popular methods are the procedures developed by Road Science, LLC and their predecessors[7], and a procedure recently adopted by the Pacific Coast Conference on Asphalt Specifications (PCCAS) (3). Both procedures follow the recommended steps outlined in the BARM (1).

Many State DOTs have adopted the Road Science mix design procedure, which uses Superpave principals including specimen compaction using the Superpave Gyratory Compactor (SGC).[8] The procedure also includes testing samples for resistance to thermal cracking using AASHTO T 322[9], and resistance to raveling using ASTM D 7196.[10] AASHTO T 322 is a complex test that few agencies have the capability to perform.

The PCCAS procedure is a simpler version of the Road Science procedure and allows the use of 75-blow Marshall compaction as well as SGC compaction for those agencies that cannot compact 4-inch SGC samples. The PCCAS procedure removes the thermal cracking test requirement (AASHTO T 322) and replaces it with a requirement that the asphalt binder used to

[7] "Formerly Koch Materials, and SemMaterials, Road Science is a developer of advanced asphalt products and technologies in the categories of ultrathin overlays, cold in-place and hot in-place recycling, microsurfacing, base stabilization, high performance chip seals, and fatigue resistant pavements."
[8] States that have incorporated the Road Science procedure include KS, MO, MT, OH, and UT.
[9] AASHTO T 322, Determining the Creep Compliance and Strength of Hot-Mix Asphalt Using the Indirect Tensile Test Device.
[10] ASTM D 7196 Test Method for Raveling Test of Cold Mixed Bituminous Emulsion Samples.

make the asphalt emulsion meet the Bending Beam requirements of AASHTO M 320[11], the Performance Graded (PG) Asphalt Binder Specification, for the project location. This modification makes the procedure much less costly and greatly increases the number of agencies/firms that can perform the mix design. Both procedures utilize the raveling test (ASTM D 7196). However, use of the raveling test could exclude currently used emulsions that contain solvents and do not rely on a chemical break.

This Best Practices Guideline presents a recommended mix design procedure, presented in detail in Appendix A, which is a combination of the Road Science and PCCAS procedures. It eliminates AASHTO T 322 testing requirements, thereby increasing the number of agencies/contractors that will be able to perform the procedure. It also makes the raveling test (ASTM D 7196) optional to allow a wider choice of recycling agents.

PROCEDURES

Establishing a mix design for a CIPR project requires the collection of field samples of the target pavement to be recycled and subsequent laboratory (mix) testing to establish a target formulation of the materials (asphalt emulsion, water, RAP, add-stone and additives, if needed) that will be used during construction.

Sample Collection

Coring the pavement to be recycled is the preferred method for collection of representative samples of the target pavement. This is undertaken to establish whether the properties of the pavement are consistent along its length, width, and depth and to obtain materials for the mix design.

Six cores per lane mile should be obtained to check for pavement consistency with additional cores where visual differences in the pavement are noticed. These cores are also used for determination of asphalt content and gradation analysis of the existing pavement (to the specified milling depth). If cores show significant differences between areas, such as different type or thickness of layers between cores, then separate mix designs are recommended for each of these pavement segments.

In this case, more material, and hence additional coring (approximately 350 lbs), is required for the mix design. Pavement (RAP) cores should be at least 6 inches in diameter and materials for the mix design should be separated from the rest of the core by collecting (by sawing off) the material to be recycled. The collected samples are then processed using a laboratory jaw crusher or other technique that will yield a material similar to material manufactured during actual milling operations.

RAP gradation will vary throughout the project due to daily temperature changes of the milled pavement and due to changes in mix composition of the pavement and normal mixture variation.

[11] AASHTO M 320 Standard Specification for Performance-Graded Asphalt Binder

To account for these changes, two mix designs are performed on RAP samples batched to meet the gradation requirements of Table 3, one on the medium gradation and one on the coarse gradation. This provides an indication of the range of expected water and emulsion contents that might be needed in the field.

Table 3: Cold Recycling Gradation Requirements

Sieve Size	Medium Gradation	Coarse Gradation
	Percent Passing	
1 inch	100	100
¾ inch	85-95	80-90
No. 4	45-55	35-45
No. 30	5-15	2-7
No. 200	0.5-3.0	0.1-3.0

Laboratory Testing

Recommended Laboratory Tests

Table 4 presents a list of laboratory tests to be performed as part of the mix design.

Table 4: Laboratory Mix Design Tests

Design Parameters	Objective	Requirement
Gradation of Design Reclaimed Asphalt Pavement (RAP), AASHTO T 27	To ensure that the mix design meets the gradation specification	Coarse & Medium Gradation of Table 3
Asphalt Content of RAP, AASHTO T 164, Method A or B	General information only	Report[1]
Bulk Specific Gravity of Compacted Samples, AASHTO T 166	To determine air voids of compacted specimens	Report[1]
Maximum Theoretical Specific Gravity, AASHTO T 209	To determine air voids of compacted specimens	Report[1]
Air Voids of Compacted and Cured Specimens, AASHTO T 269	Information only: CIPR should not be designed, nor the asphalt emulsion content altered, to meet a specific air void content	Report[1]
Marshall Stability, Cured Specimen, AASHTO T 245, 104°F (40°C)	To evaluate cured strength	1,250 lb. Minimum
Marshall Retained Stability, AASHTO T 245, 104°F (40°C) Based on Moisture Conditioning on Cured Specimen	To evaluate resistance to moisture induced damage	70% minimum
Optional - Raveling Test, ASTM D 7196, 50°F (10°C), Medium Gradation of RAP, 50% Humidity	To determine mixtures resistance to raveling and evaluate curing	Report

1. These items are reported by convention and are necessary for mix design calculations and to assess the overall quality of the mix design.

The design emulsion content is the range of emulsion contents such that the cold mix requirements listed in Table 4 are met for both the coarse and medium gradations.

Optional Raveling Test

The raveling test (ASTM D 7196) is included in the Guidelines as optional. The test was developed by Road Science and their predecessors for their Reflex® emulsion, which is a solventless engineered emulsion that utilizes a chemical induced break rather than simple water evaporation. Required use of the raveling test could exclude currently used emulsions that contain solvents and do not rely on a chemical break.

The test is a modified slurry seal wet track abrasion test that measures the resistance of a partially cured and compacted CIPR test specimen to abrasion from a weighted rubber hose. After curing for the designated time at specified temperature and relative humidity, the samples are abraded in a modified slurry seal wet track abrasion device and the weight loss that occurs is measured against specified standards to assess raveling susceptibility potential.

The raveling test should be considered for use to evaluate different emulsion formulations and additives, particularly when excessive raveling is a concern or when accelerated curing of the mixture would be beneficial. This would typically be the case on projects where the CIPR mixture is exposed to excessive moisture or continually shaded.

Mix Design Report

The findings of a mix design should be presented in a mix design report. A good report should include the following data: 1) gradation of millings, 2) recommended water content range as a percentage of dry millings, 3) optimum emulsion content as a percentage of dry millings, 4) amount of additive as a percentage of dry millings, 5) corresponding density, 6) air void level, 7) absorbed water, 8) Marshall Stability, 9) retained stability and, as an option, 9) raveling at recommended moisture and emulsion contents.

COMPONENT MATERIALS

Recycling Agent (Asphalt Emulsion)

The proposed mix design will assist the designer with selection of the appropriate amount of asphalt emulsion and additives. However, more than one emulsified recycling agent (asphalt emulsion) could meet the design requirements and many different types of recycling agents are available for use with CIPR. The most popular recycling agents are polymer and non-polymer high float emulsions, cationic medium and slow set emulsions and engineered emulsions, which are typically modified cationic slow set emulsions. The following is a brief discussion of the properties of the commonly available asphalt emulsions used in CIPR.

High Float Emulsions

High float emulsions are often selected for their ability to soften old aged binder and their ability to coat coarser aggregates. High float emulsions are manufactured with a small amount of fluxing agent to promote coating and consequently, soften the old aged binder. Coating of dense graded material with high float emulsions tends to be selective with the smaller particles coated with a thick film of asphalt while the larger particles are partially coated (14).

Cationic Slow Set Emulsions

Slow setting emulsions have long workability times to ensure good mixing with dense-graded materials. Cationic slow set emulsions contain little to no solvents and are often preferred because solvents, if trapped in a CIPR mixture, can lead to performance issues. Cationic slow set emulsions tend to coat more of the fine portion of the mix with a more uniform, thinner film thickness and, as for all bituminous additives, the coated fine material acts as a mortar that binds the material together. Pozzolonic material, lime or cement, can be added to cationic materials to act as a catalyst to accelerate the buildup of cohesion, increasing initial strength and moisture resistance, and reducing curing time (14).

Polymer Modification

Polymer modification can enhance positive characteristics of emulsions resulting in higher cohesion of the binder and more rapid strength gain. Other advantages are increased resistance to moisture damage, reduced raveling and reduced cracking. Polymer modification allows the use of softer residual binders that are better able to soften the aged binder in the RAP (15) and will increase resistance to thermal cracking.

Engineered Emulsions

Emulsions can be “engineered” to provide selective properties for a given project. Properties that are engineered include mixing and coating ability, breaking times, curing times, moisture resistance, softening ability of the emulsion and stiffness properties of the residual binder. Properties are adjusted by numerous techniques including varying the residual binder content, stiffness of the residual binder, polymer modification, pH, and adding a fluxing agent, to name a few. There are limits, however, as to how much modification can be accomplished with a given grade or classification of recycling agent.

Recycling Additives

The most common recycling additives are lime and Portland cement. Additional aggregates are sometimes used as well.

Lime & Portland Cement

Due to the higher in-place voids, CIPR mixtures can be susceptible to moisture-induced damage (stripping). Because of this fact, some agencies require that either lime or an anti-strip agent be incorporated into the CIPR mix design. Other agencies require that these supplemental additives be added only when required by the mix design.[12]

[12] Of the 13 agencies that responded to the Transportation Agency Survey, presented in detail in Attachment B (10), KS, NV, UT and WA require lime, AZ requires an anti-strip agent and IA, MT, NE and CFLHD rely on the mix design.

Mixes that fail the retained stability test generally benefit greatly from the addition of 1.0-1.5 % hydrated lime or 0.5% Portland cement. Lime or Portland cement added to cationic materials act as a catalyst accelerating the buildup of cohesion and increased cohesion improves moisture resistance (14).

The use of lime and Portland cement, or polymer modification, could also assist in improving the dry stability requirements (Marshal stability) of the mix design. The benefits of lime are well documented, including improved resistance to moisture induced damage, rapid strength gain, improved resistance to permanent deformation and improved stability (16,17,18,19,20).

Care should be taken when using additives (Portland cement and lime) because they will affect the mixture breaking and curing times. Additives should be evaluated in the mix design and then with test strips in the field before final inclusion in the mix.

Add-Stone and Mix Gradation

Recycled asphalt pavement (RAP) milled from the existing surface comprises the primary aggregate in CIPR mixes. Uncoated aggregates (add-stone) are occasionally added to CIPR mixtures to improve aggregate gradation. The addition of add-stone is a useful practice if the mix design shows a quantifiable improvement in measured mix properties.

Gradation of mineral aggregate in CIPR can have an influence on mechanical properties of CIPR mixtures. Finer aggregate gradations tend to produce tender mixtures that are susceptible to permanent deformation whereas dense aggregate gradations produce better results (14).

Table 5 provides recommendations that have been reported in the literature on when the use of add-stone may be beneficial (14). Recommendations are based on the average percent passing the No. 4 sieve of aggregate recovered from the portion of pavement cores that will be milled and incorporated into the CIPR mixture.

Table 5. Recommendations for When Add-Stone May Be Beneficial

Average % Passing No. 4 Sieve of Aggregate Recovered from Pavement Cores	Beneficial Use of Add-Stone
< 65% Passing	Add-stone not required.
65-75% Passing	Add-stone may be beneficial if at optimum emulsion content lab compacted voids are < 9.0%.
> 75% Passing	Add-stone may be beneficial

CIPR mixtures may be designed with or without additional aggregate (add-stone) as long as the mixture meets the mix design requirements.

Construction Practices

This section of the Guideline presents a description of recommended construction processes and procedures. It is divided into four sections, designed to assist the engineer in understanding the construction process and its affect on the quality of the final CIPR pavement. These sections include 1) Construction Objectives, 2) CIPR Equipment and Materials, 3) Construction Considerations, and 4) Quality Control and Process Testing.

CONSTRUCTION OBJECTIVES

The CIPR construction objectives are to:

- Pulverize (mill) the existing asphalt pavement one lane wide,
- Add and blend new asphalt binder, additives and aggregates with RAP (millings),
- Mix the material,
- Place the recycled mix with a paver,
- Compact with heavy rollers,
- Cure the mix, and
- Place a wearing surface on top of the recycled pavement.

CIPR EQUIPMENT AND MATERIALS

Equipment

The aforementioned objectives can be achieved using various configurations of equipment ranging from multi-unit construction trains to two-unit and single unit trains. Therefore, most agencies specify equipment requirements but not specific equipment. CIPR equipment should be capable of:

- Milling the pavement to the full lane width and to the required depth and cross-slope,
- Controlling RAP size to 100 percent passing the 1.5 inch sieve,
- Introducing liquid additives accurately and shutting off the flow of additives automatically when the process stops or there is no RAP present,
- Mixing all components to a homogenous mass,
- Placing the mix to full lane width to the required grade and cross slope, and
- Compacting the mix to the required density.

Types of Equipment

CIPR may be accomplished using either single or multiple unit construction trains. Multi-unit trains have the highest level of mixture control and have high production capabilities. Multi-unit trains typically consist of a milling machine, a separate crushing and screening unit and a pugmill-mixing unit. A photograph of a multi-unit train is shown in Figure 5.

Figure 5. Multi-unit CIPR train

The train places the CIPR mixture in a windrow and a conventional paver with a windrow elevator picks up the mix and places the mixture full lane width for compaction. A photograph of a CIPR paver with windrow elevator attachment is shown in Figure 6.

Figure 6. CIPR paver with windrow elevator attachment (courtesy ARRA)

Two-unit trains, as shown in the photograph in Figure 7, typically consist of a milling machine and a separate mix-paver. Control of oversize RAP is by depositing the RAP off the milling machine belt over a grizzly, as shown in the photograph in Figure 8. The RAP is mixed with additives in the mix-paver, which also places the CIPR mixture full lane width for compaction.

Figure 7. Two-unit CIPR train

Figure 8. Grizzly for removing oversize RAP on two-unit train

Single unit trains consist of a milling/cutting head that removes the pavement to the required depth and cross slope, sizes the RAP and blends the additive with the RAP. Single unit trains do not contain crushing units, making control of the maximum size more difficult. A spray bar in the cutting chamber adds the liquid additives. The amount is based on volumetrics, determined by the cutting depth and width and the forward speed. Roadways that are badly distorted due to rutting or edge drop-off are not good candidates for CIPR with the single unit train because proper additive application rates would be difficult to ensure.

Equipment Requirements

Regardless of the configuration of the CIPR equipment, basic equipment requirements exist. Milling machines should be capable of milling the pavement to the desired depth and cross-slope. A crusher and scalper screen are required to control RAP size to 100% passing the 1.5 inch sieve or the contractor must remove any millings larger than 1.5 inch and dispose of as approved by the Engineer.

Liquid additives should be introduced using mass flow meters and should be integrated with a continuous RAP weighing system with positive displacement pumps and automatic interlock systems that shut off pumps when the process stops or no RAP is present.

CIPR equipment should be capable of mixing RAP and all additives to a homogenous mixture with uniform coating and all CIPR mixing equipment should be calibrated prior to the start of work.

Materials

Liquid Bituminous Material (Asphalt Emulsions)

Liquid bituminous material should be obtained from a Department approved source and the asphalt binder used to make emulsified recycling agent should be in compliance with the Bending Beam requirements of AASHTO M 320, the Performance Graded (PG) Asphalt Binder Specification, for the location (climatic conditions) of the project. Asphalt emulsion should be metered or weighed into the mass of cold milled material using a mass flow meter that will accurately measure the amount of asphalt emulsion to within plus or minus 0.5 percent of the amount required by the mix design or as adjusted in the field.

Water

Water should be added at the milling head to facilitate uniform mixing of the emulsified recycling agent and cold milled material. Water added by the milling machine should be measured, and the rate of added water should be between 0.5 and 5.0 percent of water added by the weight of the recycled pavement mixture per the approved mix design. The quantity of residual binder in the final recycled pavement mixture should not vary due to the addition of water.

Additives

Additives are used to improve the quality of the resulting CIPR pavement. Additives may be combined with bituminous material prior to construction or may be added to the mix during construction. Care should be taken when using additives (Portland cement and lime) because they will affect the mixture's breaking and curing times. The proportion and amounts of additive should be determined by the mix design and evaluated with test strips in the field. Adjustments in additive content should only be made by qualified individuals designated by the Contractor and approved by the Engineer.

The most common additives are Portland cement and lime. Portland cement or lime can be incorporated into the recycling process by dry spreading or as slurry, spread on the existing pavement surface prior to milling, or introduced at the mill head or directly into the pugmill. Figure 9 shows a photograph of lime slurry being introduced to the milling head.

Figure 9. Lime slurry being added to the milling head (courtesy ARRA)

Liquid additives, such as lime slurry or cement slurry, should be added at the milling head or introduced into the pugmill. Liquid additives should be metered or weighed into the mass of the cold milled material using a mass flow meter that will accurately measure the amount of slurry to within plus or minus 5 percent of the amount required by the mix design or as field adjusted.

Dry additives (lime, Portland cement, add-stone) are incorporated into CIPR mixtures by first placing the material in a windrow down the center of the pavement lane being treated in front of the milling operation. For single unit trains with no pugmill, dry additives must be spread uniformly across the width of milling. Figures 10 and 11 show photographs of dry additive (fly ash) and add-stone being placed on the roadway. The milling machine incorporates the material into the mix as it mills the existing HMA pavement. Dry spreading should be undertaken by means of a mechanical spreader capable of spreading the additive at the prescribed weight per unit area.

Figure 10. Vane spreader placing dry additive (fly ash)

Figure 11. Add-stone being uniformly placed across lane ahead of milling machine

Construction Considerations

Preconstruction Considerations

Mainline Pavement

It is important that the mainline pavement exhibit uniform thickness and bearing capacity prior to recycling. Areas with insufficient base or pavement will require excavation and inferior materials replaced with material of adequate bearing capacity. Particular attention should be given to areas of base or subbase failure, where unsuitable subgrade and/or base material will need replacement. Unsuitable subgrade and/or base material should be excavated and removed to a depth of 12 inches and replaced with aggregate base or millings. Backfill should be placed in layers to ensure adequate compaction and then compacted until the level of the existing road is reached.

Shoulders

It is recommended that asphalt shoulders be recycled at the same time as the mainline pavement. This prevents existing distress in the shoulder, typically cracks, from propagating into the recycled mix and HMA overlay. There are a number of important considerations that must be addressed during shoulder rehabilitation:

- The minimum HMA shoulder depth for recycling needs to be at least 1-inch greater than the recycle depth. Insufficient depth will result in subbase material being incorporated into the recycled pavement and may lead to increased quantities of emulsion and decreased pavement performance.

- Shoulders must be in fair condition for recycling. Severe alligator cracking reduces the milling machine’s ability to grind the shoulder material to the appropriate size, leading to oversized pieces of RAP being included in the pavement.

- Pavements with shoulders 4 feet wide or less can be recycled in one pass by using an appropriate sized extension to the milling machine. A second approach is to use a smaller milling machine to mill the shoulder and deposit the RAP in a windrow in front of the train. The windrow and full lane is then recycled in one pass. Shoulders wider than 10 feet can be recycled in one pass (21).

- If shoulders cannot be recycled with the pavement, they can be boxed out and replaced before or after recycling. Replacing shoulders before recycling aids in compacting the recycled mat. A second option, if the pavement is thick enough to recycle 4 inches and the shoulders are less than 1/3 the width of the mainline, is to remove the shoulders to a depth of 4 inches, mill the pavement to 4 inches and pave the recycled mat over mainline and shoulders 3 inches thick.

- Existing granular shoulders can be incorporated into the CIPR. When granular shoulders are incorporated in the CIPR, uncoated granular material should not exceed 25% of the resulting RAP. Excessive granular material incorporated into the recycled pavement, may lead to increased quantities of emulsion, and decreased pavement performance due to a large portion of the mixture being partially coated with asphalt.

Construction Considerations

The quality of CIPR construction activities can have a significant effect on the quality of the CIPR application. Some special considerations associated with each step in the construction process are outlined below:

Field Adjustments to the Mix

Changes in gradation of RAP occur throughout the day and these changes can result in changes in CIPR mix workability. Adjustments in mix water content or recycling agent content will be necessary to promote good coating and workability. Mix design optimum moisture and recycling agent contents are starting points for construction and changes to these values should be made judiciously and only by experienced personnel. However, in some cases rigid adherence to these original recommendations will result in less than optimum performance (15). The Contractor should inform the Engineer of any changes to the emulsion application rate and any changes greater than 0.5% from the mix design value should be approved by the Engineer.

Coating of particles in the mix should be visually monitored. Complete coating is desired but may not be possible in all instances. Add-stone in particular will only partially coat. All particles however should have some emulsion coating (22). The appearance of the paving mat after initial compaction can give an indication if adjustments to emulsion content are necessary. The mat should be brown and cohesive. A shiny black mat is an indication of too much emulsion (23) and excess raveling is an indication of too little emulsion.

If the mix is not sufficiently coated the mix water content should be increased first. Too little mix water results in mix segregation, raveling under traffic or poor density (23). Excess mix water may cause asphalt to flush to the surface and will retard curing.

If the mix is adequately coated, but lacks cohesion, the emulsion content should be increased. Adjustments in emulsion are typically made in 0.2% increments and should only be made by experienced personnel. The emulsion application rate can drop below the mix design value but any changes greater than 0.5% from the mix design value should be approved by the Engineer. Changes greater than 0.5% from the original mix design could indicate a significant change in the composition of the milled pavement and a new mix design may be required. At a minimum, field samples should be obtained and minimum Marshall stability and retained Marshall stability requirements verified before approving such a change.

An increase or decrease in emulsion content should be followed by an equivalent change in mix water content to keep the content of the total liquids the same. Too much emulsion will result in an unstable mix and too little emulsion may cause the mixture to ravel, although minor raveling is generally acceptable (23). Balling of fines in the windrow is usually the result of either excessive emulsion or excessive fines in the RAP (22).

Traffic should be allowed back on the CIPR mixture after a minimum two-hour cure period and traffic can be used to help evaluate the construction of the mix. Under traffic, mixtures with too much emulsion can rut and mixtures with too little emulsion can ravel. Raveled areas are generally repaired with a fog seal. Rutted areas should be removed and replaced or reworked by the Contractor (12).

CIPR Mix Placement

Conventional asphalt pavers, with automatic screed controls for grade and cross slope, are used to place the mix. The paver should operate as close to the milling machine as possible to reduce the fluids necessary for placement and reduce the aeration time required before compaction (15). The screed should be operated cold as a heated screed causes RAP to stick, tearing the mat. A heated screed will not promote extra density or reduced breaking time (24). Recycling should end 1-2 hours before sundown to allow adequate time to place and compact the CIPR mixture before turning the mat over to traffic. Figure 12 shows a paver placing the CIPR mix.

Figure 12. Paver placing CIPR mixture

Compaction

A CIPR mix is more viscous than conventional hot mix and requires heavier rollers. Compaction is accomplished with heavy pneumatic and double drum vibratory steel wheel rollers. It is not possible to compact CIPR mix to the same density range as hot mix. Well-compacted CIPR mix could have voids in the 9-14% range or higher (25). Figures 13 and 14 show photographs of steel wheel and pneumatic rollers compacting CIPR mix, respectively.

Figure 13. Double drum steel wheel roller compacting CIPR mix

Figure 14. Pneumatic roller compacting CIPR mix

Compaction commences after the mixture begins to break and when rolling does not cause undue displacement, cracking or shoving. This could take from 1 to 2 hours depending on environmental conditions. The mix should turn from a brown to a black color when the emulsion breaks. Emulsion and/or mix water can be heated to 120 - 170^{o}F to reduce curing or breaking problems in cool or damp conditions (23) but the emulsion supplier should be consulted before the emulsion is heated to a temperature greater 140^{o}F, since excess heat can be detrimental to some emulsion formulations.

Breakdown rolling is usually accomplished with heavy pneumatic-tired rollers followed by final rolling with double drum vibratory steel wheeled rollers. One or two initial passes with a double drum vibratory steel wheeled roller is often required to prevent excessive shoving of the CIPR mat with pneumatic rollers. Breakdown rolling with pneumatic rollers is continued until the roller "walks out" of the mix. Finish rolling to remove roller marks is accomplished with vibratory steel wheel rollers operated in static mode (1).

Weather Limitations

Rain during CIPR treatment or during the curing period can have an adverse effect on the CIPR mixture. This problem is minimized by carefully monitoring weather conditions and not scheduling, or by terminating CIPR activities, when rain is anticipated. A CIPR mixture that becomes unstable or ravels excessively due to rain should be reworked to assist drying of the mixture. The addition of dry additives, such as cement or fly ash, can be used to facilitate drying.

Curing

Compacted CIPR mixtures must cure before a wearing surface is placed. Sealing the surface prior to adequate moisture loss can result in premature failure of the CIPR mix and or the wearing surface mix (22). Rate of curing depends on several factors, including temperature and humidity levels. The additions of lime or Portland cement, and engineered emulsions have been reported to greatly accelerate the curing process (16). The emulsion and/or mix water can be heated to 120 - 170^{o}F to reduce curing or breaking problems in cool or damp conditions (23) but the emulsion supplier should be consulted before heating the emulsion to a temperature greater 140^{o}F as excess heat can be detrimental to some emulsion formulations.

Wearing Surface

Due to the high in-place air void content of CIPR mixtures, a wearing surface is necessary to protect the mixture from intrusion of surface moisture. For low traffic volume roads, single and double chip seals have been successfully employed. Double chip seals are usually recommended where snow plowing is required. For higher traffic volumes, conventional hot mix wearing surfaces have been employed. A tack coat can be applied at a rate similar to the fog seal to promote good bond between the CIPR and the asphalt overlay (1).

The thickness of the overlay should be based on traffic and existing support. The minimum recommended overlay thickness is 3 times the nominal maximum size (NMS) of the aggregate in the HMA overlay. Thin lifts (< 3 X NMS) are hard to adequately compact and a poorly compacted surface mix will not protect the CIPR from moisture intrusion (26). Rolling with a steel wheel roller immediately prior to placement of the wearing surface may be required to remove minor surface rutting in the CIPR mixture and seal the surface.

QUALITY CONTROL AND PROCESS TESTING

Establishing a quality control and process-testing program is important to ensure that cold in-place recycling and placement will conform to specifications. Two significant activities include the preparation of a test strip prior to construction and compaction testing during construction.

Test Strip and Start-Up Procedures

During the first day of construction operations, the construction of a test strip (a single lane width at least 1500 feet in length) can be used to demonstrate that the equipment, materials and processes proposed will produce a recycled pavement mixture layer that conforms to the requirements of the project specifications. Such a strip can also be used to determine the optimal rates for emulsified recycling agents, additives and water recommended for the mixture, and determine the sequence and manner of rolling necessary to obtain the maximum in-place density (break-over point).

The test strip is used to establish rolling patterns that result in optimum compaction. Passes with various combinations of rollers are evaluated and a nuclear density meter or equivalent is used to evaluate relative increase in density with roller passes. The number of passes that results in no further increase in density should be selected as the rolling pattern and the corresponding relative density of the mat recorded as the target density, which is used to assist in compaction monitoring.

Compaction Testing

Rolling procedures established in the test strip are followed and after placement and compaction, but prior to opening the roadway to traffic, the in-place density for any single test should exhibit a relative compaction of not less than 97 percent or greater than 102 percent of the target density established in the test strip. If additional rolling does not achieve the minimum 97 percent relative compaction, or the relative compaction is greater than 102 percent of the target density, mix properties have possibly changed and a new rolling pattern and new target density should be established. Compactive effort is not arbitrarily reduced due to high in-place relative density, as reducing compactive effort would result in higher in-place air voids and poor performance. However, care should be taken not to over-roll the mat based on visual observations of check cracking or shoving. A new rolling pattern should be established if the material being recycled changes.

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Appendix A

Proposed NYSDOT Cold In-Place Recycling Asphalt Concrete Laboratory Mix Design

1. SCOPE

This procedure is used to determine the percent and grade of recycling agent to use for recycling asphalt concrete when using Cold In-Place Recycling (CIPR) of bituminous pavements.

2. COLD MIX REQUIREMENTS

The recycled pavement mixture shall conform to the following quality requirements shown in Table 1.

Table 1. Cold Mix Requirements

Design Parameters	Requirement
Gradation of Design Reclaimed Asphalt Pavement (RAP), AASHTO T 27	Passing 1.5 inch
Asphalt Content of RAP, AASHTO T 164, Method A or B	Report
Bulk Specific Gravity of Compacted Samples (1) (2), AASHTO T 166	Report
Maximum Theoretical Specific Gravity (2), AASHTO T 209	Report
Air Voids of Compacted and Cured Specimens (2), AASHTO T 269	Report
Marshall Stability, Cured Specimen (2), AASHTO T 245, 104°F (40°C)	1,250 lbs. Minimum
Marshall Retained Stability, AASHTO T 245, 104°F (40°C) Based on Moisture Conditioning on Cured Specimen (2) (3)	70% minimum
Optional Raveling Test, ASTM D 7196, 50°F (10°C), Medium Gradation of RAP, 50% Humidity(4)	Report

Notes:
1. 4 inch diameter mold compaction based on either 75 blow Marshall each side or gyratory compactor at 30 gyrations.
2. Measurement on specimens after 140°F (60°C) curing to constant weight for no less than 16 hours and no more than 48 hours.
3. Vacuum saturation of 55 to 75 percent, water bath at 77°F (25°C) for 23 hours, last 30 to 40 minutes in 104°F (40°C) water bath.
4. A target value of 5% loss or less can be used.

3. PREPARATION OF SAMPLES

Sampling & Processing of Existing Asphalt Pavement Materials
Obtain cores from the areas to be recycled. It is recommended that six cores be extracted for each lane mile and where visual differences in the pavement are noticed. If cores show significant differences in various areas, such as different type or thickness of layers between cores, then separate mix designs will be performed for each of these pavement segments.

Cores are to be cut to the depth specified for the cold recycling project.

Milled RAP from the areas to be recycled or alternate means of obtaining RAP samples can be used as an alternative to cores.

Obtain sufficient RAP to use for mix design purposes and additional cores for asphalt content and gradation analysis of the existing pavement (to the specified milling depth). Approximately 350 lbs of RAP is required for mix design purposes.

Obtain representative sample of the RAP to be recycled and determine asphalt content of the RAP according to AASHTO T 164.

Determine the average asphalt content (using AASHTO T 164) and recovered aggregate gradation (using AASHTO T 30) of the cores for the depth specified for milling.

Perform two mix designs, one for each grading, by recombining the RAP material in the laboratory in order to meet the gradation criteria shown in Table 2.

Table 2. Cold Recycling Gradation Requirements

Sieve Size	Medium Gradation	Coarse gradation
	Percent Passing	
1 inch	100	100
¾ inch	85-95	80-90
No. 4	45-55	35-45
No. 30	5-15	2-7
No. 200	0.5-3.0	0.1-3.0

Gradation of the RAP after milling or crushing will be determined by AASHTO T 27 with the exception that drying of RAP samples to constant mass shall be performed at 104 ± 4°F (40 ± 2°C).

Additional Aggregates
CIPR mixtures may be designed with or without additional aggregate (add-stone) as long as the mixture meets the mix design requirements. Table 3 provides recommendations on when the use of add-stone may be beneficial, based on the average percent passing the No. 4 sieve of aggregate recovered from the portion of pavement cores that will be milled and incorporated into the CIPR mixture.

Table 3. Recommendations for When Add-Stone May Be Beneficial

Average % Passing No. 4 Sieve of Aggregate Recovered from Pavement Cores	**Beneficial Use of Add-Stone**
< 65% Passing	Add-stone not required.
65-75% Passing	Add-stone may be beneficial if at optimum emulsion content lab compacted voids are < 9.0%.
> 75% Passing	Add-stone may be beneficial

Additional aggregates for cold recycling of pavements, if required, shall be crushed stone or crushed gravel conforming to the requirements of Section 703-02, Coarse Aggregate, of the Standard Specifications.

When additional aggregate is used, the minimum content is 5.0% and the maximum content is 20.0%, regardless of the recycled mixture's design gradation. The percentage of additional aggregate is calculated as a percentage of the dry mass of millings.

Design the recycled mixture to conform to the aggregate gradation shown in Table 4.

Table 4. Combined Aggregate Gradation When Additional Aggregate is Required

		Percent Passing	
Sieve	Sieve (mm)	Minimum	Maximum
1 ½ in	37.5	100	-
1 in	25.0	95	100
½ in	12.5	70	85
¼ in	6.3	48	68
1/8 in	3.2	32	54
No. 20	0.850	15	30
No. 40	0.425	8	22
No. 80	0.180	4	14
No. 200	0.075	2	8

4. **MIXING**

Specimen size:
Determine the amount that will produce a 2.4 to 2.6 inch tall specimen when compacting 4-inch diameter specimens with either the Marshall compactor based on 75 blows on each side or the gyratory compactor at 30 gyrations for stability testing. Plus 1-inch material shall be excluded from 4-inch molds and replaced with an equal amount of minus 1-inch material.

Number of specimens
Choose three emulsion contents that bracket the estimated recommended emulsion content for all stability testing outlined in Table 1. Select three emulsion contents in either 0.5% or 1.0% increments covering a range typically between 0.5% and 4.0% by dry weight of RAP. Compact 6 samples at each emulsion content for stability testing, 3 for Marshall stability on cured samples and 3 for Marshall stability on cured samples for moisture conditioning.

Two specimens are required for Theoretical Maximum Specific Gravity according to AASHTO T 209 with the exception that loose RAP mixture shall be cured in an oven at 140 ± 2°F (60 ± 1°C) to constant weight but no more than 48 hours and no less than 16 hours. Constant weight is defined as 0.05% change in weight in 2 hours. Do not break any agglomerates that will not easily reduce with a flexible spatula. Test both specimens at the highest emulsion content in the design and back calculate for the lower emulsion contents. It is normally necessary to perform the dry-back procedure of AASHTO T 209 to adjust for uncoated particles.

Add moisture that is expected to be added at the milling head, typically 1.5 to 4.5 percent.

If any additives are in the mixture, introduce the additives in a similar manner that they will be added during field production.

Mixing of test specimens will be performed manually or with a mechanical bucket mixer or a combination of the two. Mix the RAP thoroughly with water first, then mix with emulsion at room temperature, 77 ± 4°F (25 ± 2°C). One specimen will be mixed at a time. Mixing time with emulsion should not exceed 60 seconds.

5. **COMPACTION**

After mixing, compact specimens immediately. Compact the specimens at room temperature 77 ± 4°F (25 ± 2°C).

Specimens will be compacted with a Marshall compactor by applying 75 blows per side for stability testing purposes using 4-inch molds or with Gyratory compactor at 30 gyrations for stability testing purposes using 4-inch molds.

Do not heat molds or Marshall compaction hammer.

If paper disks are used, place paper disks on the top and bottom of the specimen before compaction and remove paper disks from specimens immediately after compaction.

6. **CURING AFTER COMPACTION**

Extrude specimens from molds after compaction without damaging the samples. Carefully remove paper disks if used.

Place specimens in 140 ± 2°F (60 ± 1°C) forced draft oven with ventilation on sides and top. Place each specimen in a small container to account for material loss from the specimens. Cure compacted specimens at 140 ± 2°F (60 ± 1°C) to constant weight but do not heat for more than 48 hours and not less than 16 hours. Constant weight is defined as 0.05% change in weight in 2 hours. After curing, cool specimens at ambient temperature a minimum of 12 hours and a maximum of 24 hours.

Perform same oven conditioning and volumetric measurements on moisture-conditioned specimens as on other specimens.

Perform moisture conditioning on 3 compacted samples at each emulsion content by applying a vacuum of 13 to 67 kPa absolute pressures (10 to 26 in. of Hg partial pressure) for a time duration required to vacuum saturate samples to 55 to 75 percent. Saturation calculation shall be in accordance with AASHTO T 283. Soak moisture conditioned samples in a 77 ± 2°F (25 ± 1°C) water bath for 23 ± 1 hour, followed by a 30 to 40 min soak at 104 ± 2°F (40 ± 1°C).

7. **MEASUREMENTS**

Determine asphalt content of the RAP material to be recycled according to AASHTO T 164, Method A or B.

Determine bulk specific gravity of each compacted, cured and cooled specimen according to AASHTO T 166.

Determine specimen heights according to AASHTO T 245. Alternatively, the height can be obtained from the SGC readout if the Gyratory compactor is used.

Determine maximum theoretical specific gravity, AASHTO T 209, with the exception detailed in Section 4.

Determine air voids of the compacted and oven-cured samples at each emulsion content according to AASHTO T 269.

Determine corrected Marshall Stability by AASHTO T 245 at 104 ± 2°F (40 ± 1°C) after 2 hours temperature conditioning in a forced draft oven or by immersing in water bath for 30 to 40 minutes. Dry specimens shall not come in contact with water. This testing will be performed at the same time that the moisture-conditioned specimens are tested.

Determine Marshall Retained Stability. The average moisture conditioned specimen strength divided by the average dry specimen strength is referred to as retained stability.

If the optional raveling test is used, determine the Raveling Test by ASTM D 7196, using the medium gradation of RAP. Report the test temperature and relative humidity used. Typical conditions are 50ºF (10ºC) and 50% relative humidity.

8. EMULSION CONTENT SELECTION

Choose the design emulsion content such that the cold mix requirements listed in Table 1 are met.

9. REPORT

The report will contain the following minimum information: Gradation of RAP, RAP asphalt content, recommended water content range as a percentage of dry RAP, optimum emulsion content as a percentage of dry RAP, amount of additive as a percentage of dry RAP, amount of additional aggregates if any as a percentage of dry RAP, ratio of emulsion residue to cement, and corresponding density, air void level, Marshall stability, retained stability, compaction method used to determine any reported stability, and raveling at recommended moisture and emulsion contents. Include the emulsion and additive designation, company name and location; and residue content; and the additive designation, company name and location; and certificates of compliance for both.

Appendix B

Proposed Revisions: NYSDOT CIPR SPECIFICATION

DESCRIPTION

This specification covers the requirements for cold recycling of asphalt concrete. This work shall consist of preparing a mix design in accordance with the specifications and recycling the existing asphalt concrete pavement to the specified depth. The recycling shall be a process of milling the existing pavement, remixing with bituminous material (unmodified or modified) and aggregate, if required, reshaping and compacting the asphalt mixture. Pavement locations that are milled shall have material replaced on the same day. All work under this item shall be in accordance with these specifications and in conformity with the limits established by the Engineer.

MIX DESIGN

The rate of emulsified recycling agent and additive (s) to be added to the cold milled Reclaimed Asphalt Pavement (RAP) shall be determined by performing a preconstruction mix design for the recycled pavement mixture. RAP used in the mix design shall be obtained directly from the project site. RAP may be obtained either by coring or by milling as approved by the Engineer. Based on the characteristics of the RAP taken from the project site, more than one mix design may be required. The mix design for the recycled pavement mixture shall conform to the requirements of the *NYSDOT Cold In-Place Recycling Asphalt Concrete Laboratory Mix Design*.

Adjustments to the mix design may be made in the field as needed as provided by this specification. The Contractor is responsible for the final product. The recycled pavement mixture shall conform to the quality requirements shown in Table 1.

Table 1. Cold Mix Requirements

Design Parameters	Requirement
Gradation of Design Reclaimed Asphalt Pavement (RAP), AASHTO T 27	Passing 1.5 inch
Asphalt Content of RAP, AASHTO T 164, Method A or B	Report
Bulk Specific Gravity of Compacted Samples [1,2] AASHTO T 166	Report
Maximum Theoretical Specific Gravity [2], AASHTO T 209	Report
Air Voids of Compacted and Cured Specimens[2], AASHTO T 269	Report
Marshall Stability, Cured Specimen [2], AASHTO T 245, 104°F (40°C)	1,250 lbs. Minimum
Marshall Retained Stability, AASHTO T 245, 104°F (40°C) Based on Moisture Conditioning on Cured Specimen [2,3]	70% minimum
Optional Raveling Test, ASTM D 7196, 50°F (10°C), Medium Gradation of RAP, 50% Humidity[4]	Report

1.4-inch diameter mold compaction based on either 75 blow Marshall each side or gyratory compactor at 30 gyrations.

2. Measurement on specimens after 140°F (60°C) curing to constant weight for no less than 16 hours and no more than 48 hours.

3. Vacuum saturation of 55 to 75 percent, water bath at 77°F (25°C) for 23 hours, last 30 to 40 minutes in 104°F (40°C) water bath.

4.A target value of 5% loss or less can be used.

A mix design report shall be submitted to the Engineer two weeks prior to beginning the recycling operations. The mix design report shall include gradation of millings; recommended water content range as a percentage of dry millings; optimum emulsion content as a percentage of dry millings; amount of additive as a percentage of dry millings; and corresponding density, air void level, absorbed water, Marshall Stability, retained stability and raveling at recommended moisture and emulsion contents. Include the emulsion and additive designation, company name and location; and residue content; and the additive designation, company name and location; and certificates of compliance for both.

MATERIALS

Bituminous Material

Liquid bituminous material shall be obtained from a Department approved facility. All bituminous material proposed for use on Department projects shall be approved by the Director, Materials Bureau. The asphalt binder used to make the emulsified recycling agent must be in compliance with the Bending Beam requirements of the Performance Graded (PG) Asphalt Binder Specification, AASHTO M 320. The Engineer shall take one sample from each tank truck of bituminous material arriving on the project in accordance with Materials Method - NY 8.2. The sample shall be sent to the Materials Bureau with a completed BR170d form attached.

Water

Water used for cold in-place recycling shall be clean and free of foreign substances and shall not cause an adverse effect on either the emulsified recycling agent or the recycled pavement mixture. Water added at the milling machine shall be measured, and the rate of added water, determined by the mix design, can be between 0.5 and 5.0 percent, by weight of the RAP. Adjustments to the application rate shall be based on the opinion of the Contractor and any change in water content greater than 0.5% above the range given in the mix design must be approved by the Engineer. The quantity of residual recycling agent in the final recycled pavement mixture shall not vary due to the addition of water.

Additives

Additives may be used to improve the quality of the resulting recycled pavement. Additives may be combined with the bituminous material prior to construction or may be added to the mix during construction. The proportion and amounts of additive shall be determined by the mix design and approved by the Director, Materials Bureau.

Portland cement or lime: Portland cement or lime may be added to the recycled pavement mixture as determined by the mix design. Portland cement or lime may be incorporated into the recycling process by dry spreading or as a slurry spread on the existing pavement surface prior to milling or introduced at the mill head or directly in the pugmill at the discretion of the Contractor.

Two weeks prior to beginning the recycling operation, the Contractor shall inform the Engineer of the process to be used for incorporating lime or Portland cement into the recycling process. The Contractor shall submit to the Engineer a plan to ensure that the quantity of additive is in accordance with the approved mix design and can be adjusted as needed by the person designated by the Contractor to make adjustments in the field.

Lime slurry shall be produced from high-calcium quicklime or hydrated lime conforming to the provisions of the NYSDOT.

Portland cement shall conform to the provisions of the NYSDOT.

The Certificate of Compliance shall be submitted to the Engineer with a certified copy of the mass of each delivery.

Aggregate
Additional aggregate for cold recycling of pavements, if required, shall be crushed stone or crushed gravel conforming to the requirements of Section 703-02, Coarse Aggregate, of the Standard Specifications. The gradation and source of the aggregates shall be specified and included in the mix design.

Reclaimed Material
Asphalt pavement and any milled material, which has been removed and/or processed from the pavement, will be referred to as reclaimed material. Existing asphalt concrete pavement shall be cold milled, pulverized, crushed or sized and screened to 100 percent passing the 1½ inch sieve before mixing with liquid bituminous material. The contractor shall remove any millings larger than 1½ inch by screening or other means or break down by mechanical means to pass a 1½ inch sieve. Graded millings shall uniformly be incorporated into the recycled pavement mixture and oversized or deleterious material shall be disposed of as approved by the Engineer.

Design Guidelines
The recycled mixture consists of reclaimed material, additional aggregate if required, liquid bituminous material, additives and water.

The design liquid bituminous material content shall be determined by the mix design. The liquid bituminous material is calculated as a percentage of the dry mass of millings:

[mass of liquid bituminous material / mass of millings] X 100 = % liquid bituminous material

Recycled mixtures may be designed with or without additional aggregate as long as the mixture meets the requirements of the mix design. Additional aggregate may be beneficial, depending on the existing pavement’s gradation.

When additional aggregate is used, the minimum content is 5.0% and the maximum content is 20.0%, regardless of the recycled mixture’s design gradation. The percentage of additional aggregate is calculated as a percentage of the dry mass of millings:

[mass of additional aggregate / mass of millings] x 100 = % additional aggregate)

If additional aggregate is required, design the aggregate in the recycled mixture to conform to the following gradation:

		Percent Passing	
Sieve	Sieve (mm)	Minimum	Maximum
1 ½ in	37.5	100	-
1 in	25.0	95	100
½ in	12.5	70	85
¼ in	6.3	48	68
1/8 in	3.2	32	54
No. 20	0.850	15	30
No. 40	0.425	8	22
No. 80	0.180	4	14
No. 200	0.075	2	8

The Department shall obtain cores and supply the cores to the Contractor for the determination of the mix design. The Contractor shall supply the results of the mix design to the Department for approval two weeks prior to beginning work.

EQUIPMENT

Use equipment capable of:

- milling the existing pavement to the appropriate depth
- processing the reclaimed material to pass a 1 ½ inch sieve
- mixing the reclaimed material with liquid bituminous material
- introducing additives at the correct rate
- paving the reclaimed material to the correct grade.

Calibration

Calibrate the mixing equipment prior to the start of work, in accordance with established calibration procedures as detailed in the Procedural Directives of the Director, Materials Bureau. Submit the calibration results for approval to the Director, Materials Bureau at least 7 days prior to the start of work. The first calibration of each calendar year must be witnessed by Department personnel. Submit subsequent calibrations with written certification that proper procedures were followed and that all measurements and calculations are accurate. If the results submitted in subsequent calibrations are more than 5.0% different from the first calibration of the season, the equipment must be calibrated in the presence of Department personnel. Calibration approval is valid for 90 days from the date of calibration. Provide a copy of the calibration approval letter to the Engineer before the start of work. No cold recycling will be allowed under this contract until the calibration has been completed and approved. No payment will be made for material recycled by equipment without a valid calibration.

Proportioning for Portland Cement or Lime Slurry by Continuous Mixing: When a continuous proportioning operation for the production of slurry is used the proportioning device shall determine the exact ratio of water to Portland cement or lime at all production rates. Rate-of-flow indicators and totalizers for like materials shall be accurate within 0.5 percent when compared directly. The following methods shall be used:

1. Portland cement or dry lime shall be weighed using a belt scale. Belt scale accuracy shall be such that, when operating between 30 percent and 100 percent of production capacity, the average difference between the indicated mass of material delivered and the actual mass delivered will not exceed 0.5-percent of the actual mass for 3 individual runs. For any of the 3 individual runs, the indicated mass of material delivered shall not vary from the actual mass delivered by more than one percent of the actual mass. Test run duration shall be for at least 0.5-ton of cement or lime. Tests shall be run using cement or lime, as appropriate, and shall be weighed on a certified scale.

2. Water to be used in the slurry shall be measured with a meter. Meter accuracy shall be such that, when operating between 50 percent and 100 percent of production capacity, the difference between the indicated mass of water delivered and the actual mass delivered shall not exceed one percent of the actual mass for 3 individual runs. Tests shall be weighed on a certified scale. Test run duration shall be for at least 300 gallons.

3. Meters and scales used for the continuous proportioning of cement or lime and water shall be equipped with rate-of-flow indicators to show the rates of delivery of cement or lime and water and resettable totalizers so that the total amounts of cement or lime and water introduced into slurry storage tank can be determined. Individual feeds for water and cement or lime shall be equipped with no-flow devices, which shall stop slurry production when either of the individual ingredients is not being delivered to the slurry storage tank.

Proportioning for Portland Cement or Lime Slurry by Batch Mixing: When a batch type proportioning operation for the production of slurry is used the following methods shall be used:

1. Portland cement or dry lime shall be proportioned by mass. The weighing of the cement or lime shall be performed at a certified scale.

2. Water to be used in the slurry shall be measured with a meter. Meter accuracy shall be such that, when operating between 50 percent and 100 percent of production capacity, the difference between the indicated mass of water delivered and the actual mass delivered shall not exceed one percent of the actual mass for 3 individual runs. Tests shall be weighed on a certified scale. Test run duration shall be for at least 300 gallons.

3. The water meter shall be equipped with a resettable totalizer. When an automatic controller is used to batch the cement or lime it shall also control the proportioning of the water. When an automatic controller is used to proportion the water the indicated draft of the water shall be within one percent of its total draft mass.

Proportioning During the Cold In-Place Recycling Operation: Portland cement or lime slurry shall be metered or weighed into the mass of the cold milled material using a mass flow meter that will accurately measure the amount of cement or lime slurry to within plus or minus 5 percent of the amount required by the mix design or as adjusted in the field.

Emulsified recycling agent shall be metered or weighed into the mass of the cold milled material using a mass flow meter that will accurately measure the amount of emulsified recycling agent to within plus or minus 0.5 percent of the amount required by the mix design or as adjusted in the field.

Dry spreading of lime or cement shall be by means of a mechanical spreader capable of spreading the additive at a prescribed weight per unit area. The spreader shall have working scales and distance measuring devices to control the spread rate as required by these special provisions.

CONSTRUCTION DETAILS

Weather Limitations

This work will not be permitted when the existing pavement contains frost, when heavy rain is expected, or when the air or surface temperature is below 45°F or expected drop below 45°F within 24 hours. No material shall be placed from the last Saturday in September to May 1.

Spreading

The mixture shall be deposited in a windrow or directly into an approved bituminous paver equipped with a 30 foot moving reference and mechanically spread in a uniform layer so as to produce the specified thickness and surface tolerance after compaction. Excessive amounts of non-coated reclaimed material, which spill onto the milled surface, shall be removed, as ordered by the Engineer prior to placing the mixture. Remove, by hand, and dispose of all visible oversized crack filler in the cold milled material or in the recycled pavement mixture.

Bituminous Application Rate

The Contractor shall be allowed to adjust the application rate of the bituminous material from the design value as pavement conditions change. The bituminous application rate may be allowed to drop below the minimum design value. The Contractor shall inform the Engineer of any changes to the bituminous application rate and any changes greater than 0.5% from the mix design value must be approved by the Engineer.

Compaction

After the CIPR mixture has been spread, struck off and surface irregularities adjusted, it shall be thoroughly and uniformly compacted by rolling. The surface shall be rolled when the mixture is in the proper condition and when the rolling does not cause undue displacement, cracking or shoving. The CIPR mixture shall be initially rolled with the roller traveling parallel to the centerline of the pavement beginning at each edge and working toward the center on all normal crown sections. Banked curves shall be rolled starting at the low side edge and working toward the super-elevated edge. The roller drive roll or wheel shall be nearest the paver.

A pneumatic tire roller with a minimum ground contact pressure (GCP) of 80 psi will be supplied by the Contractor for compacting the cold recycled mix. The Contractor may choose to use vibratory compaction equipment for initial or intermediate rolling. The vibratory roller shall appear on the current Approved List - Bituminous Concrete Vibratory Compaction Equipment.

Initial and intermediate rollers shall operate at a uniform speed not to exceed 2.5 miles per hour (220 feet per minute). All turning of the compaction equipment shall be completed on material that has had a minimum of one roller pass. The Contractor shall note that if vibratory compaction equipment is used, they assume full responsibility for the cost of repairing all damages, which may occur to highway components and adjacent property.

The CIPR pavement course shall be finish rolled with a steel wheel tandem roller having a minimum weight of 8 tons. This finish roller shall add a minimum of two passes. Dual vibrating drum rollers meeting the requirements of a tandem roller and operating in the static mode may be used for the finished roller. This vibratory roller may be used as the initial or intermediate roller and the finish roller.

After compaction but prior to opening the roadway to traffic, the in-place density for any single test shall have a relative compaction of not less than 97 percent nor greater than 102 percent of the maximum in-place density determined by the rolling pattern as established in the test strip as required in the specification.

If additional rolling does not achieve the minimum 97 percent relative compaction, or the relative compaction is greater than 102 percent of the maximum in-place density a new rolling pattern shall be established such that a new maximum in-place density is determined. However, care should be taken not to over-roll the mat based on visual observations of check cracking or shoving. A new rolling pattern shall be established if the material being recycled changes.

Along forms, curbs, headers, walls and other areas not accessible to the rollers, the mixture shall be thoroughly compacted with mechanical tampers as directed by the Engineer. In depressed areas, a trench roller or a small vibratory roller approved by the Engineer may be used.

Any displacement occurring as a result of reversing the direction of the roller, or from other causes shall be corrected at once by the use of rakes and addition of fresh mixture as required. Care shall be exercised in rolling not to displace the line and grade of the edges of the bituminous mixture. To prevent adhesion of the mixture to the rollers, the wheels shall be kept properly moistened with water or water mixed with small quantities of detergent or other approved material, but in no case shall a solvent having an adverse affect upon the bituminous pavement be used.

Material that cannot be properly and adequately compacted to a stable condition shall be removed and replaced, as ordered by the Engineer, at the Contractor’s expense.

Quality Control Sampling and Testing

The Contractor shall perform process and quality control sampling and testing, and exercise management control to ensure that cold in-place recycling and placement conforms to these specifications. The Contractor and Engineer shall meet one week prior to the start of the cold in-place recycling operations to review the quality control plan.

Process and quality control, sampling, and testing shall be provided during the cold in-place recycling, placement, compaction and finishing. Sampling and testing shall be performed at a rate sufficient to ensure that cold in-place recycling, placement, compaction and finishing conforms to these specifications. A testing laboratory and personnel shall be provided for the performance of process and quality control testing. The Engineer shall have unrestricted access to mix design, sampling, and testing. The proficiency of testing laboratories and sampling and testing personnel shall be reviewed, qualified, certified and accepted by the contracting agency prior to construction.

The project shall be divided into no greater than 3,000 square yard lots. For each lot the Contractor shall provide the following information:

1. Length, width and depth of cut and measured mass (tons) of material processed.
2. Amount of emulsified recycling agent added (tons) and calculated percentage of emulsified recycling agent mass compared to the total mass of the material processed in the lot.
3. Amount of any dry additive (s) mixed in the recycling process, and calculated percentage of additive mass compared to the total mass of the material processed in the lot.
4. A sample from the windrow of recycled material behind the recycling equipment or of the sized RAP prior to the addition of the emulsified recycling agent. The sample shall be tested to ensure conformance with the maximum gradation size. If the result of the gradation test does not meet the specified maximum particle size, the test results shall be reported immediately to the Engineer, and the Contractor shall take corrective action to reprocess the material, until the processed material conforms to the requirement. The Contractor shall perform a wet field gradation for materials passing the 1-inch sieve though No. 8 sieve at least 2-3 times the first day of construction and 1-2 on subsequent days. The sieved sample should be compared to the gradation band determined from the mix design for the purpose of the Contractor adjusting the emulsified recycling agent accordingly.
5. The average in-place density using five individual nuclear density tests in each lot immediately following completion of compaction.
6. The ambient temperature and compacted recycled surface temperature.

The Contractor shall measure and record the actual depth of cut at both ends of the milling drum at least once every 100 yards along the cut length.

The Contractor shall provide daily reports of emulsified recycling agent and additive application rate and quantity, water application rate and quantity and average in-place density at final compaction.

Test Strip and Start-Up Procedures
As part of the first day of operations, the Contractor shall construct within the limits to be cold in-place recycled a test strip of recycled pavement mixture of a single lane width at least 1500 feet in length. The test strip section shall:

1. Demonstrate to the Engineer that the equipment, materials and processes proposed and furnished by the Contractor can produce a recycled pavement mixture layer that conforms to the requirements of project's provisions;
2. Determine the optimal rates for emulsified recycling agents, additives and water recommended for the mixture, and
3. Determine the sequence and manner of rolling necessary to obtain the maximum in-place density possible (break-over point).

Cold in-place recycling operations may continue through the first day, unless the Contractor does not meet the specified gradation, or if it has been demonstrated that the Contractor's equipment and process fail to meet the requirements for successful completion of the cold in-place recycling process in conformance with this specification. The Contractor shall use the same equipment, materials and construction methods used to construct an acceptable test strip for the remainder of the recycling operations unless adjustments are made by the Contractor and reported to the Engineer.

Cold in-place recycling operations shall not begin until a test strip conforming to the specifications has been constructed. Test strips that do not conform to the specification shall be reworked, recompacted or removed and replaced at the Contractor's expense.

Longitudinal Joints
Plan the recycling operation to ensure that the longitudinal joints in the recycled course will correspond with the edges of the proposed traffic lanes. Other joint arrangements require the Engineer's approval.

Paving operations shall match multiple lanes at the completion of the workday to minimize the exposure of longitudinal joints to traffic overnight. If any length of longitudinal joint is exposed at the end of the working day, construct the joint using a pneumatic tire roller to form the joint into a wedge shape and provide a smooth transition for traffic. Construct the wedge of recycled material at a slope of 1 on 8 or flatter to meet the existing pavement elevation. Do not overlap recycled material onto the existing pavement.

Brooming:
During the CIPR process and prior to placement of the next pavement course, the CIPR pavement and shoulders shall be broomed by the Contractor, as ordered by the Engineer, to remove loose stone or reclaimed material resulting from the recycling process.

Tolerance
The recycled surface shall be constructed to a 3/8 inch. The elevation difference at the longitudinal joint shall be constructed to a 0.2-inch tolerance. If, in the opinion of the Engineer, the pavement has not been constructed to these tolerances based upon visual observation or upon riding quality he/she may test the surface with a 15-foot straight edge or string line placed parallel to the centerline of the pavement. He/she may also test with a 10-foot straight edge or string line placed transversely to the center line of the pavement on any portion of the pavement. Variations exceeding 3/8 inch shall be satisfactorily corrected or the pavement re-laid at no additional cost to the Department as ordered by the Engineer.

Existing Pavement Cross Slopes
The existing pavement's cross slopes shall be an item of discussion at the pre-recycling meeting. If the existing pavement's cross slopes are according to the appropriate standards, then the cross slopes of the finished cold recycling shall match the existing. If the existing pavement's cross slopes are not in accordance with the appropriate standards, then the Contractor shall present a plan to the Engineer that attempts to bring the cross slopes of the finished cold recycling into conformance with the appropriate standards. The Engineer will be responsible for providing the

Contractor with the target cross slopes. However, the Contractor shall not be responsible for corrections to the cross slopes where sufficient material does not exist in the pavement to make such corrections.

Curing:
Before placing the next pavement course allow the recycled material to cure for a minimum of at least 2 days and until there is either less than 1.5 percent moisture remaining in the CIPR mixture, or less than 0.5% moisture remaining in the CIPR mixture above the residual moisture content of the pavement prior to recycling. The provisions of the paragraphs above, Brooming and Tolerance, apply from the time of recycling until the recycled material is overlaid, not to exceed 30 days.

Fog Seal
If the Contractor or Engineer determines that the recycled pavement surface requires a fog seal to correct an overly dry surface or to reduce the quantity of dry stone or reclaimed material pulled out by traffic and the Engineer agrees with that determination, fog seal may be applied. Fog seal (material costs only) is paid for only when the originally estimated amount for liquid bituminous material (Item 618.9902--02) has not been totally utilized. The amount of bituminous material that may be paid for fog seal and for the recycling is limited to an amount equal to 110% of the originally estimated amount of liquid bituminous material.

The liquid bituminous material and rate of application for the fog seal shall be chosen by the Contractor. The Contractor shall be responsible for maintenance and protection of traffic for the fog seal operation. A maintenance and protection of traffic plan for the fog seal operation shall be developed by the Contractor and submitted to the Engineer for approval. No extra payment shall be made for the fog seal application operation or the maintenance and protection of traffic.

Repairs to Damaged or Deficient Areas
Any mixture that ravels, becomes loose or broken, mixed with uncoated in-place materials, or is in anyway defective shall be reworked or removed and replaced with fresh recycled mix or fresh hot mixture and shall be compacted to conform with the surrounding area.

Any area showing an excess or deficiency of bituminous material shall be corrected to the satisfaction of the Engineer.

Ruts 3/8 inch or greater in depth which occur in the recycled mixture which cannot be corrected by rolling shall be corrected by a method approved by the Engineer.

All repairs or remedial actions necessary to correct damaged or deficient areas of recycled pavement shall be carried out at the Contractor's expense. The Contractor shall not be responsible for damage to the recycled mix as a result of other work performed on the pavement or shoulders.

Immediately after becoming aware of damage or deficiencies in the recycled mix the Engineer will notify the Contractor or the Contractor's designated representative. The Contractor shall make arrangements to repair the damaged or deficient areas to the satisfaction of the Engineer.

METHOD OF MEASUREMENT

Cold In-Place Recycling Asphalt Concrete. Measurement will be the number of square meters of pavement surface recycled in accordance with the specifications and contract documents.

Bituminous Material. Measurement will be the number of gallons, measured at 60 degrees F, incorporated into the work in accordance with the specifications.

Aggregate. Measurement will be the number of tons incorporated into the work in accordance with the specifications.

Additives. Measurement will be the number of tons incorporated into the work in accordance with the specifications.

BASIS OF PAYMENT

Cold In-Place Recycling Asphalt Concrete. Payment will be made at the unit price per square yard for the quantities measured. The unit price bid shall include the cost of all labor, materials, equipment and incidentals necessary to complete the work except that Bituminous Material and Aggregate will be paid for under their appropriate pay items. No separate payment will be made for the use of water in the mixing process. Any work required for the maintenance, replacement, or repair of the cold in-place recycled pavement prior to the acceptance of the contract, shall be done at no additional cost to the State.

Bituminous Material. Payment will be made at the unit price per gallon for the quantities measured. The unit price shall include the cost of furnishing all labor, materials and equipment necessary to incorporate the bituminous materials into the work.

Aggregate. Payment will be made at the unit price per ton for the quantities measured. The unit price shall include the cost of furnishing all labor, materials and equipment necessary to properly incorporate the aggregate into the work.

Additives Payment will be made at the unit price per ton for the quantities measured. The unit price shall include the cost of furnishing all labor, materials and equipment necessary to properly incorporate the additives into the work.

Payment will be made under:

Item No.	**Description**	**Pay Unit**
405.0201	Cold In-Place Recycling Asphalt Concrete	Square Yard
618.9902	Bituminous Material	Gallon
623.03	Crushed Stone (By Weight)	Ton

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment B: Transportation Agency Survey

Prepared for

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INTRODUCTION

Attachment B presents the results of a survey of transportation agencies. The goal was to gather information on current state-of-the-practice of CIPR.

The following sections describe the agencies contacted, the survey questionnaire, results from the survey and a review of agency CIPR specifications. Topics covered by the survey included specifications, mix designs, recycling additives, field monitoring, project selection, and performance evaluations. Topics covered in the agency specification review included weather restrictions, equipment, field monitoring, and overlay requirements.

PRELIMINARY SURVEY ACTIVITIES

In 2005, the Office of Pavement Technology, FHWA conducted a review of state use of CIPR (1). As a part of the review, FHWA sent a survey through AASHTO to all 50 states. Figure 1 shows the states response to the survey. Eighteen states, shown in red, reported using CIPR on four or more projects per year. Five states, shown in blue, reported low or limited use. Nineteen states, shown in green, reported no use and eight states, shown in white, did not respond to the survey. This FHWA survey was used as the basis for the selection of the participating transportation agencies. Twenty-four agencies were initially contacted for the survey. Of the twenty-four states contacted, twenty indicated that they were performing CIPR. Nineteen surveys were sent out and twelve were returned. One state, Nevada, indicated the requested information could be found in the literature (2).

SURVEY FINDINGS

Thirteen agencies that use CIPR are included in the survey. The survey results are shown in Table 2. Summaries of the findings from the survey are discussed below.

SPECIFICATIONS

Six agencies have specifications for CIPR in their standard specifications with the other seven using special provisions or supplemental specifications. All but two agencies indicated a requirement for metering of all liquid additives. All 13 agencies indicated a maximum RAP size with one agency allowing greater than 2 inches, three requiring less than 1.5 inches, eight requiring less than 1.25 inches and one requiring less than 1 inch. Three agencies indicated they required pugmill mixing of RAP and additives, all agencies require the mix be homogenous.

MIX DESIGN

Nine of the thirteen agencies indicated they performed some form of preliminary pavement evaluation prior to CIPR. Nine agencies required a mix design with seven of these agencies requiring the contractor provide the mix design. Three agencies have adopted the SemMaterials (now Road Science and formerly Koch Materials) mix design procedure for engineered emulsions. Of the four agencies that did not require mix designs, two indicated using a typical recycling agent content. Five agencies required either lime or an anti-strip agent with four agencies indicating their use only when required by the mix design.

RECYCLING ADDITIVES

Recycling additives varied from cationic slow and medium set emulsions to high float emulsions, with and without polymer modification, to engineered emulsions. Two agencies reported preferring expanded asphalt (foam) to asphalt emulsions. Only two agencies indicated they occasionally added virgin aggregates and one indicated this was only used in conjunction with lane widening.

FIELD MONITORING

All agencies performed some type of density or compaction monitoring. The specifics of density testing are discussed under the specification requirements shown in table 3. The majority of the agencies indicated a yield check of additives was performed. From a check of the specifications, most agencies monitor depth of milling, RAP maximum size and occasionally moisture content. Ohio reported testing moisture resistance of field produced mix.

PROJECT SELECTION

Ten agencies indicated that they had no official traffic restrictions on the use of CIPR. Of these ten agencies, four listed unofficial restrictions or qualifications. Two of these agencies said 15-16,000 ADT was the highest traffic they had cold recycled, one recommended no heavy truck traffic and all four said the majority of CIPR had been on low to moderate trafficked pavements. Two agencies indicated they had traffic restrictions and reserved CIPR for low to moderate traffic or < 4,000 ADT. Nevada, Kansas, Iowa, New Hampshire and New Mexico have all reported using CIPR on Interstate pavements. Two agencies did not respond to the question. All agencies have a procedure for determining CIRP eligibility. Most reported the procedure is a part of the agencies pavement management program. Most agencies indicated that CIRP was reserved for pavements with functional, not structural, deficiencies. Other requirements included a minimum pavement structure to prevent pavement breakthrough of the equipment. All agencies indicated overlay thicknesses are designed based on traffic with chip seals being used for low volume roads and 1.5 to 3 inch HMA overlays reported as typical.

PERFORMANCE EVALUATION

Six agencies indicated they have procedures in place to evaluate CIPR performance and eight agencies indicated they had performed performance or economic assessments. Six agencies indicated having prepared formal written reports on CIPR performance.

Reported problems with CIPR were few and were related to equipment breakthrough due to wet/soft subgrades, minor raveling and moisture/curing issues. The most common benefits to CIPR were reported as a cost effective rehabilitation procedure and reducing reflective cracking.

REVIEW OF AGENCY SPECIFICATIONS

Many agencies referred to their standard specifications or special provisions when filling out the survey. Each agency that responded to the survey either provided copies of their specifications or indicated where they could be found on their agency's web site. Table 3 is a summary of information found in the standard specifications and special provisions.

WEATHER REQUIREMENTS

All agency specifications reviewed had weather restrictions for CIPR. All agencies, with the exception of Arizona, restricted CIPR when the weather was rainy or foggy. Arizona restricted CIPR when, in the opinion of the engineer, existing or predicted weather conditions could adversely effect operations. Seven agencies restricted CIPR if freezing or cold (< 35^{o}F) weather was anticipated either overnight or within 48 hours. Seven of 13 agencies specified a minimum air temperature only. Two agencies specified a minimum pavement or material temperature only and four agencies specified both. Minimum air or ambient temperatures ranged from 50 to 65^{o}F. Minimum pavement or mixture temperatures varied from 40^{o}F to 70^{o}F. Five agencies also specified calendar restrictions for CIPR.

EQUIPMENT REQUIREMENTS

Equipment requirements varied but most agencies specified equipment requirements but not specific equipment. Most agencies require a closed loop system consisting of a crusher and scalper screen to control RAP size and a continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when the process stops or no RAP is present. All agencies required the RAP be mixed to a homogenous mixture with uniform coating. Nine agency specifications required a binder tolerance, seven required ± 0.2% and one each required ± 0.1% and ± 0.3%.

All agencies required the use of pneumatic rollers and double drum vibratory steel wheel rollers. A minimum tonnage was usually specified. For pneumatic rollers, four agencies required greater than 25 tons, five required a minimum of 25 tons, two required a minimum of 20 tons and one required less than 20 tons. All agencies required double drum vibratory steel wheel rollers and eight agencies required a minimum tonnage. Five agencies required a minimum 10-ton roller, two required a minimum 12-ton roller and one required a minimum 9-ton roller.

FIELD MONITORING

Six agencies used test strips to control or monitor compaction, requiring a minimum compaction of 96 or 97 percent of control strip density. Four agencies required compaction based on a laboratory compacted sample. The requirements depended on the compaction procedure utilized, which included standard proctor, 50-blow Marshall and Hveem compaction (AASHTO T 247). One agency used a method specification with a rolling pattern and one agency allowed all three procedures. Smoothness was checked by 11 agencies with nine using a straightedge, one using a profilograph and one using grade control on the paver.

OVERLAY PLACEMENT

Nine agencies had minimum moisture content requirements of the CIPR mixture prior to overlay. Five agencies require less than 1.5% moisture, three less than 2.0% moisture and one less than 2.5% moisture. Two agencies also have provisions for residual moisture in the pavement, adjusting minimum moisture contents if the milled pavement had high residual moisture content. Eight agencies had minimum CIPR mixture cure times or required the mixture be overlaid within a limited time frame. Four agencies required additional rolling prior to placing the required overlay.

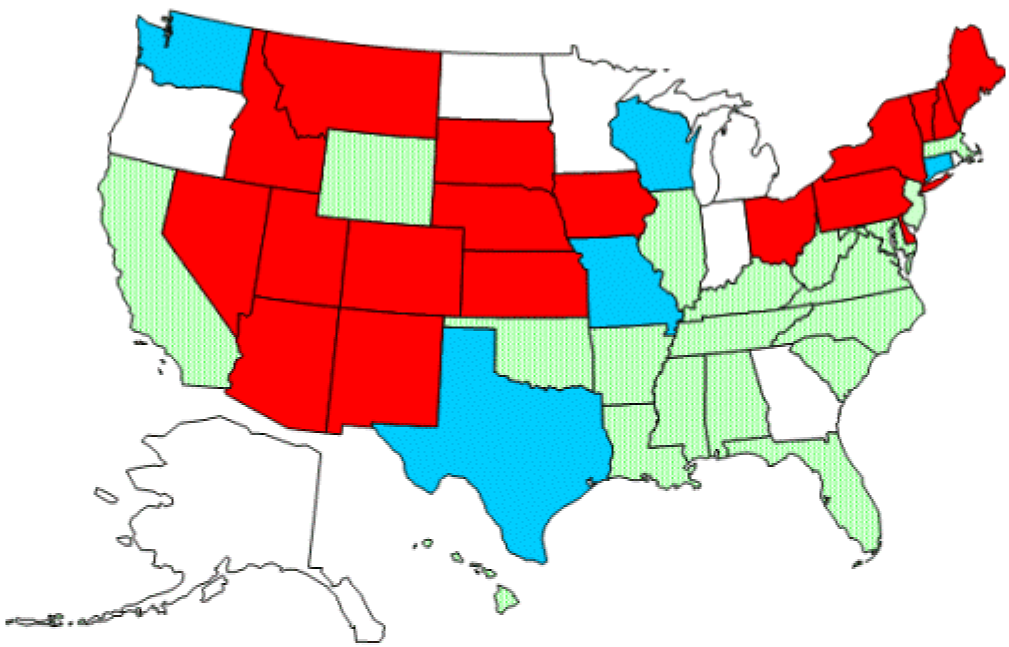

Figure 1 States use of CIPR (1).

C-06-21
Performance of Cold In-Place Recycling
Survey of CIPR Practice

Agency: _______________________ Contact person: ___________________
Date: __________________________ Title: ___________________________

1) Does your State make use of Cold In-Place Recycling (CIPR) as a pavement preservation / pavement rehabilitation method?
2) What are the CIPR design requirements and/or specifications used in your State?
3) What are the equipment requirements?
   a) Do you require computer monitoring/metering of liquid additives?
   b) Do you specify a maximum RAP size?
   c) Do you require pugmill mixing of materials?
   d) Other?
4) Do you have special construction procedures?
   a) Is pavement coring or any other preliminary pavement evaluation/testing required?
   b) Do you require a mix design? If so what procedure?
   c) Do you require the addition of lime or a liquid anti-strip agent?
   d) What recycling agents do you typically use / have you used?
   e) Do you require the addition of virgin aggregates?
   f) What type of density monitoring, if any, do you require during construction?
   g) What other QC / QA procedures are followed during construction?
   h) Other?
5) What types of roadways and/or traffic counts are eligible for CIPR in your State?
6) What type of overlay is placed over CIPR in your state and are they based on traffic?
7) Do you require a minimum cure period or minimum moisture content prior to placing the required overlay?
8) How do you determine which roadways are eligible for CIPR?
9) Do you have a procedure in-place for evaluating CIPR roadways?
10) Have you undertaken any CIPR performance or economic assessments?
11) Has your agency prepared any CIPR reports?
12) What problems has your agency experienced with CIPR?
13) What benefits has your agency experienced with CIPR?
14) Who are the primary CIPR contractors in your State?
15) Are you familiar with other agencies (e.g. states or provinces or contractors) that have significant experience with CIPR?

Figure 2 CIPR survey questionnaire.

Table 1. List of Agency Contacts and Survey Response

State DOT/Agency	Contact	Title	Status	Comments
Arizona	Chad Auker	Flagstaff Regional Materials Engr	Returned	
California	Joe Peterson	Materials Engineer	Not Sent	Use FDR not much CIPR
Colorado	Jay Goldbaum	Pavement Design Program Mgr	Not Sent	Use HIR not CIPR
Delaware	James Pappas	Chief, Materials & Research Engr	Returned	
Idaho	Mike Santi	Assistant Materials Engineer	Sent	
Iowa	Mike Heitzman	Former Bituminous Engineer	Returned	
Kansas	Rick Bareizinsky	Field Materials Engineer	Returned	
Maine	Richard Bradbury		Sent	
Montana	Dan Hill	Pavement Design Engineer	Returned	
Nebraska	Mick Syslo	Pavement Design Engineer	Returned	
Nevada	Sohila Bemanian	Former Asst. Materials Engineer	Not Sent	Referred to TRB paper
New Hampshire	Alan Rawson	Administrator	Returned	
New Mexico	Bryce Simons	Asphalt Materials Engineer	Sent	Reported use has decreased
New York	Russ Thielke		Sent	
Ohio	Dave Powers	Asphalt Materials Engineer	Returned	
Oklahoma	Danny Gierhart	Bituminius Materials Engineer	Not Sent	Only used experimentally
Oregon	Elizabeth Hunt	Pavement Services Engineer	Not Sent	Reported no use in years
Pennsylvania	Dean Maurer		Sent	
South Dakota	Gill Hedman	Pavement Design Engineer	Returned	
Utah	Scott Goodwin	Region 4 Pvmt. Management Engr	Returned	
Vermont	Mike Fowler	Pavement Management Engr	Sent	
Washington	Jeff Uhlmeyer	Pavement Design Engineer	Returned	
Ontario	Chris Raymond	Sr. Pavement Design Engineer	Sent	
CFLHD	Mike Voth	Pavement Discipline Leader	Returned	

Table 2. Survey of CIPR Practice

Survey Questions	Arizona	Delaware	Iowa	Kansas	Montana
1. Do you use CIPR?	Yes	Yes	Yes	Yes	Yes
2. Design requirements / specifications?	Special Provisions	Supplemental Specifications	Standard Specification	Standard Specification	Standard Specification
3. Equipment requirements?					
a. computer monitoring / metering of additives?	No	Metering	No	Metering	Metering
b. maximum RAP size?	< 1.25"	95% passing 2" sieve	98-100% < 1.25" 90-100 < 1"	< 1.25"	< 1.25"
c. Pugmill mixing?	No[1]	No[1]	No[1]	Yes	No[1]
d. Other?	See Specifications	See Specifications	See Specifications	See Specifications	See Specifications
4. Construction procedures **a. Pavement coring or other pavement evaluation?**	Yes		Yes, check for line and grade, weak or soft spots	Cores, DCP to 12" for CBR	
b. Require mix design?	By Contractor	By Contractor	By State	By Contractor	By Contractor
Procedure?	Not specified	Not specified	State procedure	SemMaterials	SemMaterials
c. Lime or anti-strip?	Yes, liquid anti-strip	No	As required	Lime	As required
d. Recycling additive					
1. Typical:	HFE-300P	CSS-1h	Foam	Engineered emulsions	Engineered emulsions
2. Have used:			Engineered emulsions	CSS	
3. Other:			CSS	Fly Ash	
e. Virgin aggregates?	No	No	No	No	No

[1] require uniform coating and homogenous mixture

Table 2 (Con't.). Survey of CIPR Practice

Survey Questions	Arizona	Delaware	Iowa	Kansas	Montana
f. Density monitoring during construction:	Method specification with test strip	See Specifications	See Specifications	See Specifications	See Specifications
g. Other QC/QA procedures?	See Specifications	See Specifications	Yield check of additives, line and grade	Moisture and yield check of additives	Yield check of additives
5. Roadways/traffic eligible CIPR?	2-lane hwy with ADT of 4000 vpd or less	No restrictions	Used mainly on low to moderate traffic, used as crack relief layer	All roadways, used to correct roughness & thermal cracking	
6. Overlay type & thickness?	Based on traffic, chip seal to 3" HMA		Determined by pvmt design, 3-4" HMA, highways, 2-3" County Roads	Based on traffic, 1.5" HMA low traffic to 5.5" HMA on I-70	
7. Minimum cure period or maximum moisture content prior to overlay?	1.5% or less	See Specifications	See Specifications	See Specifications	See Specifications
8. How determine roadways eligible for CIPR?	PM data, FWD testing, field evaluation		Functional overlay, min 6" existing HMA, used for reflective crack control	PMIS system, repair of rough wide transverse cracks.	
9. Procedure for evaluation of CIPR roadways?	No	No	Yes	Yes	No

Table 2 (Con't.). Survey of CIPR Practice

Survey Questions	Arizona	Delaware	Iowa	Kansas	Montana
10. Any CIPR performance or economic assessments?	Yes	No	Yes	Performance	Yes
11. Agency CIPR reports?	Yes	No	Yes	Yes	Yes
12. What problems experienced with CIPR?	No major problems - very selective in use	No major problems	Good performance, only one project with stability failure	Initially rutting with emulsions, fly ash caused cracking, now lime & engineered emulsions - no problems encountered	No major problems
13. What benefits experienced with CIPR?	Cost effective		Standard part of rehabilitation tool box	Reduced distress in reflective cracks compared to HMA overlay	
14. Primary CIPR contractors in state?	3		3	2	
15. Familiar with other agencies with CIPR experience?	Colorado, New Mexico & Nevada			New Mexico	

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	Nebraska	Nevada	New Hampshire	Ohio
1. Do you use CIPR?	Yes	Yes	Yes, 1991 - 2000	Yes - trail basis
2. Design requirements / specifications?	Special Provision	Standard Specification	Standard Specification	Special Provision
3. Equipment requirements?				
a. computer monitoring / metering of additives?	Metering	Metering	Metering	Metering
b. maximum RAP size?	< 1.25"	< 1.25"	100% pass 1.5" 90-100% pass 1"	98-100% pass 1.5" 100% pass 1"
c. Pugmill mixing?	No[1]	Yes	Yes	No[1]
d. Other?	See Specifications	See Specifications	See Specifications	See Specifications
4. Construction procedures **a. Pavement coring or other pavement evaluation?**		Identify distress and thickness of pvmt. Require min of 1.5" pvmt. below CIR depth	Asphalt content & gradation	Yes, including limited coring
b. Require mix design?	By Contractor	No	No	By Contractor
Procedure?	Not Specified	Use 1.5% recycling agent	Typically use 1-2% emulsion	Not Specified
c. Lime or anti-strip?	As required	Lime slurry at 1.5% CaO	No	
d. Recycling additive				
1. Typical:	CSS, HFE 300	CMS-2s	HFMS-2	Foam
2. Have used:	CSS-2P	Engineered emulsions	1 project w/ rejuvenating agent	Polymer modified & engineered emulsions
3. Other:	Fly Ash			
e. Virgin aggregates?	No	No	No, if not precoated could weaken CIPR mix	Allowed per some spces

[1] require uniform coating and homogenous mixture

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	Nebraska	Nevada	New Hampshire	Ohio
f. Density monitoring during construction:	See Specifications	See Specifications	See Specifications	See Specifications
g. Other QC/QA procedures?	Moisture and yield check of additives	See Specifications	Yield check of additives	Wet & Dry tensile strength, 1 set every 3 days, yield check of additives
5. Roadways/traffic eligible CIPR?	All roads, based on pavement structure & distress	All roads	No specified maximum but to date limited to 10,000 - 15,000 ADT with no significant structural failures & not used on heavy truck routes	All roads, majority on lower volume. Highest to date 16,000 ADT with 4,000 ADTT
6. Overlay type & thickness?	Min. 3" HMA most applications	Chip seal to 3" HMA. Use "a" coefficient of 0.26.	1" HMA for low traffic to 3" HMA for lower volume interstate	No standard, based on traffic
7. Minimum cure period or maximum moisture content prior to overlay?	See Specifications	See Specifications	See Specifications	See Specifications
8. How determine roadways eligible for CIPR?	PM data, Cores & FWD testing	Part of PMS procedure. CIR used to correct functional distress	Must be formally constructed with minimum pavement failures, not a heavy truck route. To date not used on roads with > 10,000 - 15,000 ADT	Sufficient thickness & sound base
9. Procedure for evaluation of CIPR roadways?	Yes	Yes	No formal procedure	No

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	Nebraska	Nevada	New Hampshire	Ohio
10. Any CIPR performance or economic assessments?	Ongoing	Yes	No formal assesments but is cheaper than FDR and appears to significantly retard reflective cracking	No
11. Agency CIPR reports?	No	Yes	No formal reports	No
12. What problems experienced with CIPR?	Only weather related issues & consistency problems	Most performing well with life expectancy of 15-20 years	No performance issues noted. Are careful with project selection and they have performed well. Traffic control can be an issue and must be an early project consideration	Weak areas during construction; road closure times
13. What benefits experienced with CIPR?	Reduced costs & maintaining pavement under traffic	Reported savings of over $600M over last 20 years compared to complete reconstruction.	Cost effective rehabilitation procedure that significantly retards reflective cracking with minimal traffic disruption	Nice crack free base to overlay at reasonable cost
14. Primary CIPR contractors in state?	Several	Several	1	
15. Familiar with other agencies with CIPR experience?			Ontario, Maine, Vermont & New York	Iowa, Maine

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	South Dakota	Utah	Washington	CFLHD
1. Do you use CIPR?	Yes	Yes	Yes	Yes
2. Design requirements / specifications?	Special Provision	Special Provision	Special Provision	Standard Specification
3. Equipment requirements?	Yes			
a. computer monitoring / metering of additives?	See Special Prov.	Metering	Metering	Metering
b. maximum RAP size?	100% pass 1.25" 95-100% pass 1"	< 1.25"	< 1.25"	< 1.0"
c. Pugmill mixing?	No[1]	Yes	Yes	Yes
d. Other?	See Specifications	See Specifications	See Specifications	See Specifications
4. Construction procedures				
a. Pavement coring or other pavement evaluation?	No	Yes	FWD testing & pavement coring to verify pavement condition.	Yes, for mix design
b. Require mix design?	No	By Contractor	No	Yes, in house
Procedure?		SemMaterials - Marshall compaction	Recommend 1.3-1.8% emulsion	Task Force 38
c. Lime or anti-strip?	No	Quick Lime	Typically require 1.5% lime injected as slurry at milling head	Lime as required
d. Recycling additive				
1. Typical:	AE 200S HFMS-2s	Engineered emulsion	CMS-2s	HFMS-2P
2. Have used:		CMS-2s	CSS-1	HFMS-2s & HFE-300
3. Other:			Engineered Emulsion	Engineered emulsion
e. Virgin aggregates?	No	No	No	For lane widening only

[1] require uniform coating and homogenous mixture

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	South Dakota	Utah	Washington	CFLHD
f. Density monitoring during construction:	See Specifications	See Specifications	See Specifications	See Specifications
g. Other QC/QA procedures?	Moisture and yield check of additives	Yield check of additives	Yield check of additives	Moisture and yield check of additives
5. Roadways/traffic eligible CIPR?	All roads	All roads are potential candidates. Performed on urban and rural Interstates to arterial and collectors	All roads, generally recommended for less 5000 ADT	All roads, decision based on economics, material compatibility & constructability issues
6. Overlay type & thickness?	3-4" HMA typical	Thickness based on thickness design, 3" to 6" HMA typical	Typically 1.75" HMA or chip seal, based on thickness design	Thickness based on traffic, is a designed overlay
7. Minimum cure period or maximum moisture content prior to overlay?	See Specifications	See Specifications	See Specifications	See Specifications
8. How determine roadways eligible for CIPR?	Min 8" agg base & 4" HMA	Any road unless moisture problems are present	Recommended for pavement with functional, not structural deficiencies	Project team decides based on field evaluation, economics, constructability & risk
9. Procedure for evaluation of CIPR roadways?	No	No formal procedure	Track performance in our Pavement Management System & occasional field reviews	Yes

Table 2 (con't.). Survey of CIPR Practice

Survey Questions	South Dakota	Utah	Washington	CFLHD
10. Any CIPR performance or economic assessments?	No	No	Yes	No formal but informal monitoring for over 20 years
11. Agency CIPR reports?	No	No	Yes	No
12. What problems experienced with CIPR?	Moisture prior to overlay, changed from 1.5% to 2% in 2008	None	Funding levels have prevented more use.	Very few problems but have experienced on a limited basis raveling under traffic, equipment breakthrough and curing difficulties in late season paving
13. What benefits experienced with CIPR?	Reduced cracking	Cost saving, use of an existing on the ground resource, and being preceived by the public as being somewhat green	CIPR pavements have shown excellent performance and have provided a cost effective rehabilitation alternative.	Cost effective, low risk rehabilitation procedure with relatively small impact to traveling public
14. Primary CIPR contractors in state?	2	3	1	4
15. Familiar with other agencies with CIPR experience?	No	Colorado & Nevada	Oregon & Nevada	Nevada

Table 3. Survey of Agency CIPR Specifications

Specification Requirements	Arizona	Delaware	Iowa
Specification	408COREC	401636	Sec 2318
Weather restrictions			
Minimum ambient temperature	65F and rising	55F and rising	≥ 60F
Minimum mixture / surface temperature	≥ 65F		
Weather conditions	No existing or expected weather that could adversely affect opperations	Not foggy and no night temps below freezing	Not rainy or foggy
Recycling window	Varies by project		May 1 to Oct. 1
Compaction requirements			
Method	Method Specification	%Gmm, %field compacted sample or % test strip	% Laboratory compacted sample
Density requirements	Min 9 pases pneumatic rollers or until no displacement or roller walks out. Min 2 coverages steel wheel roller to remove roller marks	Min 88% Gmm or 93% field compacted sample or 96% of test strip	Min 92% non primary & min 94% primary of IM 504
Density measurement			Nuclear gauge
Frequency			Min 7 moisture & density tests/day
Other	No compaction until emulsion breaks or two hours, no traffic on compacted mat for min 2 hours		

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Arizona	Delaware	Iowa
Overlay requirements			
Minimum moisture content	≤ 1.5%		Less 1.5% or Less 0.3% above residual
Minimum cover/cure time		Minimum 1 week cure	
Rerolling prior to overlay			Within 2 days if required to meet density
Other requirements			
CIR equipment			
Crusher screening unit			
Metering system	Required	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	
Mixing requirements	Mix to homogenous mixture	Mix to homogenous mixture	Mix to homogenous mixture
Binder content	Maintain binder ± 0.3%		Maintain binder ± 0.2%
Water	Requires metering	Requires metering	Requires metering

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Arizona	Delaware	Iowa
Compaction equipment			
Pneumatic rollers	Two, min 30 tons, min 90 psi tire pressure	One, min. 25 tons	One, min. 25 tons
Vibratory steel wheel rollers	One, min. 12 tons	One, min. 12 tons	One required, no weigtt spec
Other			
Smoothness	Straighedge 0.25" in 10'	Straighedge 0.25" in 10'	

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification Requirements	Kansas	Montana	Nebraska
Specification	Sec 604	Sec 405-1	Special Provision
Weather restrictions			
Minimum ambient temperature	50F and rising	≥ 55F	≥ 60F
Minimum mixture / surface temperature	≥ 50 F of mixed material		
Weather conditions	Not rainy, foggy no freezing within 48 hrs	Not rainy or foggy, no temperatures below 35F in 24 hrs	Not rainy, foggy
Recycling window		May 15 to Aug 15	June 1 to Sept 22
Compaction requirements			
Method	% Test strip	% Test strip	% Test strip
Density requirements	97% of test strip, min 6 coverages - discontinue when 4 coverages fails to increase density more than 1 pcf	97% test strip, temperature > 68F	97% field test strip
Density measurement			Nuclear gauge
Frequency			Min 1 per 0.5 mile
Other	Paver within 150 ft of mixing unit, start rolling min 30 minutes after placement	Start rolling min 30 minutes after placement, finish within 1 hr.	

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Kansas	Montana	Nebraska
Overlay requirements			
Minimum moisture content	Maximum 2.0% or as approved by engineer	Less 1.5%	Less 2.5%
Minimum cover/cure time	Fog seal after min 7 days, cover within 21 days	Cover within 2 weeks	
Rerolling prior to overlay			Next day
Other requirements			
CIR equipment			
Crusher screening unit	Closed loop system consisting of crusher and scalper screen to control RAP size.	Closed loop system consisting of crusher and scalper screen to control RAP size.	
Metering system	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.
Mixing requirements	Mix to homogenous mixture	Mix to homogenous mixture	Mix to homogenous mixture
Binder content	Maintain binder ± 0.2%	Maintain binder ± 0.2%	Maintain binder ± 0.2%
Water	Requires metering	Requires metering	Requires metering

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Kansas	Montana	Nebraska
Compaction equipment			
Pneumatic rollers	One, min 30 tons, min 90 psi tire pressure	One, min. 20 tons	One, min 13 tons
Vibratory steel wheel rollers	Min. 10 tons, 6.5 ft wide drum	Two, min. 10 tons	One, min. 9 tons
Other			Min. one 12 ton pad foot roller
Smoothness	Profilograph	Straightedge 0.25" in 10'	Straightedge 0.5" in 10'

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification Requirements	Nevada	New Hampshire	Ohio
Specification	Sec 404	Special Provision	Special Provision
Weather restrictions			
Minimum ambient temperature		min 50F	≥ 60F
Minimum mix/ surface temperature	pavement surface ≥ 60F and rising		
Weather conditions	No stormy weather or temperatures below 35F within 48 hrs	Not rainy or foggy	Not rainy or foggy
Recycling window			May 1 to Oct 1
Compaction requirements			
Method	% Test strip	Test strip to establish rolling pattern	% Laboratory compacted sample
Density requirements		Rolling shall continue until no further displacement observed by the engineer	100% of field compacted ASTM D698
Density measurement		Nuclear gauge	Nuclear gauge
Frequency			
Other	Delay compaction 1-2 hrs after placement, stop placement min 3 hrs before sunset, no traffic for min 2 hrs		No more 2 tests less 100%. Avg of ten tests > 95% or top 2" removed and replaced with HMA

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Nevada	New Hampshire	Ohio
Overlay requirements			
Minimum moisture content	Less 1%		< 0.3% above residual or 2%, whichever greater
Minimum cover/cure time	Minimum 10 day cure	Minimum 14 day cure	Minimum 2 day cure
Rerolling prior to overlay	Between 3 & 15 days		
Other requirements		No traffic for 2 hrs	
CIR equipment			
Crusher screening unit	Closed loop system consisting of crusher and scalper screen to control RAP size.		
Metering system	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	
Mixing requirements	Mix to homogenous mixture	Mix to homogenous mixture	
Binder content		Maintain binder ± 0.2%	
Water	Requires metering	Requires metering	

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Nevada	New Hampshire	Ohio
Compaction equipment			
Pneumatic rollers	Two, min 25 tons	One, min 30 tons	One, min. 25 tons
Vibratory steel wheel rollers	1 min 10 tons	Required, no weight spec	One required, no weight spec
Other			
Smoothness	Straightedge 0.25" in 12 ft		Straightedge 3/8" in 10'

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification Requirements	South Dakota	Utah
Specification	Special Provision	02968S
Weather restrictions		
Minimum ambient temperature	60F and rising	≥ 50F and projected ≥ 60F
Minimum mix/ surface temperature		≥ 50F and projected ≥ 60F
Weather conditions	No rain or foggy conditions	No rain or fog or night temperatures below 35F
Recycling window		
Compaction requirements		
Method	% Test strip	% Laboratory compacted sample
Density requirements	97% of test strip, temperature > 60F	50-blow Marshall of field sample cured at 140F for 3 hrs
Density measurement	Nuclear gauge	Nuclear gauge
Frequency		1-per day, avg 3 nuke vs 3 lab molded
Other		Paver within 300 ft of train, rollers within 1000 ft paver

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	South Dakota	Utah
Overlay requirements		
Minimum moisture content	Less 2.0%	Less 2.0%
Minimum cover/cure time		
Rerolling prior to overlay		
Other requirements		
CIR equipment		
Crusher screening unit	Closed loop system consisting of crusher and scalper screen to control RAP size.	
Metering system	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.
Mixing requirements	Mix to homogenous mixture	Mix to homogenous mixture
Binder content	Maintain binder ± 0.2%	
Water	Requires metering	Requires metering

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	South Dakota	Utah
Compaction equipment		
Pneumatic rollers	One, min. 250 lbs/in of width	Min. 20 tons
Vibratory steel wheel rollers	Min. 275 lbs/in of rolling width	Min 10 tons
Other		Min. 3 rollers
Smoothness	Stringline on paver	Straightedge 3/8" in 10'

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification Requirements	Washington	CFLHD
Specification	Special Provision	416
Weather restrictions		
Minimum ambient temperature		Air temperature in shade > 50F
Minimum mix/ surface temperature	Surface 70F & rising	Pavement surface > 40F
Weather conditions	No rain or temperatures below 40F within 48 hrs	No rain, foggy, freezing weather within 24 hrs
Recycling window		
Compaction requirements		
Method	Method specification	% Laboratory compacted sample
Density requirements	Require establishment of rolling pattern	88% of AASHTO T 247 at 140F for initial compaction; 92% for final compaction.
Density measurement		Nuclear gauge
Frequency		1 per 1200 sy
Other		Begin compaction 1-2 hrs after placing

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Washington	CFLHD
Overlay requirements		
Minimum moisture content		Less 1.5% or 21 days
Minimum cover/cure time	Minimum 10 day cure	Within 21 days with lime
Rerolling prior to overlay	After 5-7 days with pavement temperature > 90F	
Other requirements	Fog seal after compaction	
CIR equipment		
Crusher screening unit		Require milling pass 1" screen
Metering system	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.	Continuous weighing system with positive displacement pumps and automatic interlock system that shuts off pumps when process stops or no RAP present.
Mixing requirements	Mix to homogenous mixture	Mix to homogenous mixture
Binder content	Maintain binder ± 0.2%	Maintain binder ± 0.1%
Water	Requires metering	Requires metering

Table 3 (Con't.). Survey of Agency CIPR Specifications

Specification	Washington	CFLHD
Compaction equipment		
Pneumatic rollers	Two, min.25 tons	One, min. 27 tons
Vibratory steel wheel rollers	One, min. 10 tons	Required, no weight spec
Other		
Smoothness	Straightedge 0.03' in 10'	Straightedge 3/8" in 10'

REFERENCES

1. *States Use of CIR.* http://www.fhwa.dot.gov/pavement/recycling/CIR/. Accessed July 23, 2008.
2. Bemanian, Sohila, P. Polish and G Maurer. “Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice.” *Transportation Research Record: Journal of the Transportation Research Board, No. 1949*, Transportation Research Board, National Research Council, Washington, D.C., January 2006, pp. 54-71.

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment C: Indices and Models

Prepared for

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TABLE OF CONTENTS

Introduction

Attachment C presents a general overview of the three Pavement Condition Indices (PCI), the Life-Cycle Model used in the Comparative Performance Analysis and the Life Cycle Modeling presented in detail in Attachments D and E of this report, respectively. More detailed information is available in each of the aforementioned Attachments.

PCI Methodologies

Most of the "visually-based" PCI indices available have similar evaluation components. Some have qualitative rating criteria for each respective component and some have quantitative criteria. Three PCI indices were selected for use in the evaluation. In descending order of preference they include:

1) ASTM D 6433-07,
2) RSMS01, and
3) Asphalt Institute IS-169.

A brief description of each procedure follows.

ASTM D 6433-07

ASTM D 6433-07, Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys is the most comprehensive visual procedure available for determining the condition of an existing pavement. The procedure was originally developed by the US Army Corps of Engineers and has been verified and adopted by the Department of Defense and the American Public Works Association (APWA).

The practice quantifies the condition of a pavement using a Pavement Condition Index (PCI), a numerical rating of the pavement condition that ranges from 0 to 100 with 0 being the worst possible condition and 100 the best possible condition. The PCI rates the surface condition of a pavement. The practice also contains a pavement condition rating which is a verbal description of the pavement condition as a function of the PCI. Table 1 shows the PCI rating scale as listed in ASTM D 6433.

Table 1. Pavement Condition Index Rating Scale

PCI	Rating
86-100	Good
71-85	Satisfactory
56-70	Fair
41-55	Poor
26-40	Very Poor
11-25	Serious
0-10	Failed

When using ASTM D 6433, each pavement is divided into branches that are further divided into sections. Each section is then divided into sample units and the type and severity of distress is assessed by a visual inspection of each sample unit. The recommended size of a sample unit for asphalt pavements is approximately 2500 square feet, or a 100-foot long section of a two-lane highway. For large sections it is recommended that approximately 10% of each section be sampled.

RSMS01

The RSMS program is a visual distress program that was developed at the University of New Hampshire uses visual distress surveys for fatigue cracking, longitudinal and transverse cracking, edge cracking, patches and potholes, roughness, rutting and drainage.

The procedure recommends quantifying distress based on severity and extent using SHRP –P-338 Distress Identification Manual for the Long-Term Pavement Performance Project; however, other methods may be employed.

Fatigue cracking, longitudinal and transverse cracking and edge cracking are each given a rating of 0-9 based on extent and severity as shown in Table 3. Patches and potholes are rated from 0-3 based on extent as shown in Table 3. Roughness and drainage are quantified from 1-3 as good, fair and poor. Rutting is assigned a rating from 1-3 based on rut depth as shown in Table 3.

Table 3. Condition Survey for RSMS Program

Distress	Severity	Extent			
		No Defects	Low <10%	Med.10-30%	High >30%
Fatigue, Long/Trans & Edge Cracking	Low	0	1	2	3
	Medium		4	5	6
	High		7	8	9
Patch/Potholes		0	1	2	3
			Good	Fair	Poor
Roughness, Drainage		0	1	2	3
			None	0-1 inch	>1 inch
Rutting					

The RSMS program develops a Pavement Condition Indicator or PCI for each sample unit and for each class of pavement (CIPR, mill & fill. 2-course overlay). The Pavement Condition Indicator is not the same as the PCI computed from ASTM D 6433.

A RSMS Program User Manual is available (and somewhat voluminous) and can be sent under a separate cover upon request.

Asphalt Institute IS-169

The Asphalt Institute publication IS-169, A Pavement Rating System for Low-Volume Roads, is used by many local jurisdictions to evaluate roads, streets and parking lots. IS-169 provides a visually-based procedure for inspecting a pavement that involves, similar to other visually-based methods, first driving slowly over the road to get an overall impression of its condition; and then making a thorough inspection on foot, making rough notes on the type and extent of distress as one goes along. When the inspection is completed, the rating form is filled out. It may be useful to drive again slowly over the pavement after filling out the rating form.

A detailed description of the procedure is presented in Asphalt Institute Publication IS-169. A listing of the IS-169 Condition survey form is presented in Table 4.

Under this rating system, the less serious problems are assigned values between 0 and 5. Defects of a more serious nature (i.e., those directly related to the strength of the pavement) are rated on a scale of 0 to 10. A rating of 0 means that the pavement is free of that particular type of distress.

When assigning a rating to a particular type of defect, IS-169 takes into account both extent and severity. For example, a rating of 10 for "rutting" would indicate that it occurs on much or all of the road, and that the ruts are probably deep enough to be a safety hazard, especially during rain, and an impediment to traffic at all times. On the other hand, a rating of 1 for "corrugations" would indicate that corrugations, although evident, are not numerous and that at present the distortions are not very large.

After each defect is rated, the individual ratings are added. This sum is then subtracted from 100, and the result is simply called the "condition rating."

Table 4. Condition Survey for IS-169 Program

ASPHALT PAVEMENT RATING FORM

STREET OR ROUTE ___________________________ CITY OR COUNTY ______________

LENGTH OF PROJECT ________________________ WIDTH ___________________

PAVEMENT TYPE ______________________________ DATE ______________________

(Note: A rating of "0" indicates defect does not occur)

DEFECTS	RATING
Transverse Cracks	0-5
Longitudinal Cracks	0-5
Alligator Cracks	0-10
Shrinkage Cracks	0-5
Rutting	0-10
Corrugations	0-5
Raveling	0-5
Shoving or Pushing	0-10
Pot Holes	0-10
Excess Asphalt	0-10
Polished Aggregate	0-5
Deficient Drainage	0-10
Overall Riding Quality (0 is excellent; 10 is very poor)	0-10

Sum of Defects ________

Condition Rating = 100 — Sum of Defects
= 100 —___________

Condition Rating = [ ]

Recommended Life Cycle Model

The life cycle model selected for use was the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE). This model was developed at the University of California, Berkeley, under FHWA sponsorship in 2003.

The program is a computer based decision support tool to model economic costs and environmental effects of highway construction and maintenance activities.

The program and user manual is available as a free download from the Recycled Materials Resource Center web site (http://www.rmrc.unh.edu/Resources/CD/PaLATE/PaLATE.htm).

It has been used by the Transportation Ministry in Ontario Canada to perform life cycle environmental and economic analysis on its CIPR pavements.

The program evaluates life cycle costs based on design, materials production, construction, use/operation, maintenance and landfill.

Input requirements are quantities and densities for each material type in initial construction and maintenance, haul distances and modes of transportation, equipment and unit costs.

Outputs are a cost analysis and environmental impact. Cost analysis consists of net present value by initial construction, maintenances and total. The net present values are also analyzed by materials and process costs.

Environmental impact factors include energy and water consumption, air emissions of NO_x, SO_2, CO_2, PM_{10} and CO, toxic releases of lead and mercury, RCRA hazardous waste generation and human health implications (HTP cancerous and non-cancerous).

The environmental impacts are divided into a number of phases for analysis. These include materials production materials transportation and construction process (equipment).

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment D: Comparative Performance Analysis

Prepared for

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INTRODUCTION

This Attachment D report presents the results and analysis of comparative condition surveys that were conducted on selected Cold-In-Place Recycled (CIPR), Mill and Fill (MF) and Two Course Overlay (TCO) pavements. The goal was to assess whether differences in the relative performance of CIPR, MF and TCO pavements could be derived from the field surveys and the associated condition indices calculated for each pavement grouping.

The report contains a description of:

- The Pavement Survey Methods and Condition Indices (PCI) used to establish the condition of the pavements surveyed,
- The pavement sections included in the analysis,
- The comparative performance of CIPR, MF and TCO pavements based on the condition indices findings,
- The relationship between NYSDOT Sufficiency Rating index (SR) and PCI indices used in the analysis, and a
- A comparative summary of the distress encountered for CIPR, MF and TCO pavements from the condition surveys.

PAVEMENT SURVEY METHODS

Three independent pavement condition survey methods were conducted during the field evaluations:

1. ASTM D 6433-07 Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys (1);
2. RSMS01, developed by the University of New Hampshire (2); and
3. Asphalt Institute Publication IS-169, A Pavement Rating System for Low-Volume Roads (3).

A description of each method is outlined below.

ASTM D 6433-07

ASTM D 6433-07 is one of the most comprehensive visual procedures available for determining the condition of an existing pavement. The procedure was originally developed by the US Army Corps of Engineers and has been verified and adopted by the Department of Defense and the American Public Works Association (APWA). The practice quantifies the condition of a pavement using a Pavement Condition Index (PCI), a numerical rating of the pavement condition that ranges from 0 to 100 with 0 being the worst possible condition and 100 the best possible condition. The PCI rates the surface condition of a pavement based on the distress observed on the surface. According to ASTM D 6433, this observed surface distress indicates the structural integrity and operational condition of the pavement (PCI does not measure structural capacity).

PCI values are arrived at by surveying and identifying pavement defects (or distresses) in each selected sample unit (see below). Table 1 provides a list of the individual asphalt pavement distresses that are included in the ASTM D 6433 evaluation procedure.

ASTM D 6433 includes a procedure for defining the magnitude of the observed defect. This magnitude is defined as either low (L), medium (M) or high (H) severity level. For example, a longitudinal or transverse crack would be defined as L, M or H depending on the following conditions:

- L- nonfilled crack width is less than 10 mm (3⁄8 in.), or filled crack of any width (filler in satisfactory condition).
- M- nonfilled crack width is greater than or equal to 10 mm and less than 75 mm (3⁄8 to 3 in.); nonfilled crack is less than or equal to 75 mm (3 in.) surrounded by light and random cracking; or, filled crack is of any width surrounded by light random cracking.
- H- any crack filled or nonfilled surrounded by medium- or high-severity random cracking; nonfilled crack greater than 75 m (3 in.); or, a crack of any width where approximately 100mm (4 in.) of pavement around the crack is severely broken.

Similar severity level criteria are defined in ASTM D 6433 for each defect listed in Table 1.

Table 1. ASTM D 6433 Asphalt Pavement Surface Defects

	Distress	Unit
1.	Alligator Cracking	ft^2
2.	Bleeding	ft^2
3.	Block Cracking	ft^2
4.	Bumps and Sags	ft
5.	Corrugations	ft^2
6.	Depressions	ft^2
7.	Edge Cracking	ft
8.	Joint Reflection Cracking	ft
9.	Lane/Shoulder Drop Off	ft
10.	Longitudinal Cracking	ft
11.	Transverse Cracking	ft
12.	Patching & Utility Cuts	ft^2
13.	Polished Aggregate	ft^2
14.	Potholes	number
15.	Rutting	ft^2
16.	Shoving	ft^2
17.	Slippage Cracking	ft^2
18.	Swell	ft^2
19.	Weathering/raveling	ft^2

To calculate the ASTM D 6433 pavement condition index (PCI), the amount of each individual distress, by severity level, is summed and divided by the area of the survey unit and then multiplied by 100 to determine the percent density of each distress. From this percent density a deduct value is determined for each type and severity level of distress using a series of curves. A maximum corrected deduct value (CDV) is determined following an iterative procedure, explained in ASTM D 6433, and the PCI = 100 – maximum CDV.

The procedure also contains a pavement condition rating which is a verbal description of the pavement condition as a function of the PCI. Table 2 shows the PCI rating scale as listed in ASTM D 6433.

Table 2. Pavement Condition Index Rating Scale (1)

PCI	Rating
86-100	Good
71-85	Satisfactory
56-70	Fair
41-55	Poor
26-40	Very Poor
11-25	Serious
0-10	Failed

University of New Hampshire RSMS01

The RSMS method was developed by the University of New Hampshire. The program uses visual distress surveys for fatigue cracking, longitudinal and transverse cracking, edge cracking, patches and potholes, roughness, rutting and drainage. The procedure recommends quantifying distress based on severity and extent using the SHRP-P-338 Distress Identification Manual for the Long-Term Pavement Performance Project (4). However, other methods are allowed. Fatigue cracking, longitudinal and transverse cracking and edge cracking are each given a rating of 0-9 based on extent and severity as shown in Table 3. Patches and potholes are rated from 0-3 based on extent. Roughness and drainage are quantified from 1-3 as good, fair and poor. Rutting is assigned a rating from 1-3 based on rut depth.

Table 3. Condition Survey Numerical Rating for RSMS01

Distress	Severity	Extent			
		No Defects	Low <10%	Medium 10-30%	High >30%
Fatigue, Long/Trans & Edge Cracking	Low	0	1	2	3
	Medium		4	5	6
	High		7	8	9
Patch/Potholes		0	1	2	3
			Good	**Fair**	**Poor**
Roughness, Drainage		0	1	2	3
			None	**0-1 inch**	**>1 inch**
Rutting			1	2	3

The RSMS program develops a Pavement Condition Indicator or PCI for each sample unit. The Pavement Condition Indicator is not the same as the PCI computed from ASTM D 6433. The pavement distress data gathered for use in ASTM D 6433 can be converted for use in the RSMS program, requiring no additional field evaluation time.

Asphalt Institute IS-169

The third method selected to quantify pavement condition was the Asphalt Institute publication IS-169, A Pavement Rating System for Low-Volume Roads. The method provides a visually based procedure for inspecting a pavement that involves driving slowly over the road to get an overall impression of its condition and then making a thorough inspection on foot. Notes on the type and extent of distress are obtained and when the inspection is completed, a rating form is filled out. A detailed description of the procedure is presented in Asphalt Institute Publication IS-169 (3). A listing of the defects and ratings from the IS-169 Condition Survey Form is presented in Table 4.

Table 4. Pavement Defect Ratings for IS-169 Procedure (3)

Defect	Rating
Transverse Cracks	0-5
Longitudinal Cracks	0-5
Alligator Cracks	0-10
Shrinkage Cracks	0-5
Rutting	0-10
Corrugations	0-5
Raveling	0-5
Shoving or Pushing	0-10
Pot Holes	0-10
Excess Asphalt	0-10
Polished Aggregate	0-5
Deficient Drainage	0-10
Overall Ride Quality	0-10

Under the IS-169 rating system, less serious problems are assigned values between 0 and 5. Defects of a more serious nature (i.e., those directly related to the strength of the pavement) are rated on a scale of 0 to 10 with a rating of 0 meaning that the pavement is free of that particular type of distress. When assigning a rating, IS-169 takes into account both extent and severity of the defect. For example, a rating of 10 for "rutting" would indicate that it occurs on much or all of the road, and that the ruts are probably deep enough to be a safety hazard, especially during rain, and an impediment to traffic at all times. On the other hand, a rating of 1 for "corrugations" would indicate that corrugations, although evident, are not numerous and that at present the distortions are not very large. After each defect is rated, the individual ratings are added. This sum is then subtracted from 100, and the result is simply called the "condition rating" (CR).

PAVEMENTS SURVEYED

Twenty-six (26) pavements (or routes) were originally selected by the NYSDOT and surveyed by the Research team.[1] Of these 26 pavements, three were discarded (overlaid with new pavement prior to the survey) and of the remaining 23 it was determined that 12 were CIPR pavements (branches), which were subdivided into 15 sections for analysis; four were MF pavements (branches), which were subdivided into seven sections for analysis; and eight were TCO pavements (branches), which were subdivided into 14 sections for analysis. The pavement sections analyzed, age at rating and traffic data provided by the NYSDOT are shown in Table 5.

SAMPLE OR SURVEY UNITS

ASTM D 6433 defines specific procedures for selecting sample units within pavements sections on which the actual distress survey is conducted. The objective is to select a representative number of sample units to define the distresses and respective severity levels within each respective section. In the ASTM procedure, which was used in this survey, each pavement is divided into “branches” that are further divided into “sections” of similar characteristics such as traffic, age and structure. Each individual section is then divided into “sample units” and the type and severity of distress is assessed by a visual inspection of each sample unit. The recommended size of a sample unit for asphalt pavements is approximately 2,500 square feet. Sample units utilized were 100-foot long sections of two-lane highways.

In this study, each route (or selected pavement) was originally considered a “branch”. If the branch (route) had similar characteristics then it was considered as a single “section”. Branches that were not of similar character were subdivided into sections. Approximately 10% of each pavement section was sampled as recommended by ASTM D 6433.[2]

[1] The NYSDOT Pavement Management Unit supplied 2007 site data used in the analysis

[2] One of the objectives of the study was to compare NYSDOT sufficiency rating (SR) to the other pavement condition indices. To undertake this comparative analysis, pavements that had different SRs and/or large differences in traffic were also divided into sections labeled A-E, along with their route number, for analysis. Seven pavements (branches) were subdivided due to differences in traffic and/or SR values.

Table 5. Pavement Sections Analyzed and NYSDOT Provided Traffic Data

Type	Rte	Milepost Beg	Milepost End	Length (mi)	Trucks (%)	AADT (vpd)	Age at Rating (years)
CIPR	9	49.20	53.25	4.05	7	810	15
CIPR	23	13.12	18.00	4.88	7	2,780	14
CIPR	67	16.05	18.51	2.46	7	2,120	5
CIPR	346	0.00	2.37	2.37	7	1,620	12
CIPR	349A	0.00	0.96	0.96	5	3,840	11
CIPR	349B	0.96	2.98	2.02	7	3,720	11
CIPR	920V	0.00	2.12	2.12	7	480	10
CIPR	12	4.82	7.47	2.65	12	4,820	11
CIPR	26	16.57	21.76	5.19	9	2,270	9
CIPR	30	61.07	63.38	2.31	8	2,220	8
CIPR	342	0.00	1.15	1.15	7	2,390	8
CIPR	7	15.68	19.60	3.92	7	4,220	8
CIPR	9NA	39.79	45.65	5.86	7	1,500	15
CIPR	9NB	45.65	48.00	2.35	7	1,500	15
CIPR	9NC	48.00	49.60	1.60	7	1,500	15
MF	3	51.28	54.00	2.72	7	1,810	9
MF	11A	6.55	9.00	2.45	10	5,210	6
MF	11B	9.00	11.59	2.59	10	5,210	7
MF	12A	46.09	48.16	2.07	7	3,050	15
MF	12B	48.16	51.53	3.37	7	2,120	15
MF	9LA	13.89	17.56	3.67	7	2,270	12
MF	9LB	17.56	18.32	0.76	7	2,140	12
TCO	9N	0.00	4.80	4.80	7	4,070	15
TCO	22	33.67	36.32	2.65	7	6,390	20
TCO	81	0.00	2.18	2.18	5	2,070	19
TCO	86	12.70	14.35	1.65	7	3,720	20
TCO	197	1.57	4.35	2.78	13	8,520	19
TCO	11	4.85	9.92	5.07	12	3,620	9
TCO	37	12.60	15.91	3.31	8	2,850	8
TCO	126 B	8.95	9.92	10.07	8	2,120	12
TCO	126 A	10.07	11.81	1.74	8	2,820	12
TCO	9A	6.80	9.15	2.35	6	8,200	16
TCO	9B	9.84	13.11	3.27	9	12,210	16
TCO	9C	13.11	15.02	1.91	6	9,540	16
TCO	9D	15.02	15.74	0.72	6	21,300	16
TCO	9E	15.74	16.88	1.14	6	14,820	16

AADT = Average Annual Daily Traffic

DATA SET EVALUATION

Comparative Performance Issues

The accuracy of a comparative performance evaluation of CIPR, MF and TCO pavement sections is based on the selection of a sufficient number of representative “groupings” of pavements (or routes) that have similar environmental conditions, traffic conditions and age.

Environmental conditions include factors such as temperature and precipitation. The original pavements, selected by NYSDOT for analysis, were all located within Regions 1, 2, 7 and 9. Since all of these pavements are in reasonable proximity of one another, concern over highly variable environmental conditions were minimized. During the selection of pavements by NYSDOT, care was taken to include pavement sections with similar traffic and age, but due to the difficulty in selecting a sufficient number of pavements from each treatment grouping (CIPR, MF and TCO), this was not always possible.

Traffic and Age Groupings

To establish comparable section traffic and age groupings for CIPR, MF and TCO pavement sections, the Research team iteratively screened each pavement category and selectively removed sections with either very high or very low traffic and/or age numbers. The goal was to establish CIPR, MF and TCO section groupings that would exhibit statistically similar patterns of traffic and age, and to compare the PCI indices of these groupings in the analysis. Details of this screening procedure are presented below.

Section Screening Analysis

Table 6 is a summary of the length of each section, traffic (AADT) and Age from Table 5, by treatment type. There were 43.89 miles of CIPR pavement evaluated, 17.63 miles of MF pavement evaluated and 43.64 miles of TCO pavement evaluated.

Table 6. Average Data from NYSDOT, by Treatment Type

	CIPR			MF			TCO		
	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range
Length	2.93	1.50	0.96-5.86	2.52	0.95	0.76-3.67	3.12	2.35	0.72-10.07
AADT	2386	1268	480-4820	3116	1480	1810-5210	7304	5654	2070-21300
Age	11.1	3.2	5-15	10.9	3.6	6-15	15.3	3.8	8-20

The TCO pavement sections originally selected for analysis on average carried a greater traffic load and were older at the time of evaluation than the selected CIPR and MF sections. To determine if the differences in traffic and age were significant, a one-way ANOVA was performed on Age and AADT, by pavement type. The results are shown in Table 7. A level of significance of 90% ($\alpha = 0.10$) was selected to differentiate differences in means. A significant difference in means at a 90% level of significance is determined to be the case when the last column in the ANOVA table (Prob.> F) is less than or equal to 0.100. Whenever a significant difference was indicated by the ANOVA, Duncan's multiple range test was performed to determine which means were significantly different.[3]

Table 7. ANOVA on Age and AADT by Treatment

Source	Degrees of Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
		Age			
Treatment	2	154.19	77.10	6.21	0.005
Error	33	409.45	12.41		
Total	35	563.64			
		AADT			
Treatment	2	190360444	95180222	6.96	0.003
Error	33	451299253	13675735		
Total	35	641659697			

Table 7 shows there is a significant difference in Age and traffic (AADT) for the data set evaluated. Duncan's multiple range test was performed to determine which means were significantly different. The results of the analyses are graphically depicted in Figures 1 and 2. In Figure 1, the difference in Age of the TCO sections was significantly different from the CIPR and MF sections. There was no significant difference in age between CIPR and MF. Figure 2 shows the AADT of the TCO sections was significantly different from the CIPR and MF pavements. Since the analysis indicated that the TCO grouping as a whole contained sections that were older and carried more traffic than the CIPR and MF sections, further examination of the CIPR, MF and TCO sections listed in Table 5 were undertaken to examine whether selected sections (e.g., outliers) could be affecting the results.

Based on a review of the data it was determined that two CIPR and six TCO sections should be removed from the analysis. A review of Table 5 shows that two CIPR sections, Routes 9 and 920V, carry less than 1,000 vehicles per day (vpd) and no other sections carry less than 1,500 vpd. These two sections were removed from the data set as outliers. Route 9, a TCO pavement that was divided into five sections, had recorded AADT values ranging from a low of 8,200 vpd to a high of 21,300 vpd. In addition to the higher than normal AADT values, Route 9 is a 4-lane divided highway (only the northbound lanes were evaluated in the survey). No other pavement evaluated in the survey carried traffic on multiple lanes. These five sections were removed from

[3] The evaluation of the data set was carried out using a one-way analysis of variance (ANOVA). A one-way ANOVA compares the means of multiple levels of a single main effect or treatment (5). In our case, the maintenance procedures of CIPR, MF and TCO are the three levels of the single main effect, treatment. The ANOVA indicates if the treatment levels are significantly different, it does not indicate which means are statistically different. Numerous comparison methods exist to determine which means are statistically different and Duncan's Multiple Range Test was selected. Duncan's multiple range test compares all possible pairs of means for a statistically significant difference. Duncan's procedure is a powerful test with a significance level greater than or equal to the corresponding significance level used in the ANOVA (5). The statistical software package SAS (6) was used to perform all statistical analysis.

the data set as outliers. Finally, Route 197, a TCO pavement with an AADT of 8,520 vpd, was also judged as an outlier, and removed from the data set.

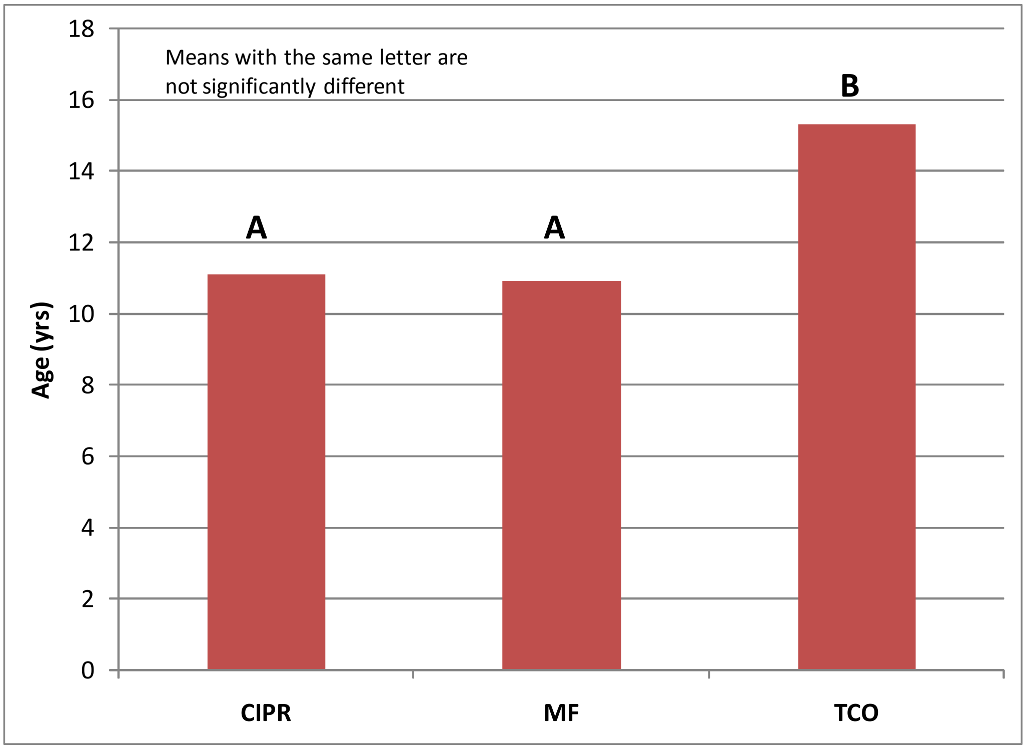

Figure 1. Mean age of treatments.

Figure 2. Mean AADT of treatments.

A one-way ANOVA was performed on age and AADT, by pavement type, on the qualified data set at a level of significance of 90% ($\alpha = 0.10$). The results are shown in Table 8 and presented graphically in Figures 3 and 4.

Table 8. ANOVA on Age and AADT for Qualified Data Set

Source	Degrees of Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
		Age			
Treatment	2	69.02	34.51	2.33	0.118
Error	25	369.66	14.79		
Total	27	438.68			
		AADT			
Treatment	2	3325839	1662920	0.99	0.387
Error	25	42157229	1686289		
Total	27	45483068			

As shown in the ANOVA tables and Figures 3, and 4, by removing the outliers (qualifying the data), age and traffic between the CIPR, MF and TCO sections exhibited statistical similarity. All subsequent data analysis was performed on the qualified data set.

Final Data Set

Table 9 is a summary of the length, age and traffic of the qualified data set, by treatment type. In the qualified data set, there are 37.72 miles of CIPR pavement, 17.63 miles of MF pavement and 31.47 miles of TCO pavement.

Table 10 shows the NYSDOT SR as well as pavement condition indices/ratings for each pavement section surveyed for the qualified data set.

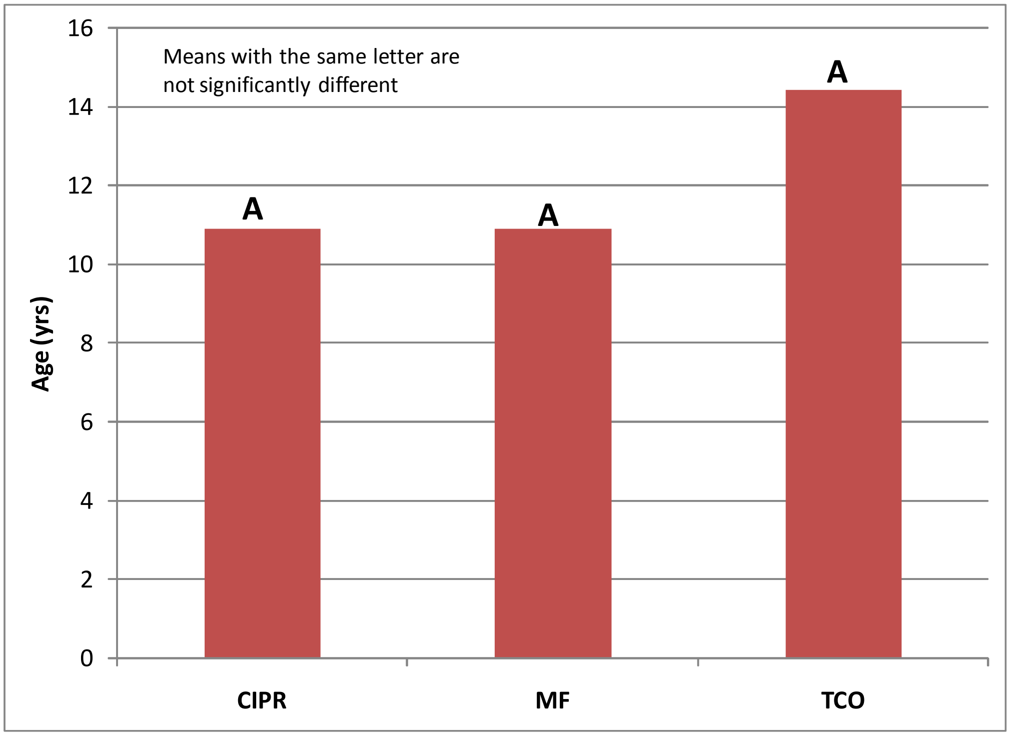

Figure 3. Mean age of treatments, qualified data set.

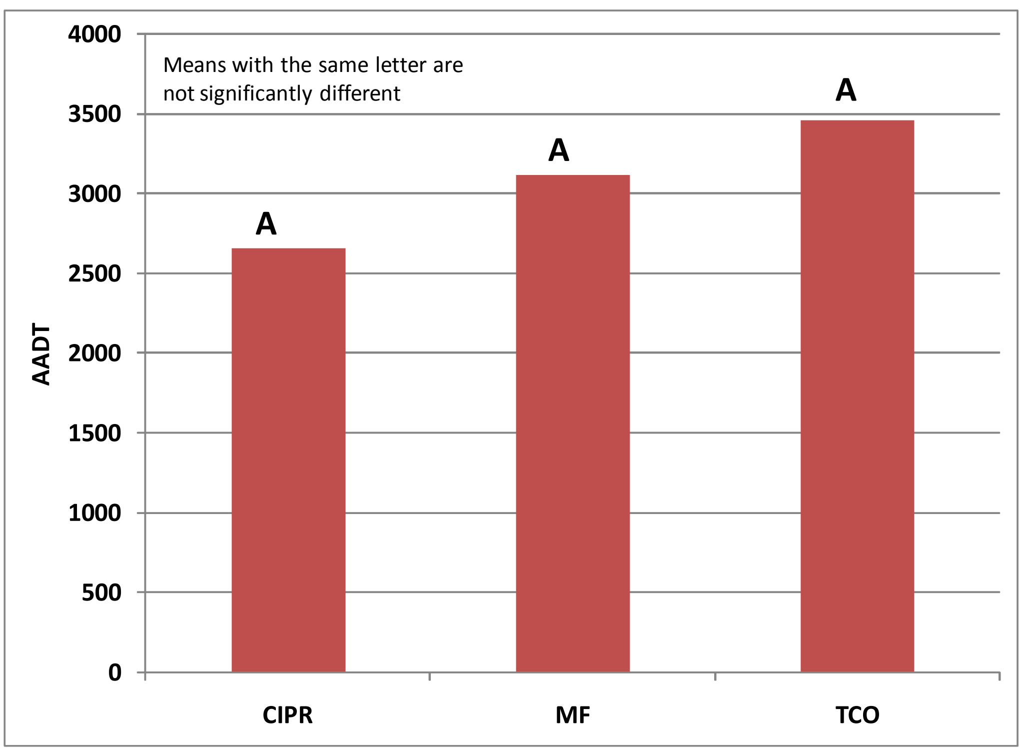

Figure 4. Mean AADT of treatments, qualified data set.

Table 9. Average Data from NYSDOT, by Treatment Type, Qualified Data Set

	CIPR			MF			TCO		
	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range
Length	2.9	1.57	0.96-5.86	2.52	0.95	0.76-3.67	3.93	2.8	1.65-10.07
AADT	2654	1135	1500-4820	3116	1480	1810-5210	3458	1392	2070-6390
Age	10.9	3.2	5-15	10.9	3.6	6-15	14.4	4.9	8-20

Table 10. Pavement Condition Index/Rating

		Rating	Pavement Rating			
Type	Rte	Sections	SR	ASTM	RSMS	AI CR
CIPR	23	25	6	43	65	75
CIPR	67	12	8	86	88	95
CIPR	346	12	6	53	62	77
CIPR	349A	5	6	63	73	80
CIPR	349B	9	7	62	76	83
CIPR	12	14	6	81	84	91
CIPR	26	25	7	72	78	85
CIPR	30	11	6	57	71	81
CIPR	342	6	7	78	90	91
CIPR	7	20	7	81	91	92
CIPR	9NA	29	7	77	86	90
CIPR	9NB	12	6	73	82	87
CIPR	9NC	9	7	77	77	86
MF	3	14	6	68	78	85
MF	11A	12	7	70	80	86
MF	11B	13	6	79	86	90
MF	12A	11	6	77	85	82
MF	12B	17	6	71	80	82
MF	9LA	18	6	70	81	86
MF	9LB	4	7	83	84	90
TCO	9N	25	6	74	85	87
TCO	22	13	6	66	72	79
TCO	81	11	5	50	71	77
TCO	86	8	5	49	62	70
TCO	11	25	6	85	88	92
TCO	37	17	6	62	72	81
TCO	126B	8	6	84	93	93
TCO	126A	6	6	96	98	96

COMPARATIVE ASSESSMENT

Pavement Rating Data

The average ASTM, RSMS and AI CR pavement condition index and sufficiency rating (SR) data for each pavement treatment grouping are shown in Table 11.

Table 11. Average Pavement Section Index/Rating, by Treatment Type

Survey	CIPR			MF			TCO		
Method	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range	Avg.	Std. Dev.	Range
SR	6.6	0.7	6-8	6.3	0.5	6-7	5.8	0.5	5-6
ASTM	69	13	43-86	74	6	68-83	71	17	49-96
RSMS	79	9	62-91	82	3	78-86	80	13	62-98
AI CR	86	6	75-95	86	3	82-90	86	9	70-96

PCI Indices

To determine whether significant differences exist between the grouped CIPR, MF and TCO indices, a one-way ANOVA was performed on each PCI rating method by pavement type. The results are shown in Table 12 and exhibited graphically in Figure 5.

Table 12. Results of ANOVA on Pavement Section Condition Rating

Source	Degrees of Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
SR					
Treatment	2	3.709	1.855	5.79	0.009
Error	25	8.005	0.320		
Total	27	11.714			
ASTM					
Treatment	2	103.61	51.81	0.31	0.736
Error	25	4171.18	166.85		
Total	27	4274.79			
RSMS					
Treatment	2	45.96	22.98	0.26	0.774
Error	25	2213.61	88.54		
Total	27	2259.57			
AI CR					
Treatment	2	6.67	3.34	0.08	0.925
Error	25	1067.55	42.70		
Total	27	1074.22			

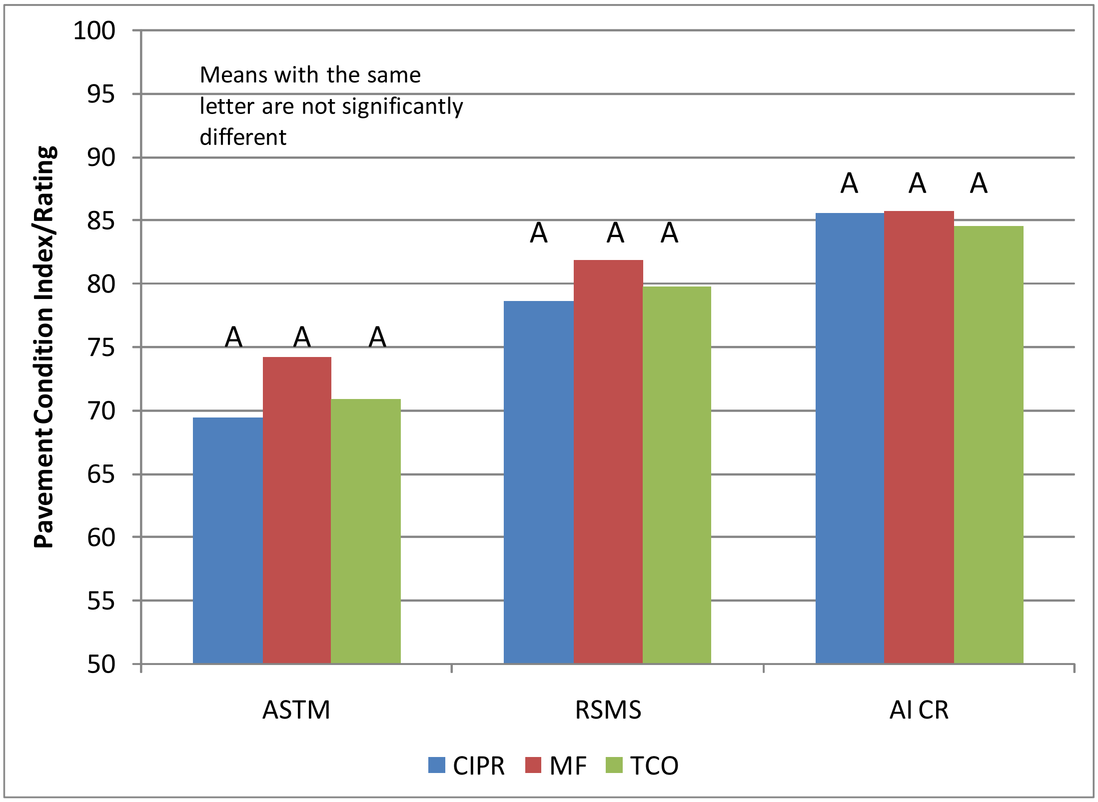

Figure 5. Pavement condition index/rating vs. treatment type by pavement section.

As shown in the one-way ANOVA table (Table 12), there was no significant difference in pavement condition, by treatment type, regardless of the field rating method used. For the ASTM method, MF had the largest average PCI (74) followed by TCO (71) and CIPR (69). Using the RSMS procedure, again MF had the largest average PCI (82) followed by TCO (80) and CIPR (79). The AI procedure resulted in a slightly different ranking; MF and CIPR had the largest average CR (86) followed by TCO (85). Means shown in Figure 5 with the same letter are not significantly different.

NYSDOT Sufficiency Rating

An examination of the differences in treatment type using the NYS Sufficiency Rating (SR) data listed in Table 11 was also undertaken. The results of the ANOVA and Duncan's multiple range test on SR, by pavement type, are shown in Table 12 and Figure 6, respectively. As shown in Figure 6, CIPR exhibits the highest SR value followed by MF and TCO. The mean SR ratings are 6.6, 6.3 and 5.8 for CIPR, MF and TCO, respectively. Means with the same letter are not significantly different at a level of significance of 90% ($\alpha = 0.10$). There is a statistically significant difference in SR, at a level of significance of 90 percent, between CIPR and TCO but no significant difference between CIPR and MF or MF and TCO.

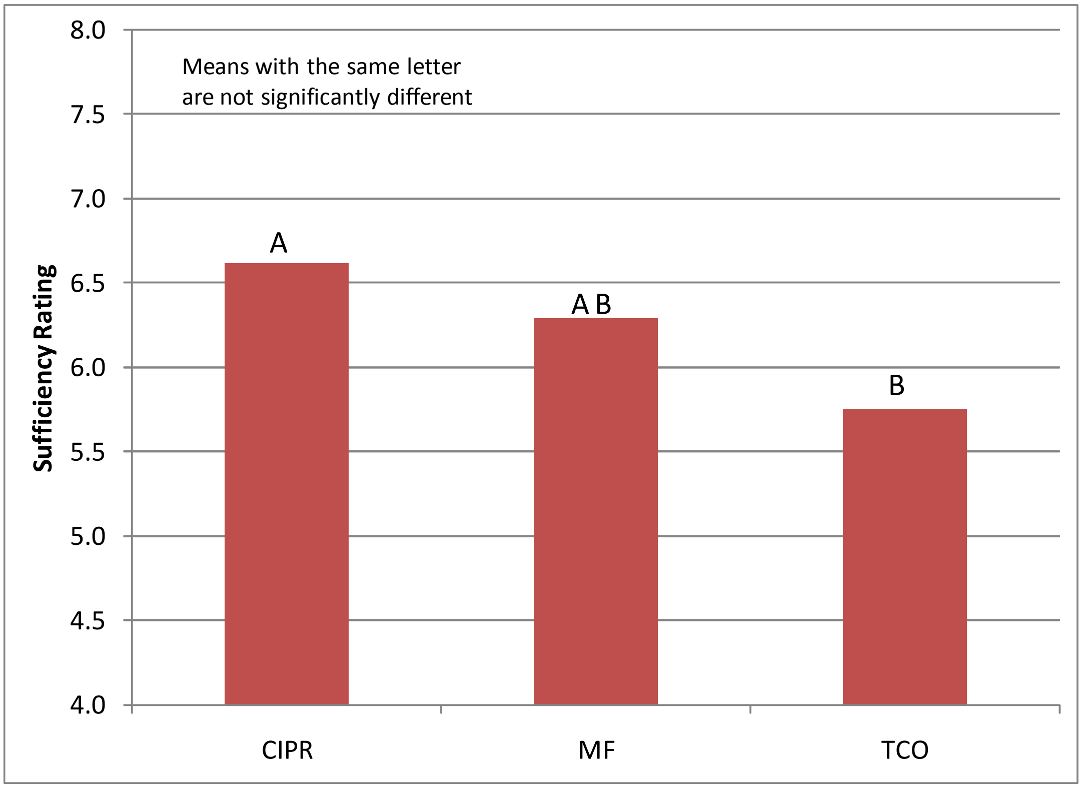

Figure 6. NYSDOT SR vs. treatment type.

PCI Indices and SR Rating

An evaluation of pavement condition projected by the use of PCI indices and the NYSDOT SR rating system was undertaken. The comparison was made by plotting PCI Indices data against SR data to determine the degree of linear correlation between the respective data. Figure 7 shows the relationships between the ASTM, RSMS and AI CR indices, and the NYSDOT SR rating. There was poor correlation found between SR and the other three pavement condition indices.

Two major factors were identified that could influence the lack of correlation shown in Figure 7,

The first factor is the relative scales (numerical resolution) of the different methods. The three field indices employed by the research team have a scale from 0 to 100 and they ranged over the upper half of the full scale. The SR scale varies from 0-9 with ratings in whole numbers. The SR data varied from 5 to 8. The second factor is the shape of the pavement condition deterioration curves with time. The typical shape of the PCI deterioration curve is convex, as opposed to the SR deterioration, which is concave, as illustrated in Figure 8.[4]

As a result, the PCI Indices and the SR rating would not be expected to exhibit good correlation.

[4] The shape of the SR curve is presented and discussed in detail in Attachment F: CIPR Service Life Projections (7).

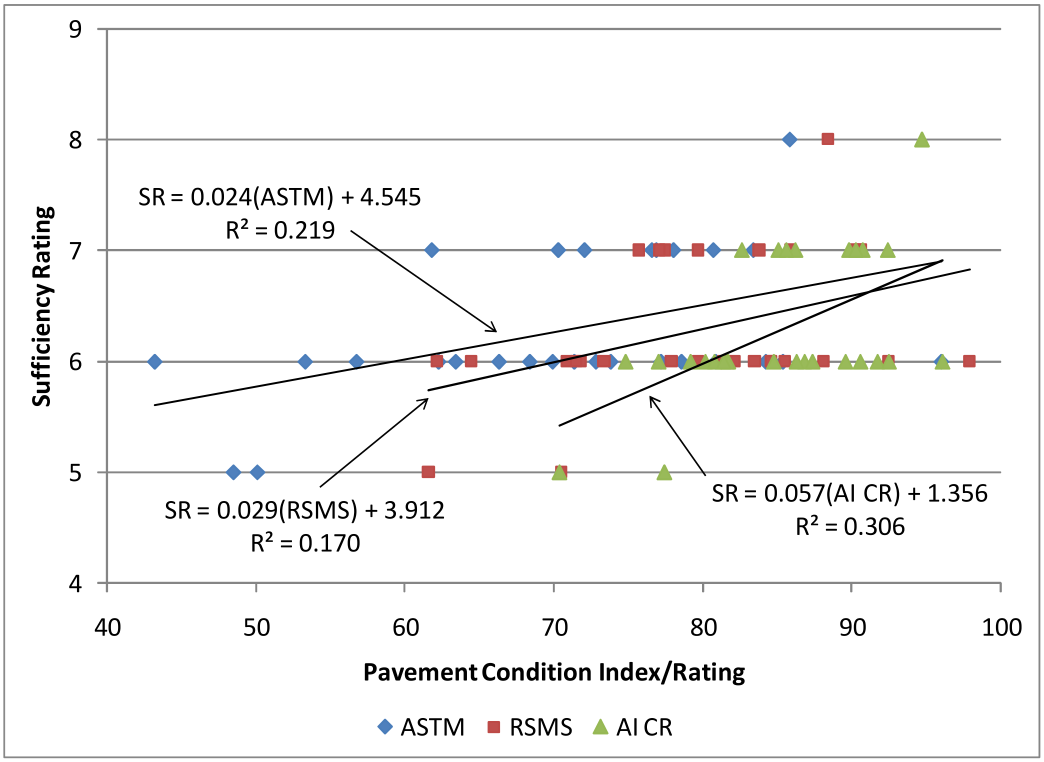

Figure 7. SR vs. ASTM, RSMS and AI CR pavement condition index/rating.

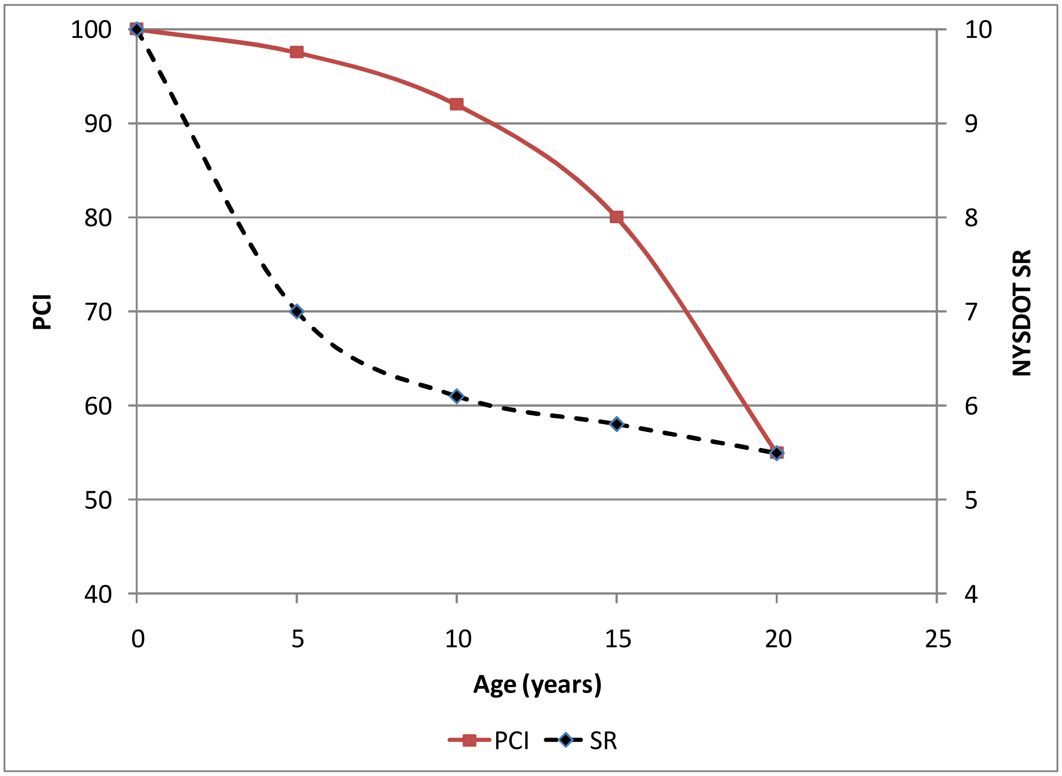

Figure 8. Generic illustration of SR and PCI deterioration curves.

PCI Indices Correlation

Figure 9 shows that better correlations were found between the ASTM, RSMS and AI CR methods. The coefficients of determination (R^2) were similar, varying from 0.87 to 0.88. The ASTM method gave the lowest PCI followed by RSMS and AI CR. The AI CR procedure is meant for very low volume roads and parking lots; therefore, a lower terminal serviceability rating would be tolerated. This could account for the higher condition ratings. The ASTM procedure is by far the most precise procedure of the three methods evaluated. The ASTM procedure requires measurements of all distresses and explicitly explains levels of distress. There is very little judgment of the evaluator involved. The RSMS procedure allows the user to define distress levels but recommends the LTPP guide (4). However, extent of distress is a judgment call, based on general extent only, and no measurements are required. The AI procedure (3) is the most subjective of the three with little guidance provided on distress levels or extent.

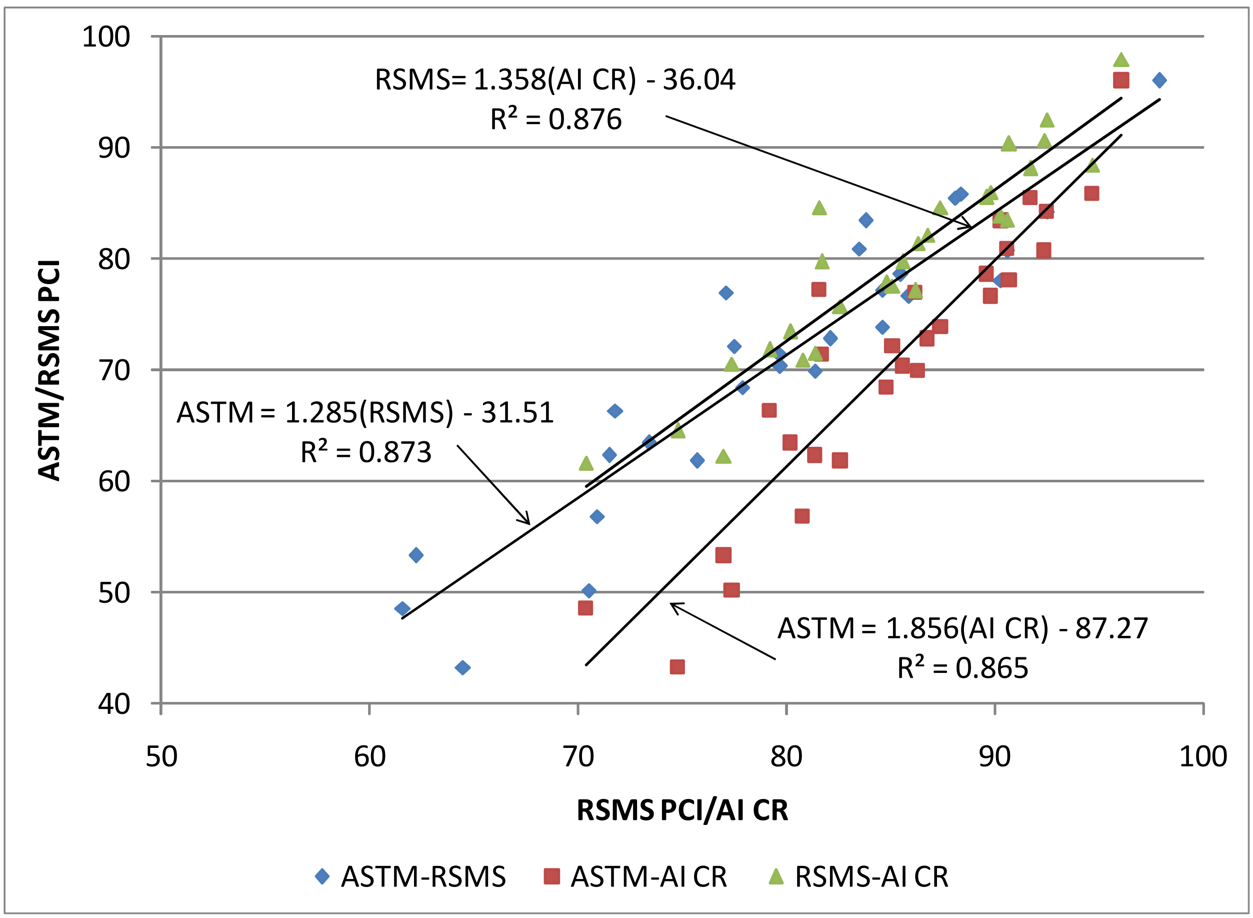

Figure 9. Comparison of ASTM, RSMS and AI pavement condition index/ratings.

PAVEMENT DISTRESS BY TREATMENT

An examination of individual pavement distresses was undertaken to determine whether the amount and severity of the quantified distress levels could be associated with specific treatment types (e.g., CIPR, MF or TCO). When undertaking such an analysis, it is important to note that not all of the distresses identified are attributable to treatment type. Some are related to pavement construction, roadway geometry (drainage, paved shoulders, etc.) or confined to the wearing surface. In addition, CIPR and MF are commonly thought of as applications that are most suitable for treatment of functional distresses, while TCO is a treatment application that better addresses structural failures. As a result, when reviewing the results of such an analysis, it might be anticipated that CIPR and MF would exhibit lower functional distresses and perhaps higher structural distress than TCO. In the results presented below and in Appendix B, the data tend to suggest that this is the case; however, such observations could not be confirmed statistically. Part of the problem is that during collection of distress data, the type and severity of distress prior to application of the treatment process was unknown.

The Pavement Distress by Treatment Analysis was performed using ASTM D 6433 deduct values as a way to quantify the amount and severity of each distress associated with each specific treatment. Deduct values, which are weighted by distress type, are incorporated into PCI calculations because not all distresses evaluated contribute equally to the deterioration of the pavement, nor would the same amount of distress at two different distress levels contribute equally. The AI CR procedure (3) addresses this fact by ranking some distresses on a 1 to 5 scale while more serious distresses are ranked 1 to10. The RSMS procedure (2) addresses this by ranking distresses on different levels ranging from 0 to 3 for some distresses and 0 to 9 for others. ASTM D 6433 addresses this fact through a series of deduct value curves. For a given amount of distress there are deduct value curves for each severity level. The actual deduct value varies by amount of distress, severity level and seriousness of distress to pavement performance (1). However, unlike the AI CR procedure, ASTM PCI is not a simple sum of all deduct values. The PCI from ASTM involves determining a critical deduct value which is subtracted from 100 to obtain the PCI. The critical deduct value involves an iterative procedure that starts with all deduct values and eliminates the lower values until the “critical deduct value” is obtained. The procedure is explained in detail in ASTM D 6433 (1).

The analysis was undertaken by:

- Using the individual pavement distress and severity level data in each treatment section as defined by ASTM D 6433[5],
- Summing the distress data by severity level, and dividing the summed data by the number of survey units in each section to determine an average amount of distress, by severity level, per survey unit (2,500 ft^2) for each pavement section,

[5] Of the three methods used in the field surveys, ASTM D 6433 is by far the most precise method of measuring pavement surface distress. Therefore, the analysis of pavement surface distress by treatment type was performed on the data generated from the distress measurements made while performing ASTM D 6433.

- Determining the deduct value for the average amount of each distress, by severity level, using the deduct value curves of ASTM D 6433 for each pavement section,

- Dividing the distresses for purposes of discussion into two categories: Non-Load and Load Associated Defects, and

- Comparing deduct values by treatment grouping (CIPR, MF and TCO) to assess whether significant differences between groupings could be identified.

As part of the analysis, distresses were divided into "Non-Load" and "Load" associated categories because CIPR and MF are generally thought to treat functional failures, whereas TCO is considered more of a structural treatment. Non-load associated distresses include longitudinal cracking, transverse cracking, block cracking, bleeding, weathering/raveling and lane/shoulder drop-off. Load associated distresses include alligator or fatigue cracking, rutting, edge cracking, patching and potholes.

A summarized listing of the average deduct values for each respective distress and pavement is presented in Table 13. A detailed tabulation of the amount and severity of each distress for each respective CIPR, MF and TCO section is presented in Appendix A.

Non-Load Associated Distress

To compare and determine whether differences between deduct values recorded in each treatment grouping were significant, an ANOVA was performed on the Non-Load associated distress using the CIPR, MF and TCO grouped data listed in Table 13. The results are shown in Table 14.

There was no statistically significant difference in means of the treatments for any of the Non-Load associated distresses at a level of significance of 90 percent ($\alpha = 0.10$). Non-Load associated distresses tended to be concentrated in specific areas of individual pavement sections. This resulted in large standard deviations, making large differences in means not significantly different.

Although at a level of significance of 90 percent, the differences between the specific treatments were found to be insignificant, the average deduct values and relative rankings of the three treatment types for each respective distress were examined to assess whether any specific trends could be determined. Table 15 presents a summarized listing of average deduct values for each Non-Load associated distress. The deduct values are reported as total deduct value and subtotaled by severity level. The ranking of the performance of the three treatments, CIPR, MF and TCO, based on average total deduct value, are shown as well. Treatments are ranked from best performance [1] to worst performance [3] for each distress. For the Non-Load associated distresses (Table 15), CIPR had the best performance against transverse cracking, bleeding and weathering/raveling. MF showed the best resistance to longitudinal cracking and block cracking. None of the treatments had deduct values for lane/shoulder drop-off.

Two similar ways to examine the relative performance of each treatment against Non-Load associated distress is to 1) sum the rankings, or 2) sum the total deduct values. The lower the sum, the better resistance to Non-Load associated distress. For a sum of rankings, CIPR has a sum of 8, MF a sum of 10 and TCO a sum of 14, indicating better resistance to Non-Load associated distress for CIPR compared to MF and TCO. For a sum of total deduct values, CIPR has a sum of 35.11, MF a sum of 40.80 and TCO a sum of 47.25, indicating better resistance to Non-Load associated distress for CIPR compared to MF and TCO. These results, as noted above, are not unexpected, since CIPR is recommended for treatment of Non-Load associated distresses or functional failures (8,10).

A detailed analytical description of deduct values based on amount and severity of each Non-Load distress and differences between CIPR, MF and TCO groupings is presented in Appendix B.

Load Associated Distress

A similar ANOVA, to assess whether differences in deduct values associated with Load associated distresses for each respective treatment were significant, was performed using the grouped data listed in Table 13. The results are shown in Table 16.

There was no statistically significant difference in means of the treatments for the Load associated distresses at a level of significance of 90 percent ($\alpha = 0.10$). As with Non-Load associated distresses, Load associated distresses tended to be concentrated in specific areas of individual pavements. Again, this results in large standard deviations making large differences in means not significantly different, indicating that performance of the three treatments is statistically similar.

Table 17 is a summary of deduct values for Load associated distress by treatment type. The deduct values are reported as total deduct value and subtotaled by severity level. The ranking of performance of the three treatments, CIPR, MF and TCO, based on average total deduct value, are shown as well. Treatments are ranked from best performance [1] to worst performance [3] for each distress. For the Load associated distresses (Table 17), MF had the best performance against rutting, edge cracking, patches and potholes. TCO had the best performance against alligator cracking. The sum of the rankings for each load associated distress was 12, 7 and 11 for CIPR, MF and TCO, respectively. The sum of the total deduct values was 52.08, 34.87 and 48.34 for CIPR, MF and TCO, respectively. CIPR had more load associated distress than MF or TCO. Once again, this trend is not unexpected since CIPR is not typically recommended as a treatment for structural failures (8,10).

A detailed analytical description of deduct values based on amount and severity of each Load associated distress and differences between CIPR, MF and TCO groupings is presented in Appendix B.

Table 13. Summary of Average Deduct Values

		Non-Load Associated Distress						Load Associated Distress				
Type	Route	Longitudinal Cracking	Transverse Cracking	Block Cracking	Bleeding	Weathering / Raveling	Ln/Shld. Drop Off	Alligator Cracking	Rutting	Edge Cracking	Patching	Potholes
CIPR	7	23.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0
CIPR	12	12.0	11.0	0.0	0.0	0.0	0.0	0.0	0.0	15.5	0.0	0.0
CIPR	23	14.5	10.0	12.0	0.0	26.0	0.0	85.5	16.0	7.5	11.0	58.0
CIPR	26	27.5	6.0	0.0	0.0	0.0	0.0	30.0	17.0	15.5	0.0	0.0
CIPR	30	31.0	18.0	0.0	0.0	0.0	0.0	8.0	55.0	20.0	0.0	0.0
CIPR	67	12.5	0.0	0.0	0.0	0.0	0.0	9.5	6.0	7.0	0.0	0.0
CIPR	342	15.0	7.5	6.0	0.0	0.0	0.0	4.0	0.0	6.5	0.0	0.0
CIPR	346	19.0	10.5	0.0	0.0	0.0	0.0	51.5	43.5	16.0	30.0	0.0
CIPR	349A	31.0	14.0	0.0	0.0	0.0	0.0	30.0	0.0	9.5	4.0	6.0
CIPR	349B	29.5	16.5	0.0	0.0	8.0	0.0	20.0	0.0	16.0	8.0	10.0
CIPR	9NA	27.5	3.0	0.0	0.0	5.0	0.0	11.0	1.0	6.0	0.0	0.0
CIPR	9NB	23.0	11.5	0.0	0.0	0.0	0.0	14.0	0.0	7.5	0.0	0.0
CIPR	9NC	25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.0	0.0	0.0
MF	3	33.0	22.0	0.0	0.0	8.5	0.0	16.0	0.0	21.0	0.0	0.0
MF	11A	29.0	16.5	0.0	0.0	10.0	0.0	11.5	0.0	10.0	0.0	2.0
MF	11B	27.5	7.5	0.0	0.0	0.5	0.0	13.0	0.0	10.0	0.0	0.0
MF	12A	17.0	14.0	0.0	5.5	0.0	0.0	7.0	0.0	3.0	0.0	0.0
MF	12B	25.0	14.0	0.0	1.0	8.0	0.0	26.0	0.0	8.5	0.0	0.0
MF	9LA	12.0	4.5	0.0	0.0	3.0	0.0	63.5	0.0	6.0	13.0	0.0
MF	9LB	13.0	14.0	0.0	0.0	0.0	0.0	30.0	0.0	3.5	0.0	0.0
TCO	11	15.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	28.5	0.0	0.0
TCO	22	30.0	35.5	7.5	0.0	12.0	0.0	4.0	0.0	23.0	3.0	0.0
TCO	37	36.0	9.0	0.0	0.0	34.5	0.0	31.0	6.0	20.0	0.0	0.0
TCO	81	31.0	21.5	0.0	0.0	0.0	0.0	70.5	2.0	5.0	29.5	6.0
TCO	86	39.0	17.0	5.5	0.0	1.5	0.0	14.0	30.5	15.5	42.0	11.5
TCO	126A	15.5	8.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
TCO	126B	0.0	2.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
TCO	9N	31.0	19.0	1.5	0.0	0.0	0.0	16.0	13.0	7.5	0.0	0.0

Table 14. CIPR, MF and TCO Groupings: ANOVA for Non-Load Associated Distress

Source	Degrees of Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
Longitudinal Cracking					
Treatment	2	30.56	15.28	0.17	0.844
Error	25	2238.40	89.54		
Total	27	2268.96			
Transverse Cracking					
Treatment	2	234.10	117.05	1.99	0.157
Error	25	1467.12	58.68		
Total	27	1701.22			
Block Cracking					
Treatment	2	13.48	6.74	0.77	0.472
Error	25	217.55	8.70		
Total	27	231.03			
Bleeding					
Treatment	2	4.53	2.26	2.24	0.127
Error	25	25.21	1.01		
Total	27	29.74			
Weathering/Raveling					
Treatment	2	44.68	22.34	0.31	0.738
Error	25	1813.43	72.54		
Total	27	1858.11			
Lane/Shoulder Drop-Off					
Treatment	2	0.00	0.00	.	.
Error	25	0.00	0.00		
Total	27	0.00			

Table 15. Average Non-Load Associated Deduct Value

Distress	Severity	Treatment CIPR	MF	TCO
Longitudinal Cracking (ft/unit)	Total	22.38	22.36	24.69
	Rank	2	1	3
	Low	8.38	7.50	6.31
	Medium	10.42	9.57	10.50
	High	3.58	5.29	7.88
Transverse Cracking (ft/unit)	Total	8.35	13.22	14.75
	Rank	1	2	3
	Low	1.46	0.36	2.44
	Medium	4.12	8.86	7.06
	High	2.77	4.00	5.25
Block Cracking (sf/unit)	Total	1.38	0.00	1.81
	Rank	2	1	3
	Low	1.00	0.00	0.75
	Medium	0.38	0.00	1.06
	High	0.00	0.00	0.00
Bleeding (sf/unit)	Total	0.00	0.93	0.00
	Rank	1	3	1
	Low	0.00	0.64	0.00
	Medium	0.00	0.00	0.00
	High	0.00	0.29	0.00
Weathering /Raveling (sf/unit)	Total	3.00	4.29	6.00
	Rank	1	2	3
	Low	0.27	1.50	1.06
	Medium	1.65	1.79	2.56
	High	1.08	1.00	2.38
Lane/Shoulder Drop-Off (ft/unit)	Total	0.00	0.00	0.00
	Rank	1	1	1
	Low	0.00	0.00	0.00
	Medium	0.00	0.00	0.00
	High	0.00	0.00	0.00

Table 16. CIPR, MF and TCO Groupings: ANOVA for Load Associated Distress

Source	Degrees of Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
		Alligator Cracking			
Treatment	2	132.12	66.06	0.12	0.885
Error	25	13396.38	535.86		
Total	27	13528.50			
		Rutting			
Treatment	2	517.80	258.90	1.34	0.280
Error	25	4831.41	193.26		
Total	27	5349.21			
		Edge Cracking			
Treatment	2	50.52	25.26	0.44	0.652
Error	25	1449.15	57.97		
Total	27	1499.67			
		Patching			
Treatment	2	228.99	114.50	0.96	0.396
Error	25	2979.25	119.17		
Total	27	3208.24			
		Potholes			
Treatment	2	147.86	73.93	0.58	0.570
Error	25	3212.17	128.49		
Total	27	3360.03			

Table 17. Average Load Associated Deduct Value

Distress	Severity	Treatment CIPR	MF	TCO
Alligator Cracking (sf/unit)	Total	20.27	23.86	17.94
	Rank	2	3	1
	Low	8.19	9.86	4.81
	Medium	11.12	10.00	9.88
	High	0.96	4.00	3.25
Rutting (sf/unit)	Total	10.65	0.00	6.45
	Rank	3	1	2
	Low	1.00	0.00	0.63
	Medium	5.38	0.00	2.69
	High	4.27	0.00	3.13
Edge Cracking (ft/unit)	Total	11.39	8.86	12.44
	Rank	2	1	3
	Low	2.00	3.07	1.75
	Medium	7.54	4.36	3.94
	High	1.85	1.43	6.75
Patching (sf/unit)	Total	4.08	1.86	9.32
	Rank	2	1	3
	Low	0.42	0.86	2.31
	Medium	1.35	1.00	4.38
	High	2.31	0.00	2.63
Potholes (number/unit)	Total	5.69	0.29	2.19
	Rank	3	1	2
	Low	0.00	0.29	0.69
	Medium	1.69	0.00	1.50
	High	4.00	0.00	0.00

PRIMARY FINDINGS

1. There was no statistical difference in performance between CIPR, MF and TCO pavements, as measured by ASTM, RSMS or AI CR condition indices.
2. CIPR pavement sections evaluated had a statistically higher SR rating than TCO but there was no significant difference in SR between CIPR and MF or MF and TCO.
3. There was poor correlation between SR and the ASTM, RSMS or AI CR methods.
4. The three field evaluation methods, ASTM, RSMS and AI CR, correlated well to each other.
5. CIPR pavement sections exhibited lower ASTM D 6433 total deduct values for Non-Load associated distress than MF or TCO pavement sections. The differences between treatments however were not statistically significant.
6. CIPR pavement sections exhibited higher ASTM D 6433 total deduct values for Load associated distress than TCO or MF. The differences between treatments however were not statistically significant.

PRIMARY CONCLUSIONS

1. CIPR, MF and TCO pavements exhibit similar field performance characteristics.
2. The NYSDOT SR rating methodology, unlike the ASTM, RSMS and AI CR rating system methodologies, generates ratings that decrease rapidly during the initial years of pavement life and asymptotically plateau during the latter years of pavement life. Such a rating system is less sensitive to end of life identification than the ASTM, RSMS and AI CR rating systems.

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APPENDIX A: Average Distress of Pavement Sections

Table A-1. Average Distress by Severity Level, CIPR Pavements

		Alligator Cracking (ft^2)			Bleeding (ft^2)			Block Cracking (ft^2)			Edge Cracking (ft^2)		
Type	Route	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
CIPR	7	0.00	0.50	0.00	0.00	0.00	0.00	15.75	0.00	0.00	6.15	1.25	0.00
CIPR	12	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	37.57	55.71	0.00
CIPR	23	105.40	257.40	2.64	0.00	0.00	0.00	132.10	47.52	0.00	10.60	10.16	0.00
CIPR	26	25.24	19.60	0.00	0.00	0.00	0.00	15.60	0.00	0.00	18.00	10.72	3.60
CIPR	30	16.36	0.00	0.00	0.00	0.00	0.00	19.09	0.00	0.00	13.18	42.36	2.09
CIPR	67	19.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.17	11.67	0.00
CIPR	342	5.00	0.00	0.00	0.00	0.00	0.00	154.42	0.00	0.00	3.33	14.17	0.00
CIPR	346	69.75	61.42	1.17	0.00	0.00	0.00	0.00	0.00	0.00	7.50	7.83	9.42
CIPR	349A	76.80	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	37.80	12.40	0.00
CIPR	349B	13.78	6.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.67	51.33	0.00
CIPR	9NA	1.90	1.76	0.00	0.24	0.00	0.00	0.00	0.00	0.00	2.10	11.03	0.00
CIPR	9NB	0.00	9.58	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.75	20.08	0.00
CIPR	9NC	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	21.67	100.89	0.00

Table A-1. (Con't.) Average Distress by Severity Level, CIPR Pavements

		Ln/Shld Drop-Off (ft)	Longitudinal Cracking (ft)			Transverse Cracking (ft)			Patching (ft^2)		
Type	Route	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
CIPR	7	0.00	245.45	19.00	0.00	12.65	4.00	0.00	0.10	0.00	0.00
CIPR	12	0.00	86.57	11.07	0.00	16.86	32.43	0.00	0.00	0.00	0.00
CIPR	23	0.00	50.76	10.80	4.24	18.84	13.28	1.44	0.56	0.00	8.00
CIPR	26	0.00	55.52	44.32	9.40	24.68	10.56	0.00	0.00	0.00	0.00
CIPR	30	0.00	163.27	90.64	0.00	8.27	7.64	20.73	0.00	0.00	0.00
CIPR	67	0.00	15.25	9.17	8.33	7.75	0.00	0.00	0.00	0.00	0.00
CIPR	342	0.00	159.67	37.00	0.00	21.33	17.67	0.00	0.00	0.00	0.00
CIPR	346	0.00	63.25	19.00	4.83	121.00	0.25	0.00	0.00	33.33	25.00
CIPR	349A	0.00	191.00	27.80	6.00	24.60	21.60	2.40	34.00	0.00	0.00
CIPR	349B	0.00	122.44	44.67	2.33	15.33	22.67	6.67	16.67	14.11	0.00
CIPR	9NA	0.00	50.41	91.69	2.07	1.79	9.79	0.41	0.00	0.00	0.00
CIPR	9NB	0.00	32.67	107.17	0.00	4.67	19.42	2.00	0.00	0.00	0.00
CIPR	9NC	0.00	103.89	61.61	0.00	1.56	2.67	1.33	0.00	0.00	0.00

Table A-1. (Con't.) Average Distress by Severity Level, CIPR Pavements

		Potholes (number)			Rutting (ft^2)			Weathering/Raveling (ft^2)		
Type	Route	Low	Medium	High	Low	Medium	High	Low	Medium	High
CIPR	7	0.05	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
CIPR	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CIPR	23	0.00	0.14	6.10	9.60	13.92	0.00	59.08	50.64	16.00
CIPR	26	0.04	0.00	0.00	1.60	6.60	3.00	0.00	0.00	0.00
CIPR	30	0.00	0.00	0.00	13.09	51.82	21.45	0.00	0.00	0.00
CIPR	67	0.00	0.00	0.00	0.42	4.17	0.42	0.00	0.00	0.00
CIPR	342	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CIPR	346	0.00	0.00	0.00	11.83	25.17	13.33	0.00	0.00	0.00
CIPR	349A	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CIPR	349B	0.00	0.47	0.00	0.00	0.00	0.00	5.56	11.11	0.00
CIPR	9NA	0.00	0.00	0.00	3.59	0.41	0.00	7.72	1.69	0.00
CIPR	9NB	0.00	0.00	0.00	0.00	0.00	0.00	18.50	0.00	0.00
CIPR	9NC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A-2. Average Distress by Severity Level, MF and TCO Pavements

		Alligator Cracking (ft^2)			Bleeding (ft^2)			Block Cracking (ft^2)			Edge Cracking (ft^2)		
Type	Route	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
MF	3	3.93	6.64	0.00	0.00	0.00	0.00	10.71	0.00	0.00	22.57	21.79	12.29
MF	11A	27.50	0.00	0.00	0.08	0.00	0.00	6.25	0.00	0.00	24.83	17.92	0.00
MF	11B	9.23	2.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.77	13.46	0.00
MF	12A	1.36	2.73	0.00	255.82	16.36	1.36	0.00	0.00	0.00	8.00	0.00	0.00
MF	12B	13.88	16.35	0.00	84.94	0.00	0.00	4.12	10.59	0.00	20.21	6.65	0.00
MF	9LA	19.56	89.72	22.94	0.00	0.00	0.00	0.00	0.00	0.00	12.22	3.06	0.00
MF	9LB	132.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.00	0.00	0.00
TCO	11	0.64	0.32	0.00	0.40	0.00	0.00	0.00	0.00	0.00	19.12	10.36	53.12
TCO	22	1.38	0.00	0.00	0.00	0.00	0.00	124.62	27.38	0.00	121.15	4.31	20.38
TCO	37	15.82	30.59	0.00	0.00	0.00	0.00	4.94	0.00	0.00	51.76	29.71	1.47
TCO	81	42.45	62.00	17.73	0.00	0.00	0.00	7.27	0.00	0.00	1.82	6.82	0.00
TCO	86	0.00	9.38	0.00	0.00	0.00	0.00	21.88	48.75	0.00	0.00	22.88	3.00
TCO	126A	5.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TCO	126B	2.50	0.00	0.00	1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TCO	9N	1.56	7.60	0.00	0.00	0.00	0.00	48.80	0.00	0.00	0.00	0.00	1.92

Table A-2. (Con’t.) Average Distress by Severity Level, MF and TCO Pavements

		Ln/Shld Drop-Off (ft)	Longitudinal Cracking (ft)			Transverse Cracking (ft)			Patching (ft^2)		
Type	Route	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
MF	3	6.43	103.36	37.71	12.29	9.64	22.50	17.14	0.00	0.00	0.00
MF	11A	0.00	72.33	30.08	12.58	2.83	14.50	10.00	1.67	0.00	0.00
MF	11B	0.00	115.08	25.85	7.69	2.69	10.92	2.77	0.00	0.00	0.00
MF	12A	0.00	91.82	25.36	0.00	5.64	52.45	0.00	0.00	0.00	0.00
MF	12B	0.00	95.47	38.94	1.76	23.41	40.24	0.71	0.00	0.00	0.00
MF	9LA	0.00	44.00	21.33	0.00	16.39	12.44	0.00	73.61	15.00	0.00
MF	9LB	0.00	51.25	25.00	0.00	8.25	50.00	0.00	0.00	0.00	0.00
TCO	11	0.00	0.00	23.48	5.20	1.60	15.48	0.00	0.00	0.00	0.00
TCO	22	0.00	127.15	19.62	12.85	133.46	29.62	15.08	6.77	3.62	1.15
TCO	37	0.00	171.06	46.71	8.82	7.94	6.00	5.65	0.00	0.00	0.00
TCO	81	0.00	54.18	78.64	7.73	17.18	22.82	13.73	241.36	53.18	0.00
TCO	86	0.00	65.63	78.13	19.38	9.63	48.88	1.88	35.63	89.38	32.50
TCO	126A	0.00	38.17	40.67	0.00	2.00	21.33	0.00	0.00	0.00	0.00
TCO	126B	0.00	3.75	0.00	0.00	22.50	0.00	0.00	0.00	0.00	0.00
TCO	9N	0.00	135.20	30.72	8.24	54.92	29.48	1.44	0.00	1.12	0.00

Table A-2. (Con’t.) Average Distress by Severity Level, MF and TCO Pavements

		Potholes (number)			Rutting (ft^2)			Weathering/Raveling (ft^2)		
Type	Route	Low	Medium	High	Low	Medium	High	Low	Medium	High
MF	3	0.00	0.00	0.00	0.00	0.00	0.00	61.43	8.57	0.00
MF	11A	0.19	0.00	0.00	0.00	0.00	0.00	116.67	0.00	2.50
MF	11B	0.00	0.00	0.00	0.00	0.00	0.00	6.46	0.00	0.00
MF	12A	0.00	0.00	0.00	0.00	0.00	0.00	1.64	0.00	0.00
MF	12B	0.00	0.00	0.00	0.00	0.00	0.00	52.47	6.35	0.00
MF	9LA	0.00	0.44	0.00	0.00	0.00	0.00	112.50	0.00	0.00
MF	9LB	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.00
TCO	11	0.00	0.00	0.00	0.00	0.00	0.00	1.80	0.00	0.00
TCO	22	0.00	0.15	0.00	0.00	0.00	0.00	124.62	32.00	0.00
TCO	37	0.00	0.00	0.00	0.00	0.00	2.35	198.24	80.59	41.18
TCO	81	0.00	0.34	0.00	5.45	0.00	0.00	0.00	0.00	0.00
TCO	86	0.38	0.13	0.00	0.00	11.25	10.38	12.50	0.00	0.00
TCO	126A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TCO	126B	0.00	0.00	0.00	0.00	0.00	0.00	3.13	0.00	0.00
TCO	9N	0.00	0.00	0.00	9.20	8.72	0.00	2.40	0.00	0.00

APPENDIX B: Description of Individual Distresses

INTRODUCTION

Appendix B presents a descriptive assessment of the Non-Load and Load associated distresses observed for each treatment type surveyed. The objective of this assessment was to introduce some engineering rationale to assist in understanding the observed data. The degree of severity was measured by the deduct value associated with each pavement section as defined by ASTM D 6433. To facilitate the discussion deduct values (DV) are graphically presented in the text and depicted on a scale of 0 to 30 to provide a visual comparison of the relative deduct values between the different distresses.

NON-LOAD ASSOCIATED DISTRESS

Longitudinal Cracking

Longitudinal cracks are cracks parallel to the centerline and are caused by a poorly constructed paving lane joint, thermal shrinkage of the HMA and/or daily temperature cycling (1). Most longitudinal cracks are the result of HMA paving operations. They occur at a paving joint or in the middle of a lane where mix segregation (paver segregation) was the cause. The pavement condition survey methods do not distinguish centerline longitudinal joint cracking from other longitudinal cracks. However, the survey team did note the high occurrence of centerline longitudinal joint cracking and started recording the distress separately on survey sheets. Centerline longitudinal joint cracking was recorded on all but two sites (Routes 67 and 346), which are CIPR pavements. Centerline longitudinal joint cracking accounted for 77% of the longitudinal cracking for CIPR sections, 62% for MF sections and 81% for TCO sections.

The average deduct values for longitudinal cracking, by severity level, for the three treatment types are shown in Figure B-1. TCO had the most total deductions for longitudinal cracking and the most deductions for high severity longitudinal cracking. CIPR had the highest deduct value for low severity. The ANOVA indicated that differences in means for total deduct values were not statistically significant.

Longitudinal cracking is more a function of the placement of the HMA wearing surface and not the type of maintenance treatment. Low longitudinal joint density has been identified by the National Center for Asphalt Technology (NCAT) as one of the current issues relating to asphalt pavement performance and is a major factor in premature deterioration of HMA pavements (11). Low longitudinal joint density can lead to premature raveling of the joint and the lower density results in increased permeability of the pavement. The increased permeability allows water to easily enter the pavement resulting in increased susceptibility to moisture induced damage or stripping (1,11). While the data did not reveal any special issue with CIPR pavements, it is noteworthy that CIPR pavements, due to their higher in-place air voids (8,10), can be sensitive to moisture- induced damage. Improved longitudinal joint construction should lead to improved performance of all three maintenance treatments.

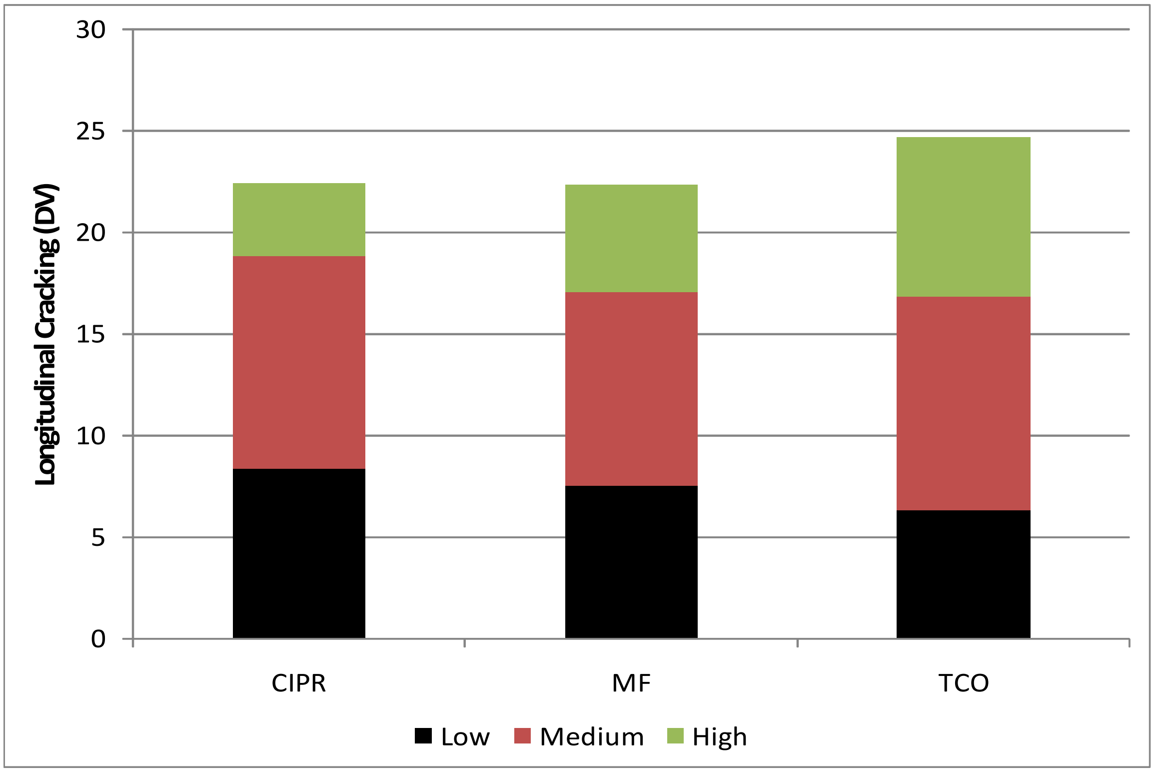

Figure B-1. Longitudinal cracking by treatment type.

Transverse Cracking

Transverse cracks are often either thermal shrinkage cracks or reflective cracks. Thermal shrinkage cracks are mainly a function of the low temperature grade of the binder (1,9). In an HMA overlay, they can also be reflective cracks from the pavement section below. As previously noted, CIPR and MF are often used to address reflective cracking (8,10). Figure B-2 shows the average deduct values for transverse cracking, by severity level, for the three treatment options. The ANOVA on total transverse cracking indicated no significant difference in means by treatment type. Nonetheless, CIPR exhibited the lowest total deduct value for transverse cracking followed by MF and TCO. CIPR also had the lowest deduct values for medium and high severity transverse cracking.

Better CIPR transverse cracking performance relative to MF and TCO was attributed to the fact that CIPR breaks up four inches of the existing pavement (crack pattern) and binds it with softer binder, CIPR plus the HMA overlay provide the thickest mat of the three treatments to resist reflective cracking and CIPR pavement is more flexible than HMA.

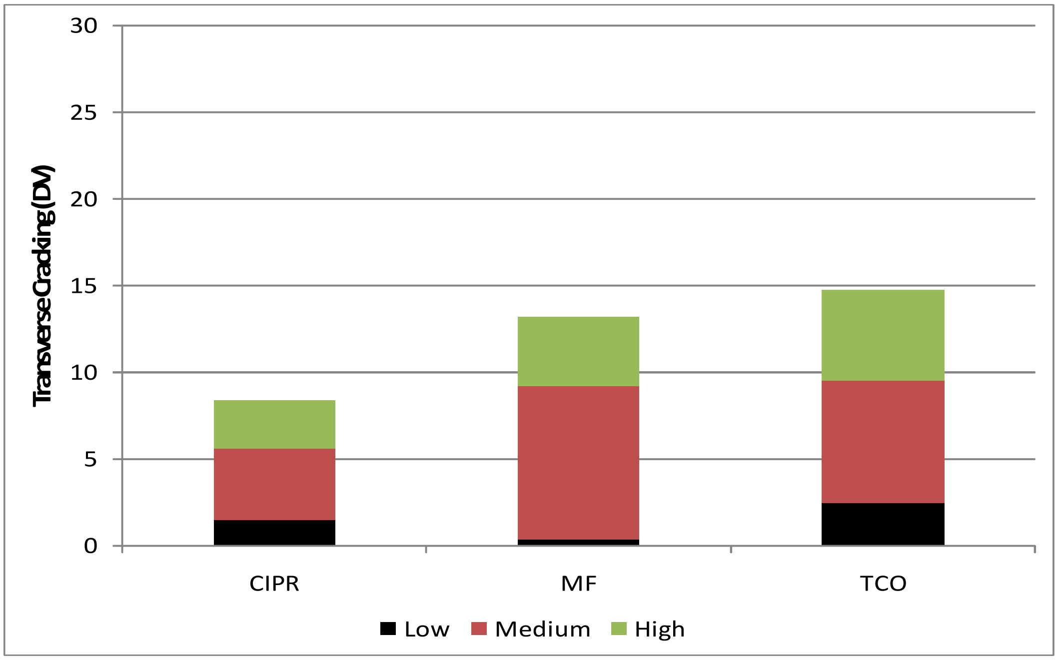

Figure B-2. Transverse cracking by treatment type.

Block Cracking

Block cracking is typically related to excess oxidation of the binder in the surface course and/or thermal shrinkage (1). The average block cracking deduct values are shown in Figure B-3.

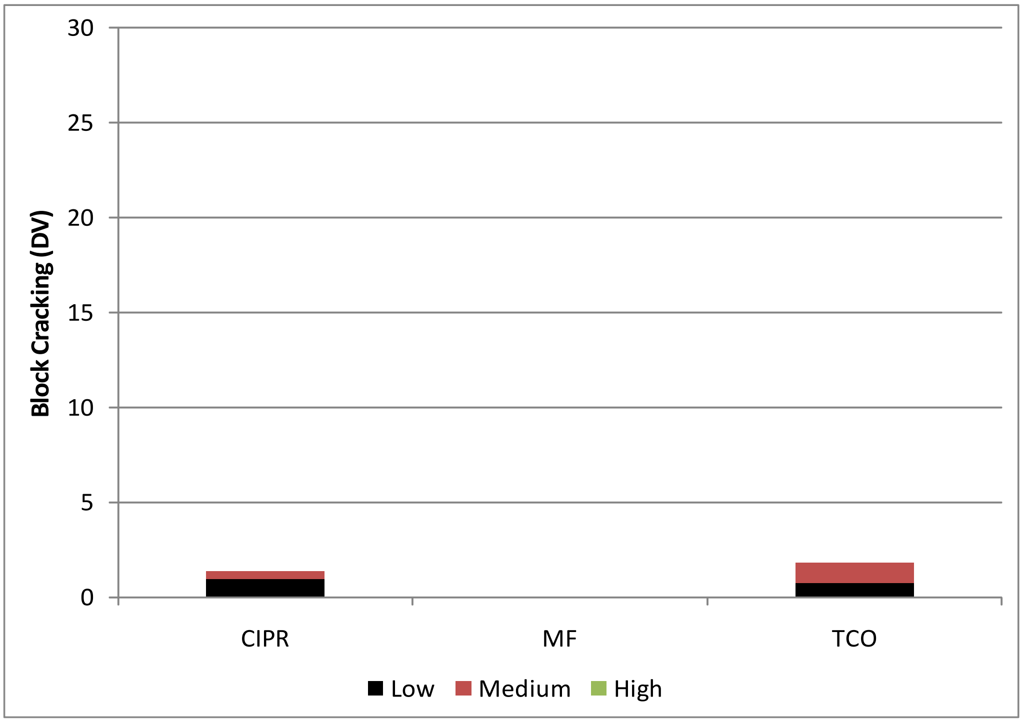

Figure B-3. Block cracking by treatment type.

There was no high severity block cracking. Block cracking was not a universal distress (see Tables A-1 and A-2) but was limited to a few individual pavements. Excess densification of a soft CIPR layer or a soft subgrade could cause a stiff oxidized HMA overlay to exhibit block cracking that could lead to alligator cracking. Two of the 13 CIPR pavement sections (Routes 23 and 342) accounted for 87 percent of the total CIPR block cracking. Route 23 was one of two CIPR pavements noted by the survey team as having areas of poor drainage and soft subgrades. Route 22, a TCO pavement, accounted for 54 percent of the total TCO block cracking. Block cracking was not a significant source of distress for the pavement sections evaluated. The ANOVA indicated no significant difference in block cracking by treatment type.

Bleeding

Bleeding is an accumulation of excess asphalt on the surface of the pavement (1). It is usually a defect of the wearing surface and therefore, would not be a function of treatment type. Figure B-4 shows that MF pavements had a minor deduct for bleeding. Only one CIPR pavement (Route 9N sections A, B and C) had any bleeding and only two TCO pavement sections had any bleeding (Route 11 and 126B). Three MF pavement sections had bleeding (Routes 11A and 12A and B). Route 12B was the only section with a significant amount of bleeding, accounting for 76% of the total MF bleeding. Except for a few places along MF Route 12, bleeding was not a significant distress for the pavements evaluated (see Tables A-1 and A-2). The ANOVA indicated there was no significant difference in means by treatment type for bleeding.

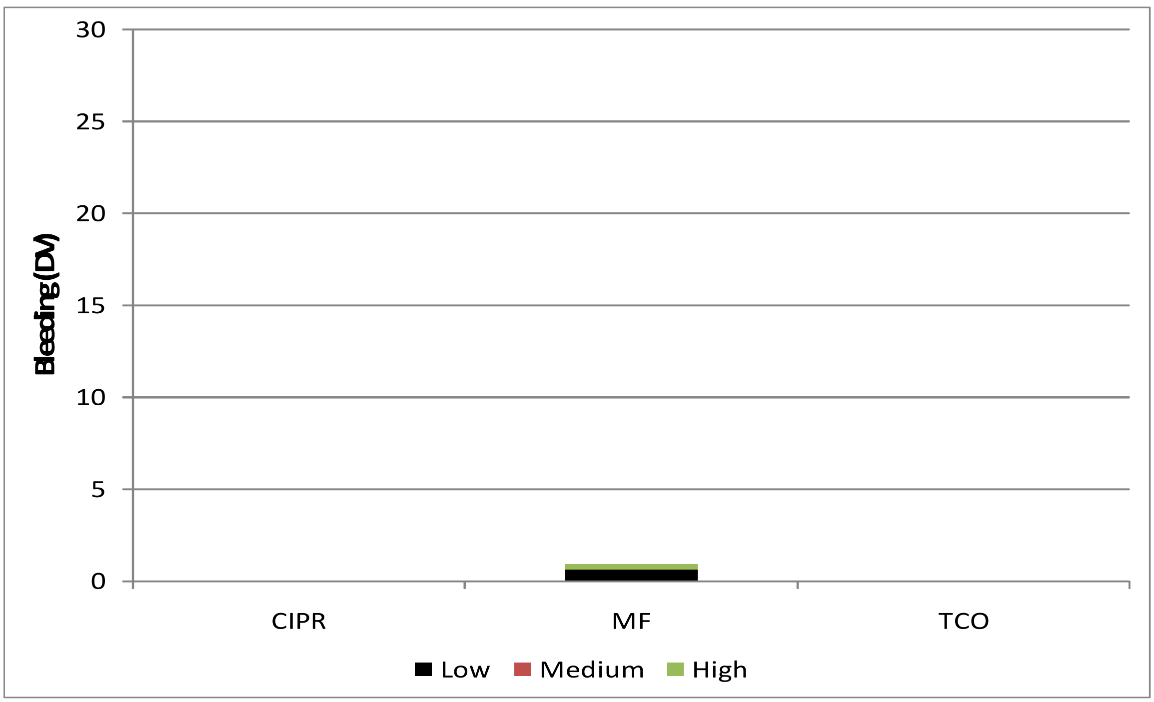

Figure B-4. Bleeding by treatment type.

Weathering/Raveling

Weathering is defined as wearing away of the binder and raveling is the loss of aggregate from the surface of the pavement (4). Weathering and raveling are often associated with poor compaction, moisture susceptible aggregates and/or low binder contents (9). Weathering can also be associated with reflective cracking. Although traffic is generally required for raveling, the causes listed above are non-load associated and therefore weathering and raveling was classified as a non-load associated distress. All of the MF sections and all but one of the TCO sections had some raveling (see Tables A-1 and A-2). Only five of the 13 CIPR pavement sections had weathering/ raveling and three of those had minor amounts. The average deduct values for weathering/raveling are shown in Figure B-5.

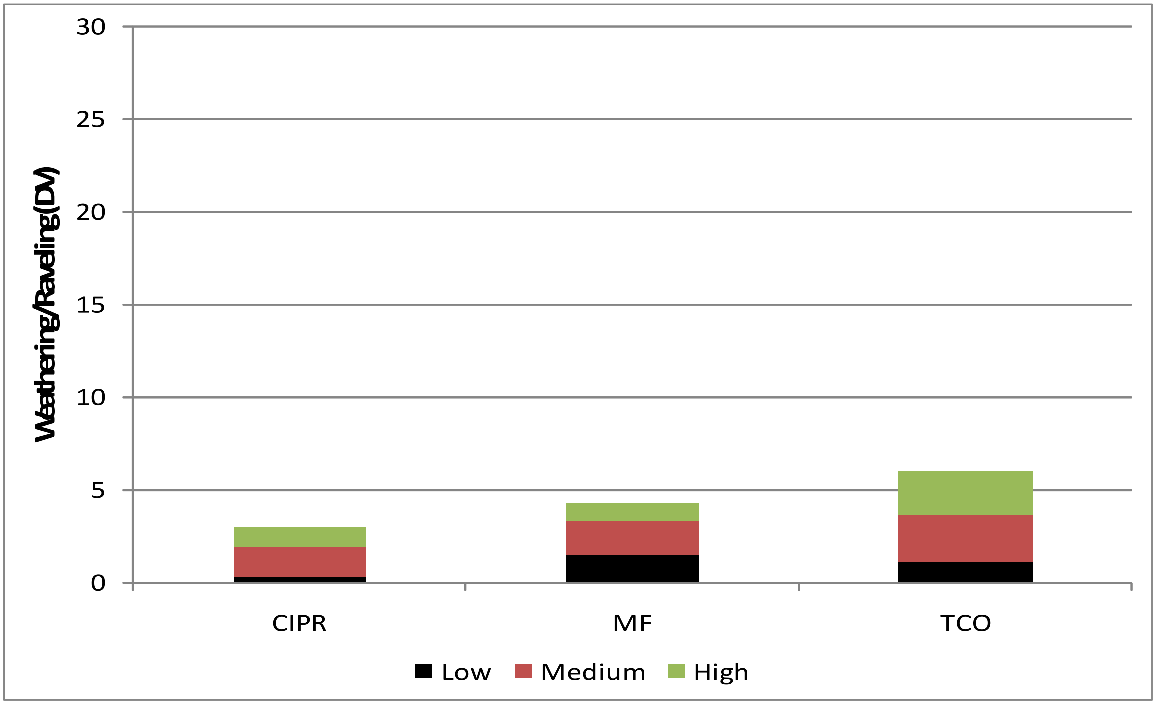

Figure B-5. Weathering and raveling by treatment type.

TCO exhibited the highest total deduct value for weathering/raveling and also exhibited higher deduct values for medium and high severity weathering/raveling. If the observed weathering/raveling is associated with reflection cracking, then reflective cracking explains the higher deduct values for TCO and MF compared to CIPR. The ANOVA indicated the means by treatment type were not significantly different.

Lane/Shoulder Drop-Off

Lane/shoulder drop-off is defined as a difference in elevation between the pavement edge and shoulder. This distress is caused by shoulder erosion, settlement or by buildup of the roadway without adjusting the shoulder level (1). It is not a function of treatment type. Only one pavement section, MF Route 3, recorded any lane/shoulder drop-off (see Tables A-1 and A-2) and this distress was so isolated that there was no average deduct value for MF pavements or the other two treatments.

LOAD ASSOCIATED DISTRESS

Alligator Cracking

Alligator cracking is usually associated with fatigue cracking. Fatigue cracking is caused by repetitive loadings that produce excessive tensile stresses or strains at the bottom of the bound layer (1); hence, fatigue cracks propagate from the bottom to the top. A soft base or subgrade and/or insufficient HMA thickness are often associated with fatigue cracking (9). Treatment options that supply the most new structure should provide the most resistance to fatigue cracking. The average deduct values for alligator cracking are shown in Figure B-6.

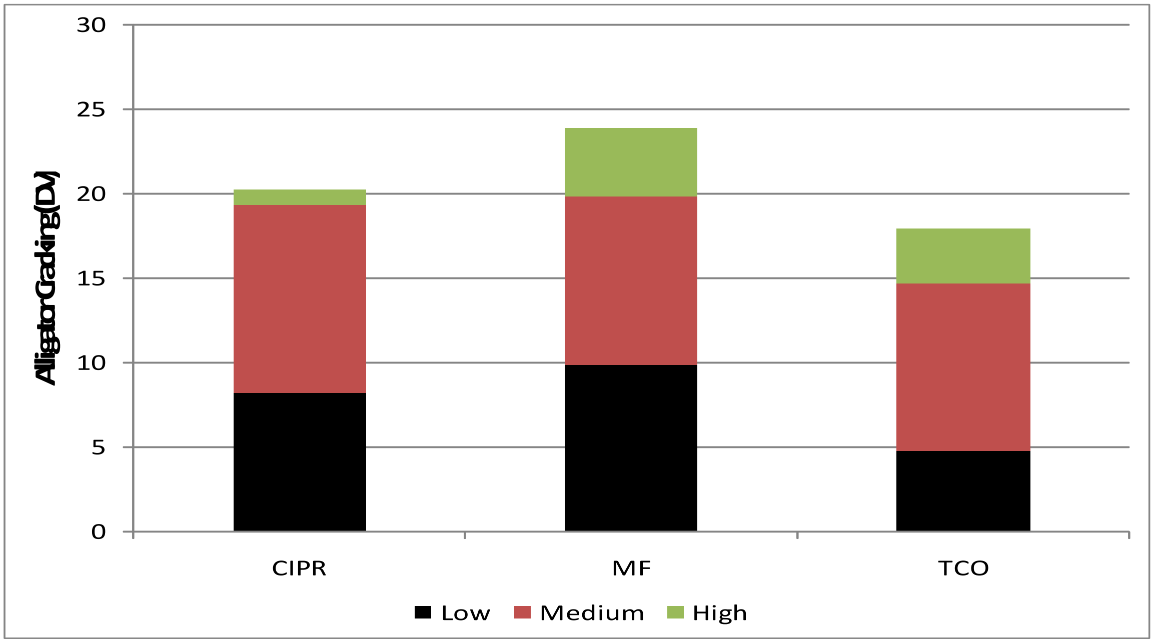

Figure B-6. Alligator cracking by treatment type.

Alligator cracking occurred in isolated areas. MF had the highest total alligator cracking deduct values and the highest deduct values for low and high severity level alligator cracking. CIPR has the lowest deduct value for high severity alligator cracking and TCO had the lowest total deduct value of the three treatments. This is not unexpected since TCO provides the most structure followed by CIPR and MF. The ANOVA indicated that the differences in means for total alligator cracking were not statistically significant.

Most alligator cracking on CIPR pavements appeared to be limited to the HMA layer, although the CIPR layer often appeared distressed as well. In most cases, alligator cracking appeared to be associated with areas of poor drainage. Two CIPR pavement sections (Routes 23 and 346) accounted for 71% of the reported alligator cracking (see Tables A-1 and A-2). These two pavement sections were also noted by the survey team as having areas of poor drainage and soft subgrades.

Rutting
Rutting is a depression in the wheel path that is caused by plastic shear failure of the HMA mix, excess densification of the mix or base or subgrade failure (9). Rutting caused by excess densification usually stabilizes quickly and does not cause appreciable rut depths. Plastic shear failure results in an unstable mix and large rut depths. The same distress may result from base or subgrade failure. The average deduct values for rutting are shown in Figure B-7.

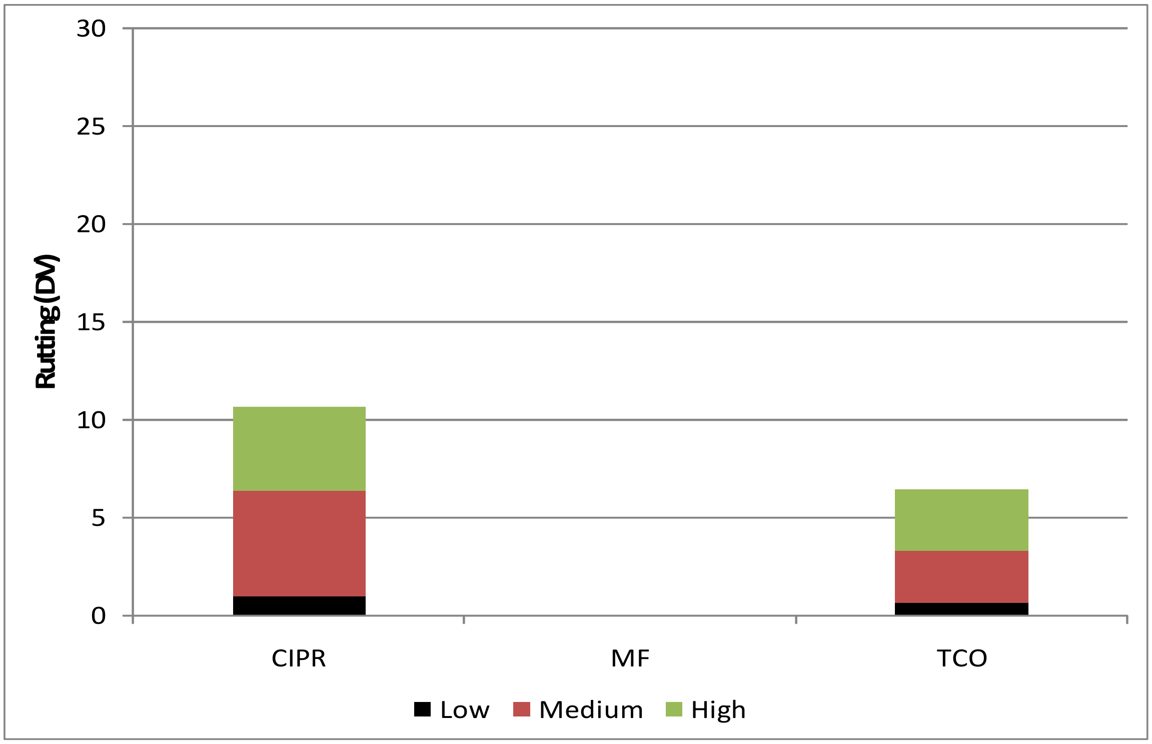

Figure B-7. Rutting by treatment type.

Rutting was not a major distress encountered on any of the pavement sections. Where rutting was encountered, it occurred in isolated areas. No rutting of any severity level was reported on the MF pavement sections. CIPR had higher deduct values for rutting than TCO. Two of the 13 CIPR pavement sections accounted for 76% of the rutting (see Tables A-1 and A-2). One of these sections, Route 346, was reported by the survey team as having poor drainage and a soft subgrade. It is noteworthy that CIPR mixtures require time to fully cure and gain their ultimate strength (8,10). As a result, CIPR pavements can be susceptible to rutting during this cure time, especially if curing is delayed due to environmental conditions. Lime, cement and polymer modified asphalts have all been used to speed cure time and improve initial mixture stiffness (8,10,12). The ANOVA indicated the differences in means by treatment type were not statistically significant.

Edge Cracking
Edge cracks are parallel to and within 1 to 1.5 feet of the outer edge of the pavement (1). Edge cracking is generally associated with a loss of support along the edge of a pavement and is load associated (9). Frost-weakened bases along the edge of the pavement are also associated with

edge cracking (1). The survey team did not survey shoulders as not all routes had paved shoulders. For pavements with paved shoulders, cracking at the longitudinal joint between the shoulder and surface course was identified as an edge crack by the survey team. Edge cracking, as defined by the survey team (see Tables A-1 and A-2), was a major distress. The average deduct values for edge cracking are shown in Figure B-8.

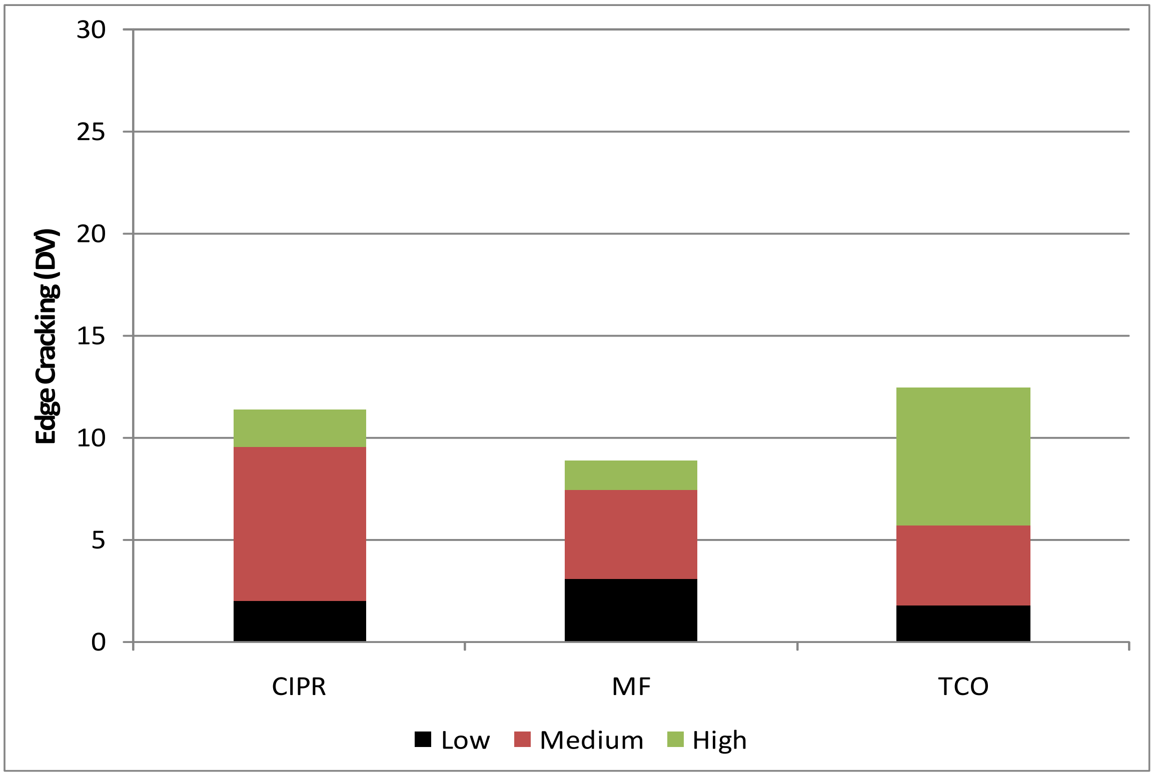

Figure B-8. Edge cracking by treatment type.

Many of the same factors that affect longitudinal joint cracking affect lane shoulder joint cracking and they are not a function of treatment type. Edge cracking is a function of the geometry of the pavement and not treatment type. TCO had the highest deduct values for edge cracking followed by CIPR and MF. The ANOVA indicated no significant difference in means for edge cracking by treatment type.

Patching

All patching is considered a distress regardless of its condition and distress in a patch is not counted separately but goes toward the severity level of the patch (1). Patches are used to repair both load associated and non-load associated distress. Patching was included in the category of a load associated distress. Five of 13 CIPR pavement sections had patching and one section, Route 346, accounted for 44% of the CIPR patching (see Table A-1). Route 346, as previously noted, was identified by the survey team as having areas of poor drainage and a soft subgrade. Two MF pavement sections had patches but only one, Route 9LA, had a significant amount (see Table A-2). Four of the eight TCO pavement sections had patches with two pavements (Routes 81 and 86) accounting for 97% of the patches. The average deduct values for patching are shown in Figure B-9.

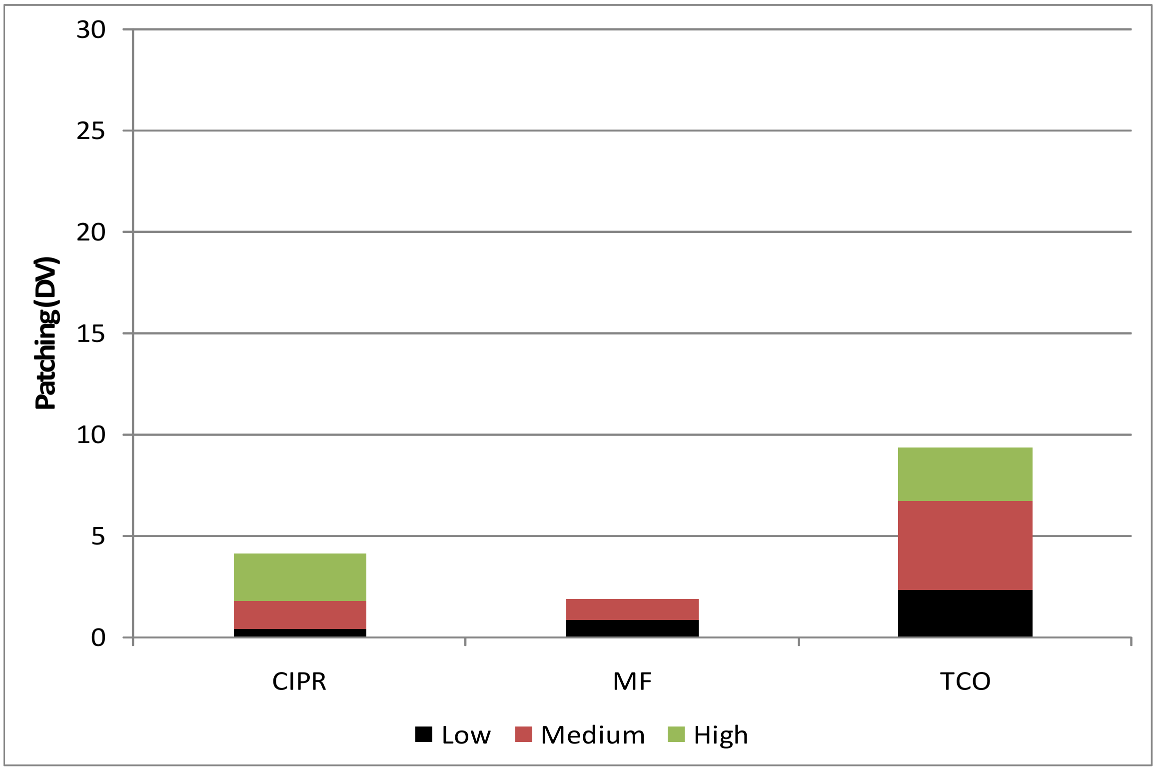

Figure B-9. Patching by treatment type.

Patching was much more prevalent in TCO pavement sections than CIPR and MF pavement sections, resulting in higher deduct values. If the observed patching is a result of reflection of existing distress, then TCO might be expected to exhibit more patching because TCO does not disrupt/destroy existing distresses. According to the ANOVA, the differences in means were not significantly different.

Potholes

Potholes are a load associated distress that is associated with advanced alligator cracking, severe raveling and freeze thaw damage (1,9). Figure B-10 shows higher deduct values for CIPR pavement sections than for MF or TCO pavement sections. One pavement section (Route 23) accounted for 89% of the potholes in CIPR pavement sections and was one of two CIPR pavements identified as having poor drainage and a soft subgrade (see Table A-1). CIPR pavements have higher in-place air voids than HMA pavements and can be susceptible to moisture damage if water enters the CIPR layer (8,10). This could also account for the higher average deduct values for CIPR pavements. Many agencies require lime or require CIPR mixtures pass a moisture susceptibility test during the mix design stage (10,12).

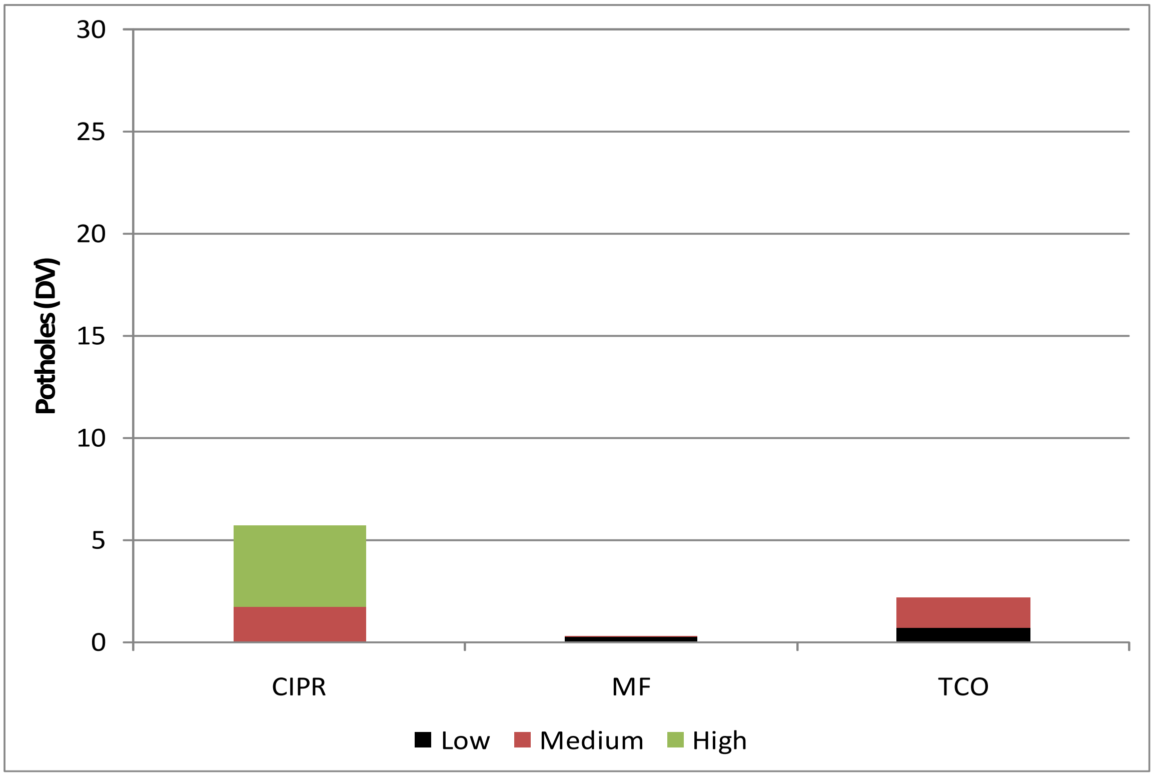

Figure B-10. Potholes by treatment type.

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment E: CIPR Life Cycle Modeling

Prepared for

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INTRODUCTION

The computer program Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was used to compare the costs and environmental burden of employing cold in-place recycling (CIPR) with the respective costs and environmental burdens of mill and fill (MF) and two course overlay (TCO) maintenance options.

PaLATE is a computer based decision support tool to model economic costs and environmental effects of highway construction and maintenance activities (PaLATE User Manual, 2004). It was developed at the University of California, Berkeley, under Federal Highway Administration (FHWA) sponsorship (Horvath, 2004). The program and user manual are available as a free download from the Recycled Materials Resource Center web site (http://www.rmrc.unh.edu/Resources/ CD/PaLATE/PaLATE.htm).

PaLATE has been used by the Transportation Ministry in Ontario, Canada to perform life cycle environmental and economic analysis on its CIPR pavements (Alkins, 2008), and the Recycled Materials Resource Center at the University of New Hampshire (RMRC) has presented comparisons of CIPR and hot in-place recycling (Gardner, 2005).

Economic effects are evaluated in PaLATE by performing a Life Cycle Cost Analysis (LCCA) using net present value (NPV). Costs and factors considered are initial construction costs, maintenance costs, salvage value, discount rates and treatment lives. Outputs consist of NPV by initial construction cost, maintenance cost and combined total cost (PaLATE User Manual, 2004).

Environmental effects are evaluated in PaLATE by performing Life Cycle Environmental Analysis (LCEA). LCEA is a way to provide a system wide assessment of the environmental burden resulting from a specific industrial activity, from raw material acquisition through production, use and disposal (ISO 1997). The LCEA approach differs from traditional environmental analyses, which tend to focus exclusively on specific impacts at or in the immediate geographic vicinity of the site where the activity is occurring. The development and application of LCEA models is an outgrowth of the desire to develop a more global perspective on the environmental and resource burden imposed by specific industrial activities. It is particularly useful for policy makers who must address issues such as energy use, greenhouse gas emissions and overall health impacts induced by specific policy decisions. In the case of PaLATE, the industrial activity is the highway construction and maintenance industry. Such an approach has particular utility to Transportation Agencies faced with decisions as to whether to promote or limit the use of alternative pavement construction or maintenance technologies, such as CIPR.

This report is divided into six main sections and four supporting Appendices. The first three sections of the report describe alternative treatment options that were compared to CIPR in the model, the specific inputs (assumptions) used in the assessment, and a description of some of the limitations of the analysis. The next two sections, which constitute the bulk of the report, present the life cycle cost and environmental findings (model outputs). The final section provides the assessment conclusions.

TREATMENT OPTIONS

Eight different treatment options were analyzed using PaLATE. They included:

1. CIPR with four inch mill depth,
2. CIPR with three inch mill depth,
3. CIPR with four inch mill depth and 20% add-stone,
4. CIPR with three inch mill depth and 20% add-stone,
5. MF with 1.5 inch mill depth,
6. MF with 2 inch mill depth,
7. MF with 3 inch mill depth, and
8. Two Course Overlay (TCO).

Hot mix asphalt (HMA) overlays for each treatment were assumed as follows:

1. TCO - two 1.5 inch lifts
2. MF- two 1.5 inch lifts, and
3. CIPR – one 1.5 inch lift

CIPR with 20% add-stone was included in the analysis because many CIPR contractors in New York State introduce additional stone (add-stone) into the CIPR layer. The decision to use add-stone is based on the existing pavement's gradation, with quantities ranging from 5% to 20%. Add-stone is included to increase the coarseness of aggregate in CIPR made from fine graded HMA mixtures to a 25 mm nominal aggregate size meeting the CIPR gradation requirements of NYSDOT ITEM 405.0201-02.

The use of add-stone in CIPR is not a common practice. According to the results of the Transportation Agency Survey, presented in Attachment B to this report (NYSDOT, 2008), only two other agencies besides NYSDOT reported the occasional use of add-stone, and one of these reported that it was only used in lane widening operations. As will be shown in the analysis presented below, supplementing CIPR with add-stone can alter the cost and environmental benefits of CIPR as a pavement maintenance strategy.

Table 1 provides a listing of the abbreviated nomenclature (code) used to identify the treatment options in this report, and the design basis for each respective option.

Table 1. Treatment Codes

CODE	Treatment	Mill Depth	Add Stone	Emulsion Content	HMA Overlay
CIPR-4-AS	CIPR	4 inch	20%	3.0%	One 1.5 inch lift
CIPR-4	CIPR	4 inch	0%	2.5%	One 1.5 inch lift
CIPR-3-AS	CIPR	3 inch	20%	3.0%	One 1.5 inch lift
CIPR-3	CIPR	3 inch	0%	2.5%	One 1.5 inch lift
MF-1.5	MF	1.5 inch	N/A	N/A	Two 1.5 inch lifts
MF-2	MF	2 inch	N/A	N/A	Two 1.5 inch lifts
MF-3	MF	3 inch	N/A	N/A	Two 1.5 inch lifts
TCO	TCO	N/A	N/A	N/A	Two 1.5 inch lifts

N/A = Not applicable

MODEL INPUTS

Pavement design data used as input to PaLATE were as follows:

a. All HMA was assumed to have 6.0% asphalt cement, a compacted unit weight of 150 pcf and a loose or haul unit weight of 107 pcf.
b. All HMA assumed to contain 10% RAP at 6.0% asphalt cement.
c. CIPR was assumed to have a compacted unit weight of 150 pcf.
d. CIPR with add-stone was assumed to have 3.0% emulsion, based on the dry mass of the millings.
e. CIPR without add-stone was assumed to have 2.5% emulsion, based on the dry mass of the millings. The reduced emulsion content provides the same emulsion content for all CIPR when based on the total mass of material (millings + add-stone).
f. Haul or loose unit weight of add-stone for CIPR-AS was assumed at 89 pcf.
g. The emulsion was assumed to have a residual asphalt content of 67%.
h. The modeled pavements were assumed located at a distance of 25 miles from the HMA plant.
i. The HMA plant was assumed located at a distance of 25 miles from the quarry; so the aggregate haul distance from quarry to the plant was assumed at 25 miles.
j. Haul distance from the refinery/asphalt terminal to the HMA plant was assumed at 100 miles.
k. Haul distance from the emulsion plant to the modeled pavements was assumed at 100 miles.
l. Pavement treatments were analyzed and compared on a centerline mile basis for the mainline pavement only[1], a two-lane, 24-foot wide pavement, as the modeled roadway.

[1] The PaLATE analysis was limited to the mainline pavement only. Shoulders were excluded since there are numerous combinations of width, composition and potential treatment options that complicate the modeling analysis. Treating shoulders will however result in increased costs and environmental outputs above those that are presented in the reported results, and these may not be equal for all the treatments evaluated. Since the TCO option is a surface treatment option only, it is likely that additional shoulder treatment, which may not be needed with CIPR and MF, may be required to ensure that the grade and elevation of the mainline pavement and the shoulder conform to specifications.

The analysis and conclusions in the following sections are based on and limited to the above model inputs. Changes in asphalt and emulsion contents, percent RAP, pavement sections, and haul distances all impact results.

TREATMENT EQUIVALENCIES

Comparative environmental and life cycle cost analysis of pre-selected maintenance treatment options is complicated by the fact that the respective options selected for comparison are rarely equivalent. Each option will have specific structural ramifications, will preferentially relieve specific functional distresses (e.g., reflective cracking), and will respectively extend the life of the pavement for a given period. It is unlikely that such periods will be equal. Comparative environmental and life cycle cost analyses tend to imply equivalency, but this may not necessarily be accurate.

It is noteworthy that nationwide, asphalt overlays (TCO) have historically been the most common maintenance treatment options. CIPR and MF are newer maintenance procedures. From a structural perspective, TCO adds the most structure followed by CIPR and MF. However, CIPR and MF are not generally considered treatment options for structural distresses but for functional distress. One of the major concerns when applying maintenance treatments to distressed HMA pavements is reflective crack control (AASHTO, 1993). CIPR and MF were developed to address, among other issues, reflective crack control. The greater the depth of existing crack removed, the less likely the crack is to return or reflect through the surface (ARRA, 2001). CIPR provides the thickest depth of treatment and removes the greatest depth of existing pavement, both of which would be important in treating functional distress and reflective crack control. A quantitative analysis of the relative structural equivalency for each selected treatment option is presented in Appendix A.

LIFE-CYCLE COST ANALYSIS (LCCA)

Background

PaLATE was used to perform a life cycle cost analysis (LCCA) of the CIPR, MF and TCO treatment options. PaLATE uses Net Present Value (NPV), the discounted monetary value of expected benefits or benefits minus costs associated with the specific treatment option (PaLATE User Manual, 2004). The option with the lowest NPV has the lowest life cycle cost. Since the benefits of keeping a roadway above a minimum serviceability rating is (assumed to be) the same for all treatment options, the benefits component drops out of the equation and NPV becomes the initial cost plus the sum of the discounted rehabilitation costs minus the discounted salvage value at the end of the analysis period (Wallis, 1998).

Model Qualifications

Life cycle cost analysis requires assumptions pertaining to treatment life and discount rate as part of the analysis. There is an inherent uncertainty in projecting the exact service life of any treatment. Discount rates can be expected to vary over time as well. Best estimate treatment life projections and discount rates were used in the primary analysis presented in the main body of the text, and is the primary basis for the LCCA conclusions. A sensitivity analysis, presented in Appendix B, was performed to provide the supplementary data to assess the influence of treatment life and discount rate on the overall LCCA results.

Input Variables

Required input variables for PaLATE include treatment costs, maintenance costs, salvage values, treatment lives, discount rates and analysis period (PaLATE User Manual, 2004). Input variables used in the analysis are outlined below.

Initial Treatment Costs: HMA, CIPR and milling cost data were obtained from interviews with resident engineers and contractors and by reviewing average NYSDOT bid items (WAIPR, Nov 2009). Table 2 is a summary of the average unit costs used to determine initial construction costs.

Maintenance Costs: Routine maintenance costs are often ignored in life cycle analyses due to the minimal impact on NPV and the assumption that they will be similar for each option. Routine maintenance costs were not included in the analysis.

Table 2. Average Unit Costs for Treatment Options

Process	Cost
HMA	$64.00 per ton
4-inch CIPR with 20% add-stone	$6.45 per sy
4-inch CIPR	$5.01 per sy
3-inch CIPR with 20% add-stone	$5.19 per sy
3-inch CIPR	$4.12 per sy
1.5-inch Cold Milling	$1.50 per sy
2-inch Cold Milling	$1.75 per sy
3-inch Cold Milling	$2.25 per sy

Salvage Value: Salvage value consists of two parts: residual value and serviceable life. Residual value is the net value from recycling the pavement at the end of the analysis period and serviceable life is the net value of the remaining life in the pavement treatment at the end of the analysis period. It was assumed that all treatment options would have the same residual value at the end of the analysis; hence, the residual value was ignored. Therefore, Salvage Value consists of the serviceable life or the discounted value of the life (years of expected service) remaining in the pavement treatment at the end of the analysis period. This value is subtracted from costs.

Treatment Life: The average life of NYSDOT CIPR pavements was assumed at 11 years (NYSDOT, Nov. 2009). Projected treatment lives of 11 and 14 years for MF and TCO pavements, respectively, were provided by NYSDOT.

Discount Rate: FHWA (Wallis, 1998) suggests that real discount rates be used in conjunction with non-inflated dollar cost estimates of future costs when estimating maintenance or rehabilitation costs. A discount rate of 3.0 percent was chosen for the analysis.

Analysis Period: FHWA (Wallis, 1998) recommends the analysis period should be long enough to capture the true costs and should exceed the design life of the alternatives. An analysis period of 20 years was selected.

NPV Calculation

LCCA was performed on a one-mile section 24-foot wide (the mainline pavement). Shoulders were excluded. Initial treatment costs are shown in Table 3. HMA was assumed to have an in-place unit weight of 150 pcf, which equates to 112.5 lbs/sy/inch. CIPR was assumed to have an in-place unit weight of 150 pcf. A 24-foot wide pavement one mile long has an area of 14,080 square yards.

Table 3. Initial Costs per Centerline Mile

Treatment	Materials	Unit Cost	Area / Mass	Cost	Initial Treatment Cost
CIPR	1.5” HMA	$64/ton	1,188 tons	$76,032	
	CIPR-4-AS	$6.45/sy	14,080 sy	$90,816	$166,848
	CIPR-4	$5.01/sy	14,080 sy	$70,541	$146,573
	CIPR-3-AS	$5.19/sy	14,080 sy	$73,075	$149,107
	CIPR-3	$4.12/sy	14,080 sy	$58,010	$134,042
MF	3” HMA	$64/ton	2,376 tons	$152,064	
	1.5” Milling	$1.50/sy	14,080 sy	$21,120	$173,184
	2” Milling	$1.75/sy	14,080 sy	$24,640	$176,704
	3” Milling	$2.25/sy	14,080 sy	$31,680	$183,744
TCO	3” HMA	$64 / ton	2,376 tons	$152,064	$152,064

From the above inputs, the NPV for each treatment was determined for a 20-year analysis period in accordance with Equation 1 (Wallis 1998).

$$NPV = \text{Initial Cost} + \sum_{t=1}^{T} \text{Rehab Cost}_t \left[1/(1+i)^t\right], \qquad [1]$$

where
i = discount rate
t = time of each treatment (years)
∑= sum of all treatments from t=1 to t=T

A discount rate of 3.0 percent was used and treatment lives were calculated at 11, 11 and 14 years for CIPR, MF and TCO, respectively. Each treatment option was repeated when it reached the end of its treatment life. Any remaining life in the treatment at the end of the analysis period was considered salvage value. The line diagram used for the NPV analysis is shown in Figure 1.

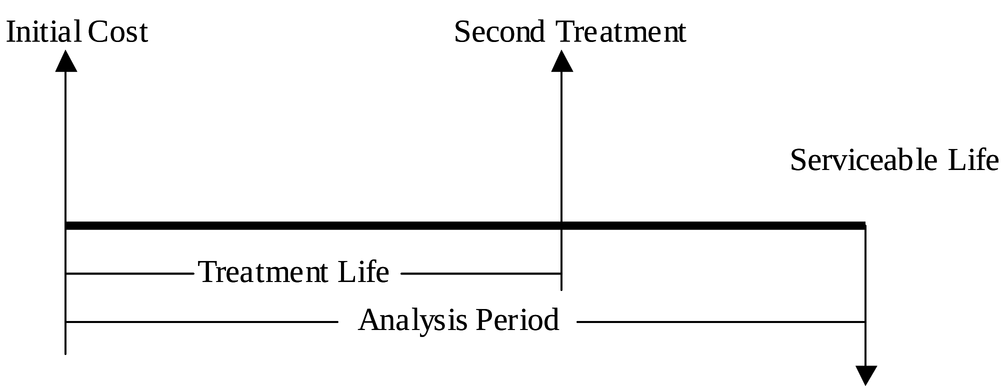

Figure 1. Time Line diagram for LCCA analysis.

Initial Treatment Costs

Initial cost is often an important factor in maintenance decisions. Estimated initial costs per mile, presented in Table 3 for each of the treatment options, are comparatively analyzed in Figure 2 and Table 4. Table 4 lists the savings in initial cost per mile of pavement for each treatment option using TCO as the benchmark. A positive value in the table represents a savings compared to TCO and a negative value indicates an increased initial cost.

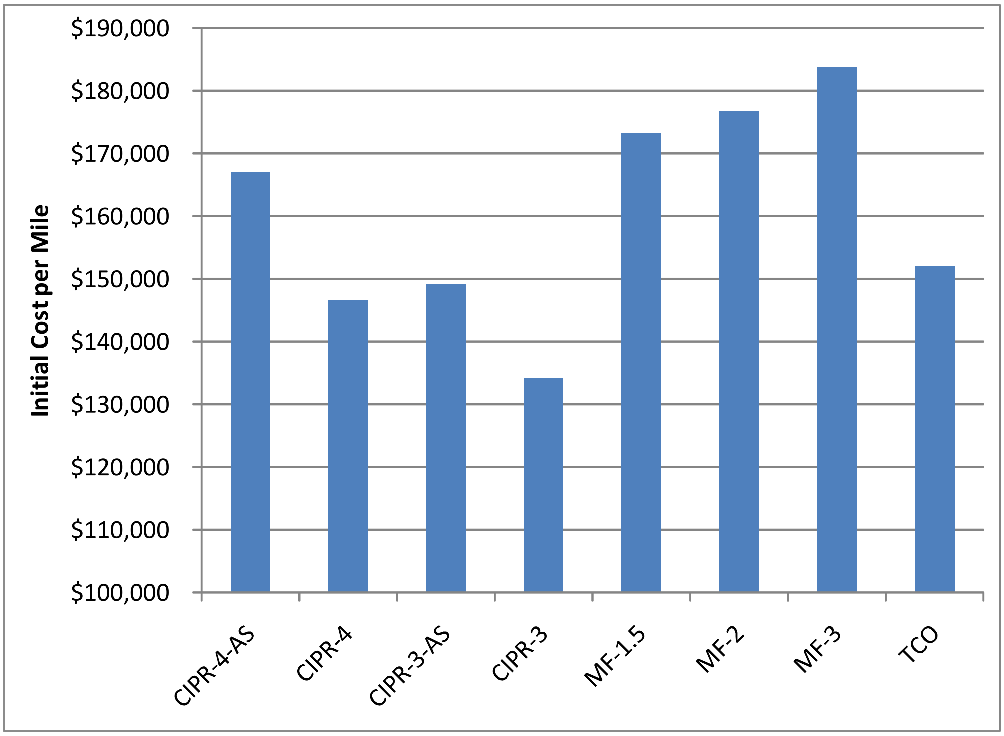

Figure 2. Initial treatment costs.

Table 4. Comparison of Initial Treatment Costs

Treatment	Initial Costs	Savings	% Savings
	Per Centerline Mile		
CIPR-4-AS	$ 166,848	-$14,784	-9.7
CIPR-4	$ 146,573	$5,491	3.6
CIPR-3-AS	$ 149,107	$2,957	1.9
CIPR-3	$ 134,042	$18,022	11.9
MF-1.5	$ 173,184	-$21,120	-13.9
MF-2	$ 176,704	-$24,640	-16.2
MF-3	$ 183,744	-$31,680	-20.8
TCO	$ 152,064	-	-

The data in Figure 2 and Table 4 illustrate the following:

- CIPR-3, CIPR-4 and CIPR-3-AS options have the lowest initial costs.
- CIPR-4-AS and TCO have similar initial costs.
- Add-stone increases the initial cost of CIPR-3 and CIPR-4 approximately 11% and 14%, respectively.
- CIPR initial costs without add-stone are 4 to 12% lower than TCO.
- The MF options have the highest initial costs.

LCCA Findings

In the LCCA, the treatment option with the lowest NPV has the lowest life cycle cost. Initial cost, anticipated treatment life and discount rate all have an effect on NPV (per mile). NPV values for each treatment option were calculated using a 20-year analysis period and a 3.0 percent discount rate. The results for an 11-year treatment life for CIPR and MF and 14 years for TCO are shown in Figure 3 and Table 5. The data show the following:

- TCO has the lowest life cycle cost followed by the CIPR and MF options.
- CIPR-3 had the second lowest life cycle cost.
- The addition of 20% add-stone increases the life cycle costs of CIPR-3 and CIPR-4 by approximately 12% and 14%, respectively.
- The MF options have the highest life cycle costs.

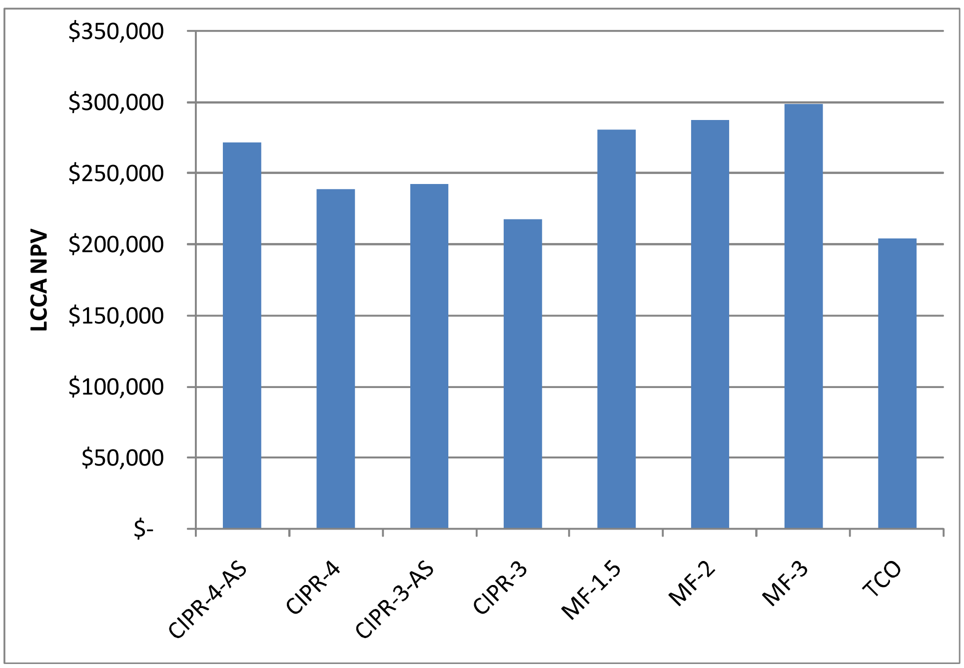

Figure 3. LCCA results (3% discount rate, 20-year analysis period).

Table 5. NPV Results, 3.0% Discount Rate, 20-Year Analysis Period

Treatment	NPV	Savings	% Savings
	Per Centerline Mile		
CIPR-4-AS	$ 271,000	-$67,000	-32.8
CIPR-4	$ 238,000	-$34,000	-16.7
CIPR-3-AS	$ 242,000	-$38,000	-18.6
CIPR-3	$ 217,000	-$13,000	-6.4
MF-1.5	$ 280,000	-$76,000	-37.3
MF-2	$ 287,000	-$83,000	-40.7
MF-3	$ 298,000	-$94,000	-46.1
TCO	$ 204,000	-	-

LIFE CYCLE ENVIRONMENTAL ANALYSIS (LCEA)

Background

PaLATE makes use of two different analytical methods to characterize and quantify the environmental burden of a selected option and defines the burden in terms of energy (fuel) use, water use, emissions and health risks of selected options.

The first approach is a Process-based LCA (PB-LCA). In PB-LCA, the major material and energy inputs and outputs are identified and quantified, and the impacts from the resulting environmental emissions are estimated. Much of the emission factor information for these operations is derived in PaLATE from the U.S. Environmental Protection Agency's Factor Information Retrieval (FIRE) software[1]. FIRE is a database containing EPA's recommended emission estimation factors for criteria pollutants and hazardous air pollutants.[2] These emission factors are average factors compiled by EPA for specific operations. The major material and energy inputs and outputs are identified and quantified, and the impacts from the resulting environmental emissions are estimated. The PB-LCA method uses the traditional approach to define the environmental burden of a specific operation and activity.

The second method is a life-cycle assessment approach known as the Economic Input-Output Life-Cycle Assessment (EIO-LCA). The EIO-LCA method is designed to provide an estimate of both direct and supply chain effects for commodities using average U.S. Department of Commerce data (Horvath 2004a). Its methodology is based on estimates of the environmental burden resulting from raw material acquisition through production, use and disposal. For example, the use of asphalt bitumen in asphalt paving induces an environmental burden, not only at the construction site where the pavement is being constructed, but also at the hot mix asphalt plant where the aggregate and asphalt cement are mixed. Hot mix asphalt production in turn induces impacts at the crude oil refinery where the asphalt bitumen used in the asphalt concrete is produced, at power generating facilities where power is generated to run the refinery, and in oil and gas extraction operations that must pump, store and transport the crude oil, etc. All of these impacts result from the increased demand for asphalt bitumen generated by the roadway construction project. Similar supply chain impacts are induced due to the need for aggregate materials in the hot mix asphalt.

In PaLATE, the two approaches (PB-LCA and EIO-LCA) are combined into what is referred to as a hybrid model. The objective is to obtain greater insight into the environmental burden resulting from a specific action as opposed to the limited action, in this case, taking place on the roadway.

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[1] Formerly referred to as FIRE, EPA has since upgraded the FIRE database to an online database referred to as WebFIRE: http://www.epa.gov/ttn/chief/software/fire/

[2] Criteria pollutants are air pollutants, including carbon monoxide, hydrocarbons, lead, oxidants, particulates, nitrogen oxides, and sulfur oxides, for which maximum permissible concentrations in ambient air are established.

PaLATE categorizes the highway construction process into three operations:

- Materials Production,
- Materials Transportation and
- Process (Equipment).

Table 6 lists the specific operations and the respective activity under each operation.

Table 6. Highway Construction Operations and Activities Defined in PaLATE

Construction Operation	Activity	CIPR-AS		CIPR		MF		TCO
		HMA	CIPR	HMA	CIPR	HMA	Cold Milling	HMA
Materials Production	Virgin Aggregates	X	X	X		X		X
	Asphalt Cement	X		X		X		X
	Asphalt Emulsion		X		X			
	RAP in HMA mix	X		X		X		X
	Run HMA Plant	X		X		X		X
	Cold Milling						X	
Materials Transportation	Haul Aggregates	X	X	X		X		X
	Haul Asphalt Cement	X		X		X		X
	Haul Asphalt Emulsion		X		X			
	Haul HMA from Plant to Project	X		X		X		X
	Haul Cold Millings to Plant	X		X		X	X	X
Process (Equipment)	HMA Paving	X		X		X		X
	CIPR		X		X			

For each respective activity listed in Table 6, PaLATE focuses on 12 different environmental parameters, designed to quantify the environmental burden through resource use (e.g., energy and water) and polluting emissions (Horvath, 2004). These include:

1. Energy consumption in MJ,
2. CO_2 (Carbon dioxide) emissions in kg,
3. Water consumption in kg,
4. NO_x (Nitrogen oxides) emissions in kg,
5. PM_{10} (particle size less than 10 micrometer) emissions in kg,
6. $S0_2$ (Sulfur dioxide) emissions in kg,
7. CO (Carbon monoxide) emissions in kg,
8. Hg (Mercury) emissions in g,
9. Pb (Lead) emissions in g,
10. RCRA (Resource Conservation Recovery Act) hazardous waste generated in kg,
11. HTP (human toxicity potential cancerous) in g,
12. HTP (human toxicity potential non-cancerous) in kg.

Model Qualifications

The development of EIO-LCA models for environmental life cycle analysis is a relatively new process. The databases currently available to predict supply chain environmental impacts are in early stages of development and generally rely on simplifying assumptions and aggregate or average resource use and pollutant release data associated with broad industrial sectors to project environmental burdens.

In running the model, the Authors found it necessary to make selected adjustments in the data input to compensate for specific supply chain calculations, which were judged to be of questionable accuracy.[1] The model results presented in the main body of the report reflect these adjustments. The original unadjusted PaLATE projections are presented in Appendix C for reference. The primary adjustment incorporated into the model was an adjustment on the relative environmental burden associated with the use of asphalt bitumen (asphalt cement and asphalt emulsion) in each option. The environmental burden associated with asphalt bitumen demand projected by PaLATE was reduced by 90 percent.[2] Detailed discussion of this qualification is presented in Appendix C.

Despite the aforementioned adjustment and database limitations, the model served as a useful tool and provided results that would not have been apparent using traditional methods alone. For example, as will be shown herein, the environmental burden of CIPR is in most cases lower than that of other maintenance options (i.e., TCO and MF), however the benefits can be readily lost if additional aggregate is introduced into CIPR blends, which necessitates the addition of extra bitumen (asphalt emulsion) into the blend. This is because, as previously noted, asphalt bitumen production induces additional environmental burdens in the supply chain (e.g., petroleum refining sector) that can exceed the reduction in the environmental burden realized when CIPR is used in lieu of other methods.

Model Projection Presentation

The model projections are presented in the following subsections. The presentation format includes a comparative graphical assessment of the CIPR, MF and TCO options, followed by an itemized summary of the findings. A detailed listing of the PaLATE data projections in tabular form is presented in Table 7. The data in Table 7 form the basis for the graphical presentation that follows.

[1] The reallocation of specific supply chain environmental burdens is an accepted method in EIO-LCA when the environmental burdens are judged erroneous. (Hendrickson 2006)
[2] A reduction of 90 percent of the asphalt bitumen environmental burden projected by PaLATE means that only 10 percent of the projected impact associated with the production (see Materials Production, Table 6) of asphalt cement and asphalt emulsion was included in the analysis.

Table 7. Summary of Total Outputs from PaLATE

PaLATE Output	Treatment							
	CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
Energy (MJ)	976,815	833,054	883,797	775,972	1,271,892	1,293,565	1,336,909	1,209,419
Water (kg)	182.4	154.1	158.6	137.4	174.2	174.2	174.2	175.3
CO2 (kg)	48,925	39,048	42,790	35,382	60,718	64,500	72,064	48,763
NOx (kg)	804.3	705.6	712.4	638.4	1,113.9	1,196.2	1,379.0	873.8
PM 10 (kg)	365.3	249.9	329.5	243.0	534.6	485.8	508.3	444.6
SO2 (kg)	18,167	18,148	18,149	18,135	36,205	36,210	36,221	36,190
CO (kg)	171.4	149.4	146.7	130.3	183.7	195.8	219.8	145.8
Hg (g)	0.59	0.53	0.51	0.47	0.58	0.59	0.60	0.55
Pb (g)	32.5	27.6	28.4	24.7	33.3	33.6	34.3	32.2
RCRA Hazardous Waste (kg)	6,150	5,419	5,351	4,803	6,124	6,201	6,357	5,909
HTP Cancerous (g)	62,751	53,083	60,287	53,036	106,352	106,585	107,052	105,792
HTP Non-Cancerous (kg)	305,839	191,461	279,438	191,404	383,151	383,437	384,010	382,464

Energy Consumed

Figure 4 graphically depicts the energy consumed for each treatment option, expressed in terms of mega joule (MJ) per mile. General findings are as follows:

- The CIPR options consume the least amount of energy, ranging from 25 to 35% less than TCO and 30 to 60% less than the MF options.
- Add-stone increases the energy demand of CIPR-3 and CIPR-4 by 14% and 17%, respectively.
- Materials Production accounts for over 80% of the total energy consumed in each treatment.
- The TCO and MF options consume significantly more transportation energy than the CIPR options, with TCO consuming approximately 40 to 80% and the MF options 70 to 160% more transportation energy than the CIPR options.

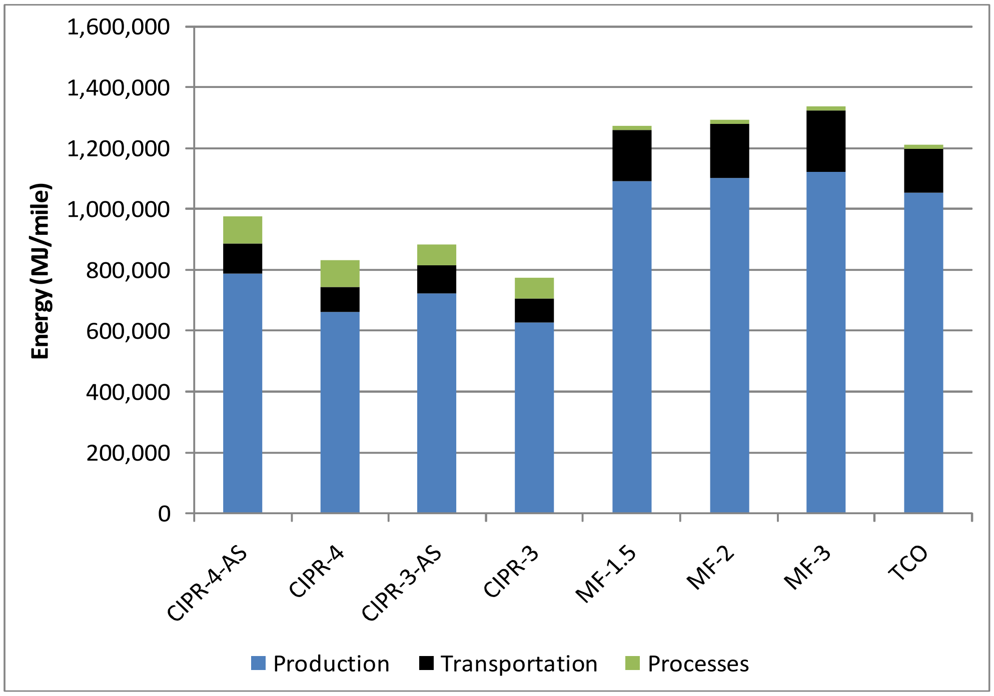

Figure 4. Energy consumed by treatment.

Greenhouse Gas Emissions

Greenhouse gases included in PaLATE are $C0_2$, CO and NO_x. CO_2 is by far the predominant component, accounting for approximately 98% of greenhouse gas emissions. (Note: NO_x and CO are also precursors for photochemical smog production) Total greenhouse gas emissions for materials production, materials transportation and process operations, expressed in terms of kg released per mile, are shown in Figure 5. Individual plots of the component parts of greenhouse gas are shown in Figures 6 through 8. General findings are as follows:

- The CIPR options generate the least amount of greenhouse gas emissions.
- CIPR-3 generates the lowest quantity of greenhouse gas followed by CIPR-4.
- The addition of 20% add-stone increases greenhouse gas emissions in CIPR-3 and CIPR-4 treatment options by approximately 10 and 20%, respectively.
- CIPR-4-AS and TCO produce similar amounts of greenhouse gas, approximately 40% more than CIPR-3.
- The MF options generate the most greenhouse gas, approximately 70 to 100% more than CIPR-3.
- Materials production constitutes the major source of greenhouse gas emission, accounting for 65 to 75% of the total emitted for each treatment
- CO_2 emissions account for 98 to 99% of greenhouse gas emissions
- The CIPR options produce the lowest NO_x emissions
- A larger portion of NO_x emissions is generated from transportation than the other components of greenhouse gas.

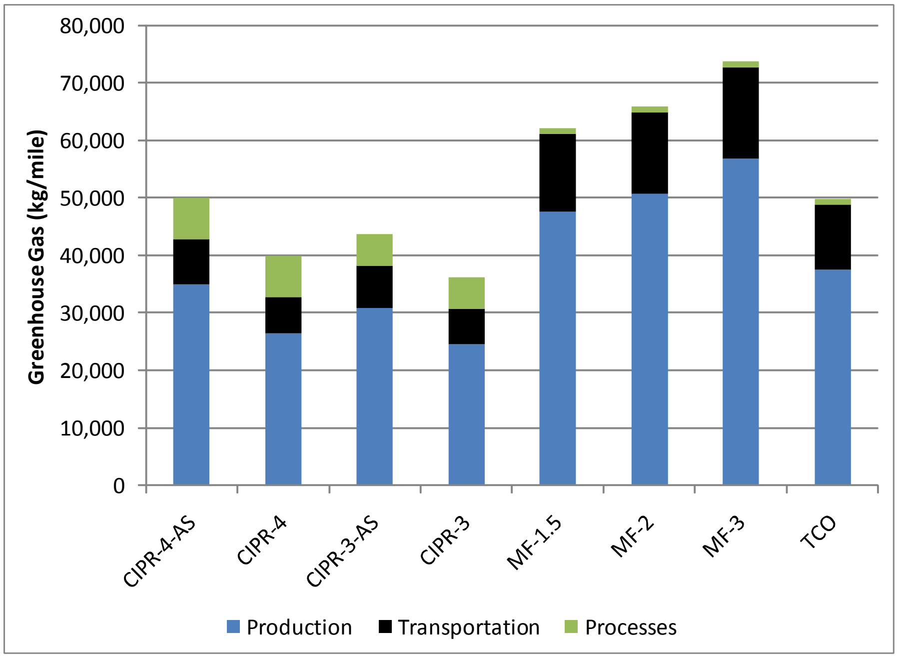

Figure 5. Total greenhouse gas emissions.

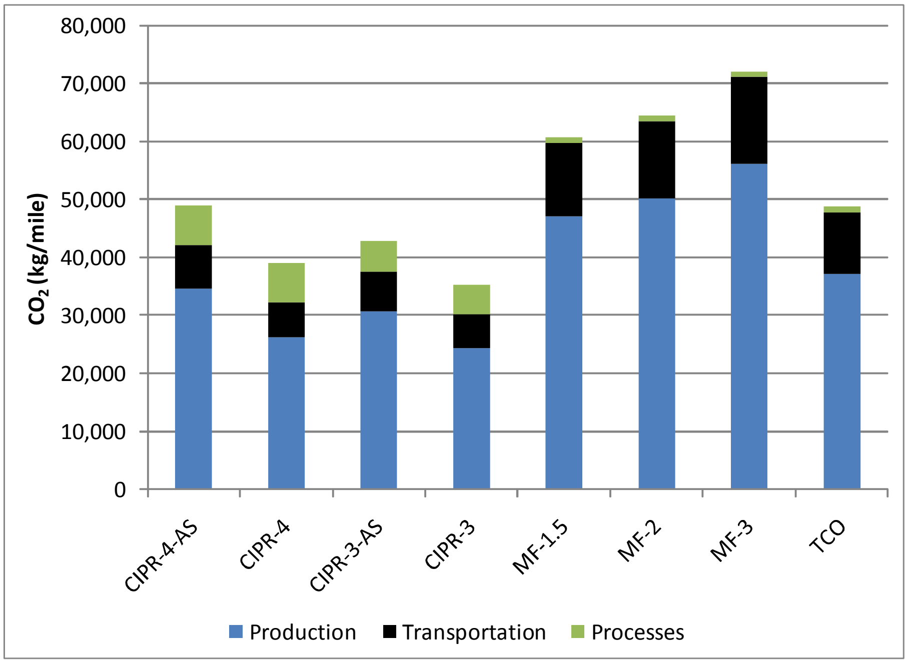

Figure 6. Total CO_2 emissions.

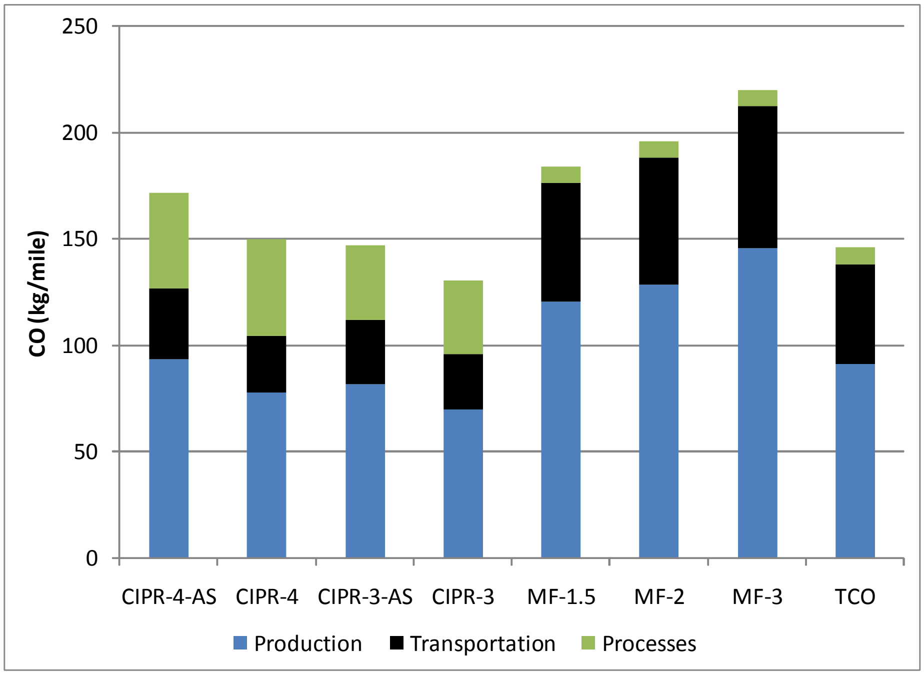

Figure 7. Total CO emissions.

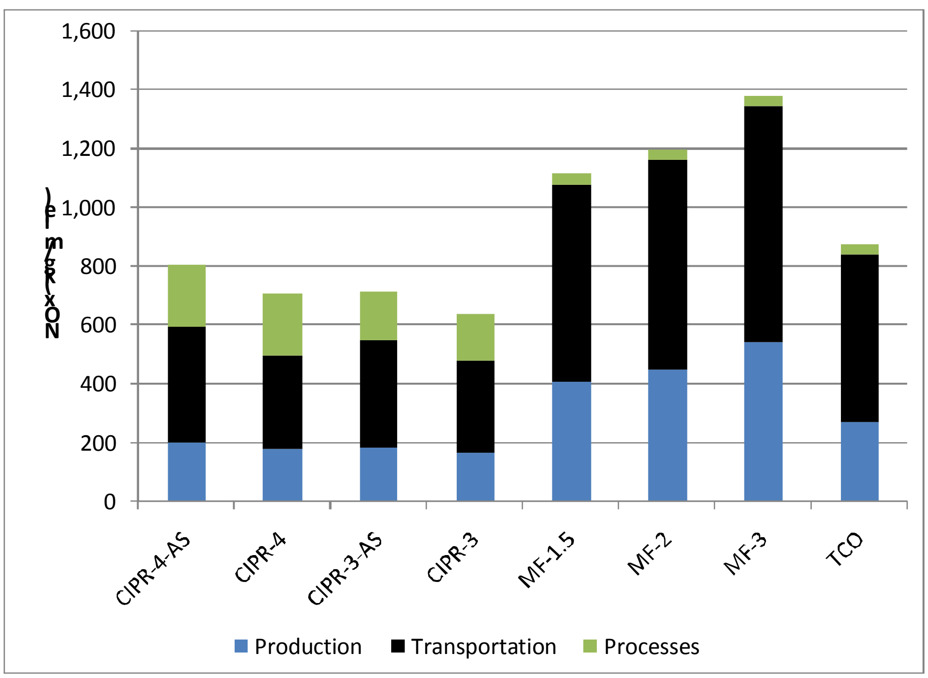

Figure 8. Total NO_x emissions.

<u>Water Consumption</u>

Total water consumption for materials production, materials transportation and process operations, expressed in terms of kg per mile, are shown in Figure 9. General findings are as follows:

- CIPR-3 uses the least amount of water followed by CIPR-4 and CIPR-3-AS.
- CIPR-4 and CIPR-3-AS consume approximately 12 and 15% more water, respectively, than CIPR-3.
- Water consumption projections are essentially the same for the three MF options and TCO.
- The vast majority of water consumed is used in the materials production operations, specifically, the production of asphalt bitumen.
- CIPR-4-AS consumes the largest quantity of water, approximately 5% higher than the MF and TCO options.
- CIPR with add-stone consumes approximately 15 to 18% more water than CIPR without add-stone.

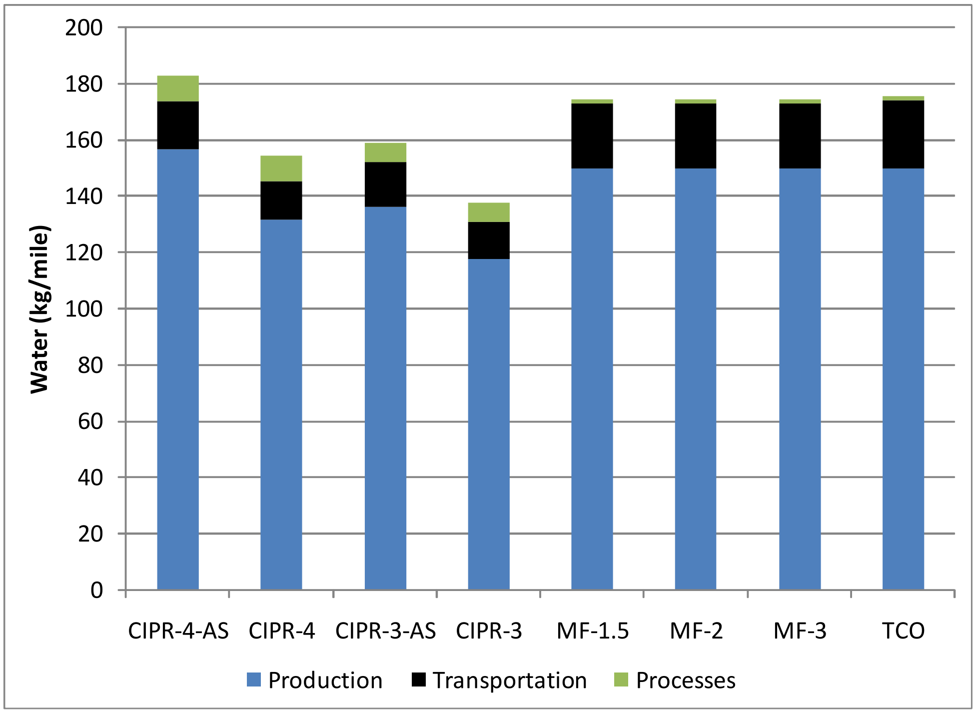

Figure 9. Water consumption by treatment.

<u>Sulfur Dioxide Emissions</u>

Sulfur present in fuels will be emitted as sulfur dioxide during the fuel combustion process. According to PaLATE, 98% of SO_2 emissions are associated with running the hot mix asphalt (HMA) plant. Total sulfur dioxide emissions for materials production, materials transportation and process operations, expressed in terms of kg per mile, and are shown in Figure 10. General findings are as follows:

- The Materials Production operation accounts for over 99% of sulfur dioxide emissions and almost all of these emissions are attributable to the HMA plant.
- The MF options and TCO generate approximately 100% more sulfur dioxide than the CIPR options. This is due to the two 1.5-inch HMA layers for these options compared to the single 1.5-inch HMA layer for CIPR.

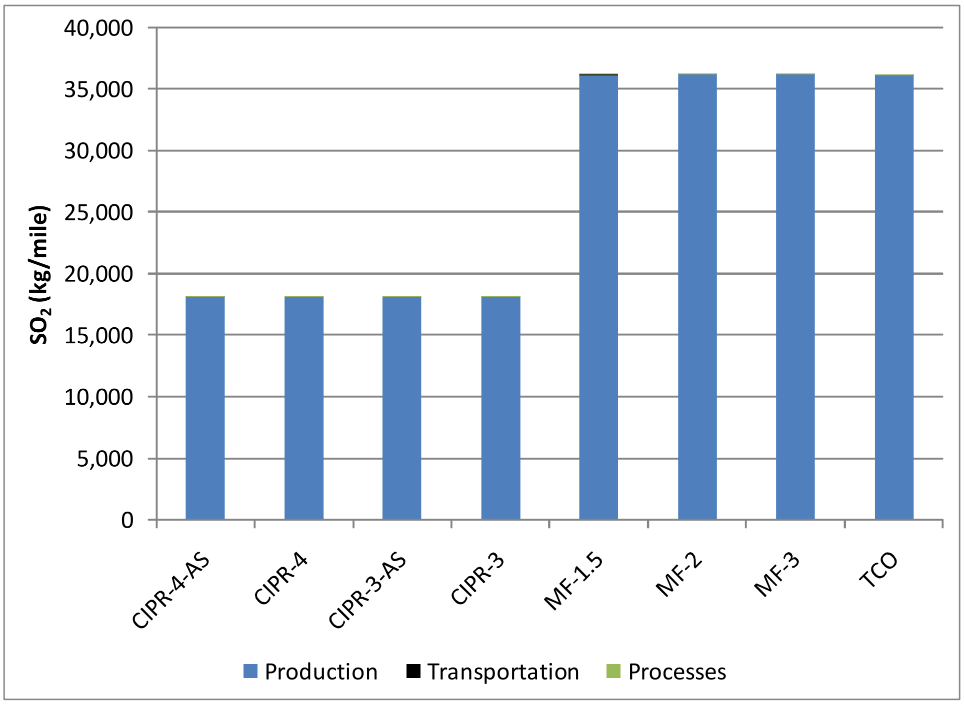

Figure 10. Sulfur dioxide by treatment.

PM_{10} Emissions

PM_{10} emissions are very fine particles (less than 10 microns, aerodynamic diameter) that can penetrate the lungs. They are typically associated with particles and aerosols generated by fuel consumption and dust generated during aggregate production operations and construction operations. PM_{10} emissions for materials production, materials transportation and process operations, expressed in terms of kg per mile, are shown in Figure 11. General findings are as follows:

- The CIPR options (with and without add-stone) generate significantly lower PM_{10} emissions than the MF and TCO options.
- TCO and MF options generate approximately 80 to120% more PM_{10} than CIPR without add-stone.
- TCO and MF options generate approximately 30 to 50% more PM_{10} than CIPR with add-stone.
- Materials production accounts for the majority of PM_{10} emissions.

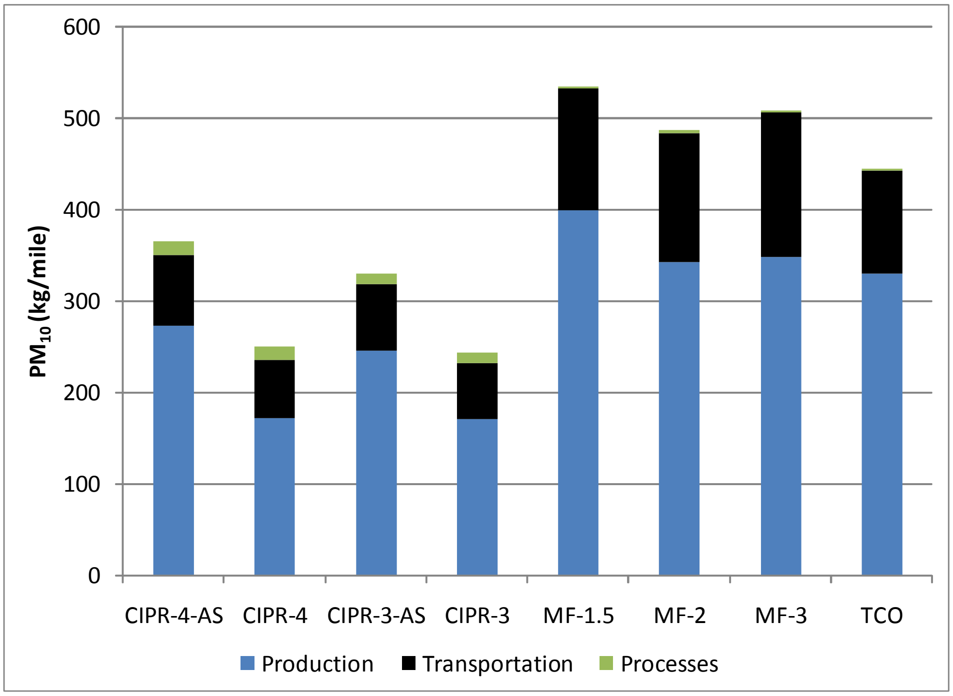

Figure 11. Particulate matter less than 10 microns (PM_{10}) by treatment.

Lead and Mercury Emissions

Lead (Pb) emissions are associated with the refining of asphalt bitumen with only minor amounts associated with the production of aggregates and cold milling. Mercury (Hg) emissions are almost entirely associated with the production of asphalt bitumen. Pb and Hg emissions for materials production, materials transportation and process activities, expressed in terms of g per mile, are shown in Figures 12 and 13, respectively. General findings are as follows:

- CIPR-3 produces the least Hg and Pb followed by CIPR-4 and CIPR-3-AS.
- CIPR without add-stone produces the least Hg and Pb, approximately 15 and 20% less than the TCO and MF options.
- CIPR-4-AS, TCO and the MF options produce approximately the same amount of Hg and Pb.
- Materials Production accounts for approximately 80 to 90% of lead and mercury emissions.
- PaLATE attributes no lead or mercury to process (equipment) operations.

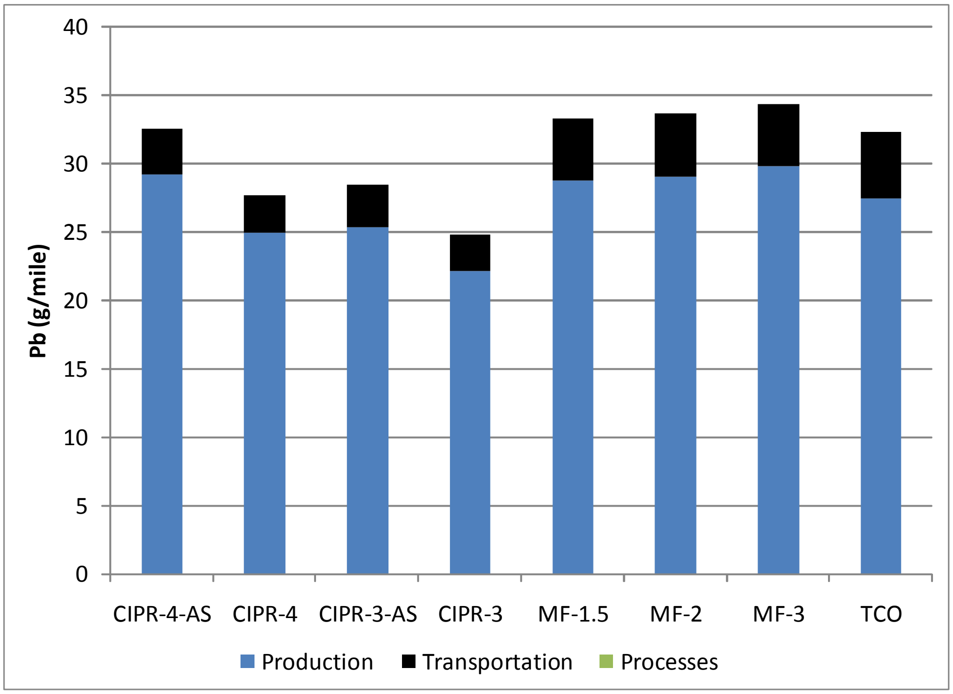

Figure 12. Lead emissions by treatment.

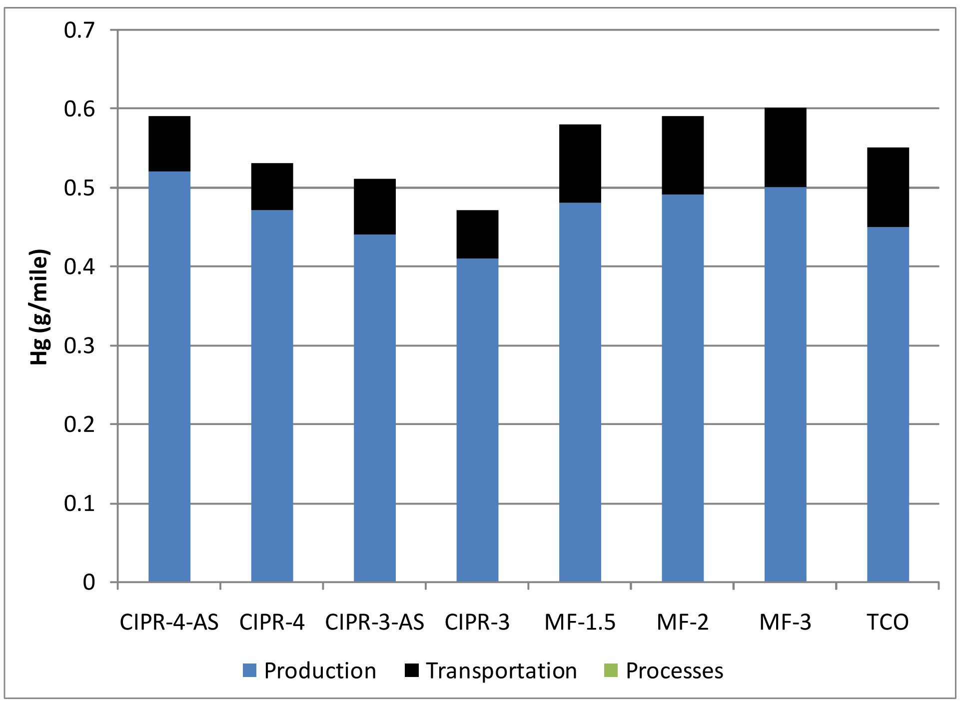

Figure 13. Mercury by treatment.

RCRA Hazardous Waste

RCRA hazardous wastes are waste products that are classified by the Resource Conservation Recovery Act as hazardous. Production of RCRA hazardous waste is primarily associated with the refining of asphalt bitumen. RCRA hazardous waste production during materials production, materials transportation and process activities, expressed in terms of kg per mile, are shown in Figure 14. General findings are as follows:

- CIPR-3 produces the least RCRA waste followed by CIPR-3-AS and CIPR-4, approximately 10 to 20% less than the other options.
- CIPR-4-AS, TCO and the MF options produce approximately the same amount of RCRA waste.
- Materials production accounts for 80 to 90% of RCRA hazardous waste generated.
- PaLATE attributes no RCRA hazardous waste generation to process (equipment) operations.

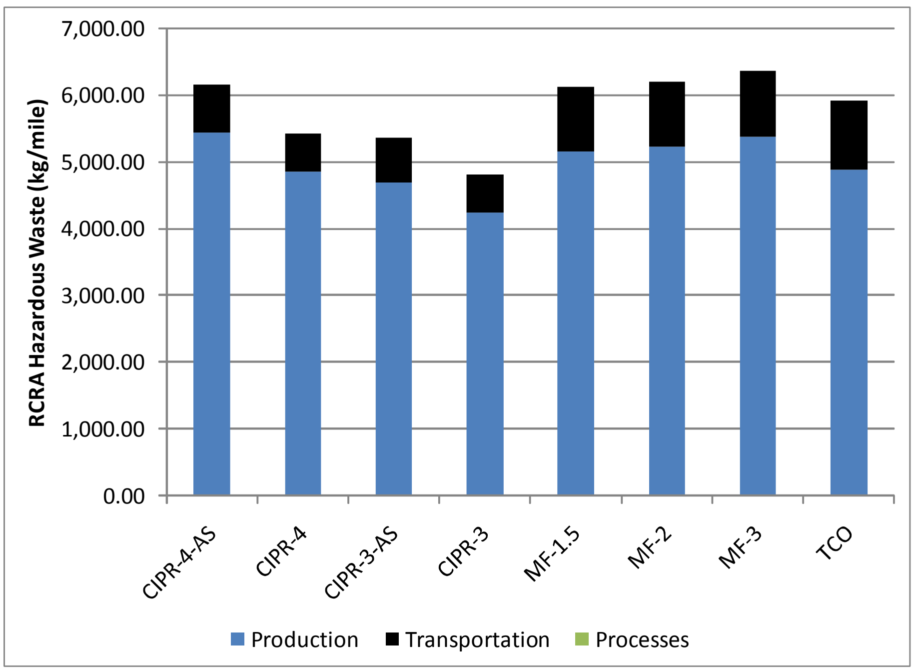

Figure 14. RCRA hazardous waste generated by treatment.

Human Toxicity Potential (Cancerous and Non-Cancerous)

Certain chemicals released into the environment are known to result in carcinogenic and non-carcinogenic human health impacts. The human toxicity potential (HTP) method is used by PaLATE to allow comparison of the potential health effects of pollutant releases from road construction and maintenance and relevant supply chain activities. Human toxicity-cancerous is based on benzene equivalents and human toxicity non-cancerous is based on toluene equivalents. Benzene-equivalents and toluene-equivalents provide common denominators for comparing toxic carcinogenic emissions and non-carcinogenic emissions, taking into account variations in toxicity and exposure potential of specific chemicals released in the respective processes. The units indicate the number of g of benzene or kg of toluene, respectively that would have to be released into the air to pose the same approximate level of health risk as the reported release of the selected chemical. HTP for toxic cancerous and non-cancerous emissions, released during materials production, materials transportation and process activities, expressed in terms of benzene and toluene equivalents, respectively, are shown in Figures 15 and 16. General findings are as follows:

- The MF options and TCO produce 40 to 50% more cancerous human toxicity than the CIPR options.
- Materials production accounts for over 95% of HTP Cancerous emissions and the majority of this is related to the production of asphalt cement.
- PaLATE attributes no HTP Cancerous emissions to process (equipment) operations.
- The MF options and TCO produce approximately 100% more non-cancerous human toxicity than CIPR without add-stone and approximately 25 to 35% more than CIPR with add-stone.
- Materials production accounts for approximately 99% of HTP Non-Cancerous emissions and the majority of this is related to the production of aggregates.
- PaLATE attributes no HTP Non-cancerous emissions to process (Equipment) operations.

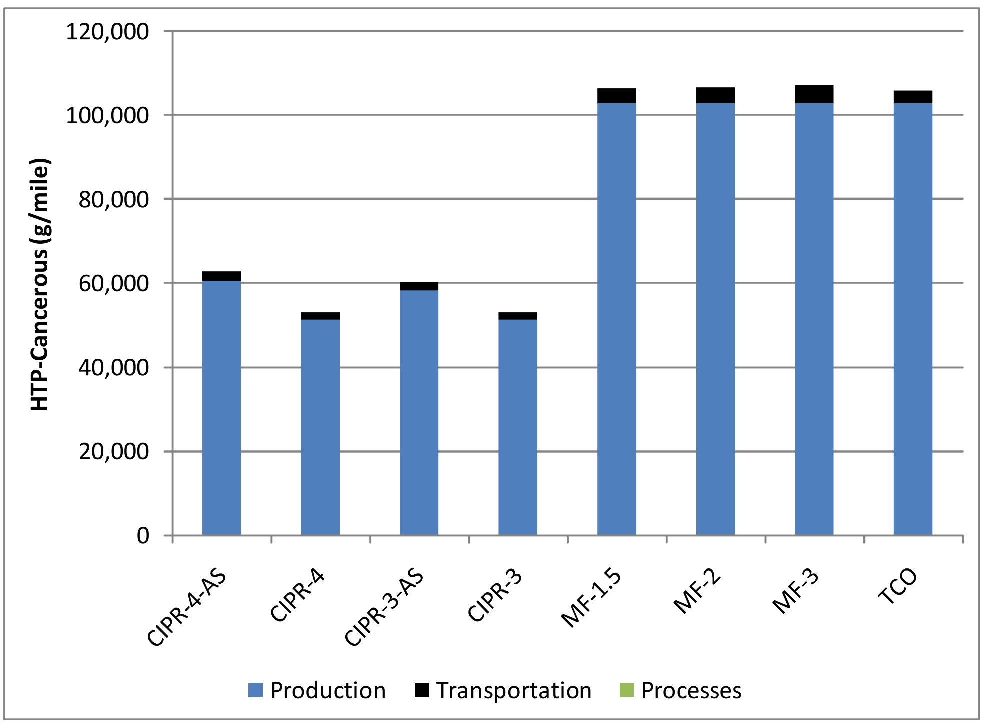

Figure 15. Human toxicity potential (carcinogenic) by treatment.

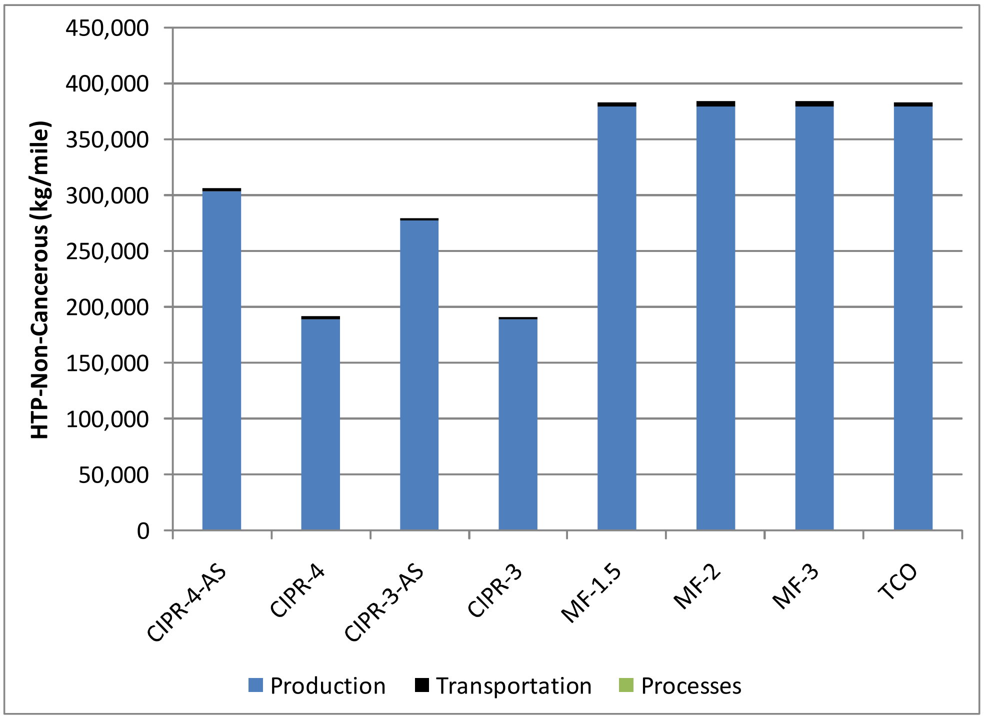

Figure 16. Human toxicity potential (non-carcinogenic) by treatment.

LCEA Findings

Table 8 provides a ranking from 1 to 8 of each environmental parameter included in the PaLATE analysis for each respective treatment option. The lowest ranked value (e.g., 1) corresponds to the lowest environmental burden and the highest ranking (e.g., 8) the greatest burden.

If the rankings for each effect are summed by treatment then an overall, but not completely scientific, picture of the environmental impact of each treatment option is available.[1]

Table 8 reflects the fact that:

- CIPR-3 ranks lowest (ranking of 1) for each of the environmental parameters examined, and as a result generates the best total ranking (lowest value).
- CIPR-4 and CIPR-3-AS, respectively, have the next lowest rankings indicating a distinct environmental advantage for CIPR as a maintenance option compared to TCO and the MF options.

[1] This type of total ranking gives equal weight to each environmental parameter, which is a simplifying assumption.

- The addition of add-stone to CIPR-4 (CIPR-4-AS) removes the distinct environmental advantage of CIPR as a maintenance option over TCO.

Table 8. Ranking of PaLATE Outputs from Low to High[1]

PaLATE Output	Treatment CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
Energy (MJ)	4	2	3	1	6	7	8	5
Water (kg)	8	2	3	1	4	4	4	7
CO2 (kg)	5	2	3	1	6	7	8	4
NOx (kg)	4	2	3	1	6	7	8	5
PM 10 (kg)	4	2	3	1	6	7	8	5
SO2 (kg)	4	2	3	1	6	7	8	5
CO (kg)	5	4	3	1	6	7	8	2
Hg (g)	6	3	2	1	5	6	8	4
Pb (g)	5	2	3	1	6	7	8	4
RCRA Hazardous Waste (kg)	5	3	2	1	6	7	8	4
HTP Cancerous (g)	4	2	3	1	6	7	8	5
HTP Non-Cancerous (kg)	4	2	3	1	6	7	8	5
Sum	58	28	34	12	69	80	92	55

1. Note: Greenhouse gas is not included in the ranking table due to the redundancy with the individual greenhouse gas components (primarily CO2)

CONCLUSIONS

LCCA

While the CIPR options (CIPR-3, CIPR-4 and CIPR-3-AS) exhibit the lowest initial cost, TCO and CIPR without add-stone exhibit the lowest life cycle costs. The lower TCO life cycle cost can be attributed to the longer projected treatment life used for TCO (14 years) compared to the 11year life used for both the CIPR and MF options. The MF options exhibit the highest initial and highest life cycle cost.

Based on the LCCA findings it is concluded that

- CIPR-3 and TCO are comparable life cycle cost options.
- Treatment life is the most critical parameter when comparing the CIPR and TCO options.
- When deciding between TCO and CIPR as treatment options, the deciding factor should be based on the structural requirements and functional distresses exhibited by the pavement.
- The MF options are the least cost effective of the treatments evaluated.

LCEA

The use of CIPR (without add-stone) exhibits the best environmental ratings when compared with all other CIPR, MF and TCO options. This advantage can be lost however if add-stone is incorporated into the mix design. This is primarily due to the need for additional asphalt emulsion in the CIPR treatment.

Based on the LCEA findings it is concluded that

- The CIPR maintenance options of CIPR-3, CIPR-4 and CIPR-3-AS, from a life cycle environmental perspective, are the best treatment options.
- The TCO maintenance option is similar to CIPR-4 if add-stone is included in the mix (CIPR-4-AS).
- The MF options exhibit the highest life cycle environmental burdens, when compared to the CIPR and TCO options.

CIPR and TCO

Although the TCO option exhibited the lowest life cycle cost and a similar environmental burden when compared to CIPR with add-stone, the PaLATE analysis was limited to the mainline pavement only. Shoulders were excluded from the analysis. Treating shoulders will result in higher costs and increased environmental outputs for all the options examined. Since the TCO option is a surface treatment option only, it is likely that additional TCO shoulder treatment, which may not be needed with CIPR and MF, may be required to ensure that the grade and elevation of the mainline pavement and the shoulder conform to specifications. If such is the case, then it is likely that the CIPR option will exhibit more favorable relative costs and environmental outputs compared to TCO.

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APPENDIX A: Structural and Functional Distress Equivalency

It is possible to compare the structural equivalency of different maintenance options by making use of structural number (SN) from the AASHTO Design Guide (AASHTO, 1993). The SN is the sum of the thickness of each pavement layer multiplied by its respective a coefficient. To do this, an "a" coefficient of the milled material (existing pavement) would need to be established or assumed.

Treatment depths and structural equivalency for the eight treatments evaluated are shown in Table A-1. Milling removes structural support and SN would be negative; CIPR and HMA add structural support and SN is positive.

From the information in Table A-1, the treatment options do not have the same structural equivalencies. TCO adds the most structure followed by CIPR and MF.[1]

Table A-1. Structural Equivalency Analysis

	Milled Mat'l. (existing pvmt.)		CIPR		HMA Overlay		Total	Treatment Depth
Treatment	a coef.	SN	a coef.	SN	a coef.	SN	SN	(in.)
CIPR-4-AS	0.25	-1.00	0.30	1.20	0.44	0.66	0.86	5.5
CIPR-4	0.25	-1.00	0.30	1.20	0.44	0.66	0.86	5.5
CIPR-3-AS	0.25	-0.75	0.30	0.90	0.44	0.66	0.81	4.5
CIPR-3	0.25	-0.75	0.30	0.90	0.44	0.66	0.81	4.5
MF-1.5	0.25	-0.38	-	-	0.44	1.32	0.95	3.0
MF-2	0.25	-0.50	-	-	0.44	1.32	0.82	3.0
MF-3	0.25	-0.75	-	-	0.44	1.32	0.57	3.0
TCO	-	-	-	-	0.44	1.32	1.32	3.0

[1] While TCO adds the most structure to a pavement, adding the most structure to a pavement with functional distresses, such as reflective cracking, may be superfluous.

APPENDIX B: Life-Cycle Cost Sensitivity Analysis

Appendix B presents the results of a sensitivity analysis in which discount rate and treatment lives were varied to assess the affect of discount rate and treatment life changes on the results of the LCCA. Costs presented are per mile of 24-foot wide mainline pavement.

Discount Rate

Discount rate has an effect on NPV and hence the LCCA. Higher discount rates are more favorable to treatment options with lower initial cost and shorter treatment lives. To evaluate the extent of this effect, NPV values for each treatment option were calculated using a 20-year analysis period for a 3.0 and 6.0 percent discount rate. Treatment lives were left unchanged from the original analysis presented in the main body of the report (11 years for CIPR and MF and 14 years for TCO). The influence of discount rate on NPV is shown in Table B-1.

Regarding the order of rankings, the data show that

- Discount rate did not affect the rankings of the options and the order, from lowest to highest life-cycle cost was TCO, CIPR-3, CIPR-4, CIPR-3-AS, CIPR-4-AS, MF-1.5, MF-2 and MF-3.

Table B-1. NPV for 3 and 6% Discount Rates

Treatment	Discount Rate	
	3%	6%
	NPV (per Centerline Mile)	
CIPR-4-AS	$ 271,000	$ 245,000
CIPR-4	$ 238,000	$ 215,000
CIPR-3-AS	$ 242,000	$ 219,000
CIPR-3	$ 217,000	$ 197,000
MF-1.5	$ 280,000	$ 255,000
MF-2	$ 287,000	$ 260,000
MF-3	$ 298,000	$ 270,000
TCO	$ 204,000	$ 190,000

Treatment Life

The selected treatment life in a LCCA will have a significant effect on the results of the analysis. To evaluate the effect of treatment life on NPV, a sensitivity analysis was undertaken using both a 3.0 and 6.0 percent discount rate, a 20-year analysis period and alternative treatment lives of 8, 11, 14, 17 and 20 years for each treatment. The results are tabulated in Tables B-2 and B-3.

The cost matrices presented in Tables B-2 and B-3 can be used to estimate how long a treatment must last to have the same life-cycle cost (NPV) as one of the alternative treatments. For example, in Table B-2 (at a 3% discount rate), an 11-year treatment life for CIPR has a life cycle cost (NPV) of approximately $217,000. With some minor interpolation in the table, it is readily seen that an equivalent life cycle cost TCO option must last approximately 13 years; and an equivalent MF-3 option would need to last approximately 17 years.

Table B-2. Results of LCCA for 3.0% Discount Rate, 20-Year Analysis Period

Treatment	Treatment Life (Years) 8 (NPV)	11	14	17	20
CIPR-4-AS	$ 356,000	$ 271,000	$ 224,000	$ 192,000	$ 167,000
CIPR-4	$ 313,000	$ 238,000	$ 197,000	$ 168,000	$ 147,000
CIPR-3-AS	$ 318,000	$ 242,000	$ 201,000	$ 171,000	$ 149,000
CIPR-3	$ 286,000	$ 217,000	$ 180,000	$ 154,000	$ 134,000
MF-1.5	$ 370,000	$ 281,000	$ 233,000	$ 199,000	$ 173,000
MF-2	$ 377,000	$ 287,000	$ 238,000	$ 203,000	$ 177,000
MF-3	$ 392,000	$ 298,000	$ 247,000	$ 211,000	$ 184,000
TCO	$ 325,000	$ 247,000	$ 204,000	$ 175,000	$ 152,000

Table B-3. Results of LCCA for 6.0% Discount Rate, 20-Year Analysis Period

Treatment	Treatment Life (Years) 8 (NPV)	11	14	17	20
CIPR-4-AS	$ 311,000	$ 245,000	$ 211,000	$ 186,000	$ 167,000
CIPR-4	$ 273,000	$ 215,000	$ 185,000	$ 163,000	$ 147,000
CIPR-3-AS	$ 278,000	$ 219,000	$ 188,000	$ 166,000	$ 149,000
CIPR-3	$ 250,000	$ 197,000	$ 169,000	$ 149,000	$ 134,000
MF-1.5	$ 323,000	$ 255,000	$ 219,000	$ 193,000	$ 173,000
MF-2	$ 330,000	$ 260,000	$ 223,000	$ 197,000	$ 177,000
MF-3	$ 343,000	$ 270,000	$ 232,000	$ 205,000	$ 184,000
TCO	$ 284,000	$ 224,000	$ 192,000	$ 169,000	$ 152,000

Regarding the order of rankings, the data show that

- Using an average treatment life of 11 years for CIPR and MF and a treatment life of 14 years for TCO, offsets the higher initial TCO cost to give TCO the lowest life cycle cost.
- At a 3 and 6 percent discount rate, respectively, TCO needs a service life at least 0.5 to 1.0 years longer than CIPR-4 to have an equivalent life cycle cost.
- At a 3 and 6 percent discount rate, respectively, TCO needs a service life at least 1.0 to 2.0 years longer than CIPR-3 to have an equivalent life cycle cost.

APPENDIX C: Life Cycle Environmental Analysis: Qualifications

Appendix C presents a discussion of some of the limitations of the LCEA conducted in this investigation and the qualifications incorporated by the Authors into the analysis presented in the main body of the report.

As noted in the main body of the report, PaLATE is a hybrid model that makes use of two different analytical methods to characterize and quantify the energy (fuel) use, water use, emissions and health risks. These include the Process-Based LCA (PB-LCA) and the Economic Input-Output Life-Cycle Assessment (EIO-LCA). An excellent description of the EIO-LCA method is presented by Hendrickson et al. (Hendrickson 2006).

PaLATE is unique in that it focuses specifically on highway construction and maintenance activities, incorporating both the PB-LCA and the EIO-LCA methods of analysis. The EIO-LCA method used by PaLATE is based on industrial sector data maintained at Carnegie Mellon University, which is available online (Carnegie Mellon, 2008).

In general, the EIO-LCA model works as follows:

1. When a demand for a product is initiated in any one sector; for example hot mix asphalt, it can generate demand in up to 500 economic sectors (only a few will actually be measurably impacted).
2. The demand is characterized monetarily (in dollars). For example, if a contractor purchases $100 of HMA, he can induce demand defined in terms of dollars in petroleum refinery, power generation, pipeline transport, sand and gravel mining, etc.
3. Each dollar demand in a particular sector generates some environmental burden (expressed in terms of resource use or polluting emission). For example, in sand and gravel mining, each 100 dollars spent could result in the use of 10 gallons of water, 20 kwh of power, 50 grams of PM10 emissions, etc.
4. So in effect, each industrial sector has environmental burden factors built into the EIO-LCA database that are defined in terms of emissions per dollar of demand or water use per dollar or energy use per dollar, etc.
5. By summing up the environmental burden across all economic sectors associated with a specific activity, the total environmental burden can be determined.

The EIO-LCA method of analysis for LCEA is a powerful tool that provides a much broader picture of overall environmental and resource impacts than conventional environmental assessment approaches. It is however a relatively recent development in environmental analysis, accelerating in its application over the past decade. It is recognized that the data available from many industrial sectors to project an accurate environmental burden is currently limiting. In some instances available data may be outdated or incomplete or nonspecific. In addition, the model assumes proportionality in production and hence environmental burden. What this means is that a $1,000 economic demand in an industrial sector will have 10x the environmental burden as a $100 demand.

This linear assumption can introduce significant error if the relationship between demand and environmental burden is nonlinear. When this is the case, the readjustment or reallocation of environmental burden factors is an acceptable procedure (Hendrickson 2006).

The Authors believe that the assumption of a linear relationship between asphalt bitumen demand and the environmental burden induced by this demand is erroneous and results in a significant overestimate of the environmental burden projected by PaLATE.[1] The environmental burden associated with bitumen is induced in great part by its association with petroleum refining. Asphalt bitumen is a byproduct material in the petroleum refining process. In this process, crude petroleum is separated into its various fractions through a distillation process at the oil refinery. After separation, these fractions are further refined into other products which include asphalt, paraffin, gasoline, naphtha, lubricating oil, kerosene, and diesel oil. Since asphalt is the base or heavy constituent of crude petroleum, it does not evaporate or boil off during the distillation process. Asphalt bitumen is essentially the heavy residue of the oil refining process. It is not the primary product or even a major secondary product. It is a residue byproduct, which would be generated whether or not a demand existed for it. As a result, the vast majority of the energy and emissions in an oil refinery would occur with or without a demand for the product. The linear assumption that as asphalt bitumen demand increases the energy and emissions in a petroleum refinery increases proportionately is highly questionable.

In the main body of the report, the asphalt bitumen-related environmental burden projected by PaLATE was reduced by 90%.[2] To examine the affect of asphalt bitumen-related environmental burden estimates on the LCEA, the Research Team generated three scenarios:

1. The 100% asphalt bitumen environmental burden projected by PaLATE,
2. A 50% asphalt bitumen environmental burden, which assumes that one-half of PaLATE’s projection is a better estimate than the 100% value, and
3. A 0% asphalt bitumen environmental burden, which assumes that there is no bitumen burden.

A detailed tabulation of the results of this analysis is presented in Table C-1. Graphical presentation of the data is presented in Figures C-1 through C-12. A discussion of the findings is presented in Appendix D.

[1] Since PaLATE was developed specifically for highway construction and maintenance activities it incorporates detailed roadway construction-related items in its algorithm such as the demand and cost for virgin aggregates, asphalt bitumen, RAP milling, water, hot-mix asphalt plant process, and asphalt emulsion that are not included in general EIO-LCA models. (Carnegie-Mellon 2010)
[2] A 90% reduction in the asphalt bitumen-related environmental burden was based on NYSDOT input.

Table C-1. PaLATE Results for Total Emissions and Environmental Effects

Emission /	Treatment							
Environmental Effect	CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
Energy (MJ)								
Mat'l. Production								
100% Bitumen	3,387,941	3,020,074	2,958,063	2,682,126	3,372,618	3,383,403	3,404,972	3,336,275
50% Bitumen	1,901,205	1,695,383	1,680,794	1,526,409	2,067,402	2,077,828	2,098,678	2,031,340
0% Bitumen	414,470	370,692	403,525	370,692	762,186	772,252	792,383	726,405
Mat'l. Transportation	98,986	79,847	92,024	77,669	168,402	179,290	201,065	142,272
Processes (Equip.)	91,031	91,031	69,921	69,921	13,182	13,182	13,182	13,182
Water Consumption (kg)								
Mat'l. Production								
100% Bitumen	1,248.3	1,121.2	1,074.7	979.4	1,107.6	1,107.6	1,107.6	1,107.6
50% Bitumen	641.8	571.4	553.3	500.5	575.5	575.5	575.5	575.5
0% Bitumen	35.30	21.66	31.86	21.66	43.30	43.30	43.30	43.30
Mat'l. Transportation	16.85	13.59	15.67	13.22	23.11	23.11	23.11	24.22
Processes (Equip.)	8.85	8.85	6.80	6.80	1.28	1.28	1.28	1.28
CO2 (kg)								
Mat'l. Production								
100% Bitumen	182,400	160,100	157,700	141,000	176,700	179,700	185,700	166,700
50% Bitumen	100,350	85,750	87,150	76,200	104,700	107,700	113,650	94,700
0% Bitumen	18,300	11,400	16,600	11,400	32,700	35,700	41,600	22,700
Mat'l. Transportation	7,400	5,970	6,880	5,810	12,590	13,400	15,030	10,630
Processes (Equip.)	6,830	6,830	5,250	5,250	990	990	990	990

Table C-1 (Con't.) PaLATE Results for Total Emissions and Environmental Effects

Emission /	Treatment							
Environmental Effect	CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
NOx (kg)								
Mat'l. Production								
100% Bitumen	1,022.0	922.8	890.5	816.0	1,127.7	1,166.7	1,244.7	991.7
50% Bitumen	565.7	509.1	498.2	455.7	727.3	766.3	844.3	591.3
0% Bitumen	109.4	95.5	105.9	95.4	326.9	365.9	443.9	190.9
Mat'l. Transportation	394.3	318.0	366.5	309.3	670.7	714.1	800.8	566.7
Processes (Equip.)	209.4	209.4	161.6	161.6	36.2	36.2	36.2	36.2
PM 10 (kg)								
Mat'l. Production								
100% Bitumen	411.7	298.2	365.3	280.1	461.4	464.1	469.7	451.7
50% Bitumen	334.4	228.1	298.8	219.1	393.5	396.3	401.8	383.9
0% Bitumen	257.0	158.0	232.3	158.0	325.6	328.4	333.9	316.0
Mat'l. Transportation	77.9	63.0	72.5	61.3	132.8	141.3	158.2	112.5
Processes (Equip.)	14.90	14.90	11.50	11.50	2.60	2.60	2.60	2.57
SO2 (kg)								
Mat'l. Production								
100% Bitumen	18,874	18,790	18,756	18,693	36,815	36,818	36,823	36,806
50% Bitumen	18,461	18,415	18,401	18,367	36,453	36,455	36,461	36,444
0% Bitumen	18,047	18,040	18,046	18,040	36,090	36,092	36,098	36,081
Mat'l. Transportation	23.70	19.08	22.00	18.60	40.20	42.85	48.00	34.00
Processes (Equip.)	13.80	13.80	10.70	10.70	2.39	2.39	2.39	2.39

Table C-1 (Con't.) PaLATE Results for Total Emissions and Environmental Effects

Emission /	Treatment							
Environmental Effect	CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
CO (kg)								
Mat'l. Production								
100% Bitumen	716.9	643.0	617.5	562.0	667.2	675.6	692.4	637.9
50% Bitumen	370.5	329.0	319.7	288.5	363.3	371.7	388.5	333.9
0% Bitumen	24.1	15.0	21.8	15.0	59.3	67.7	84.5	30.0
Mat'l. Transportation	32.9	26.5	30.5	25.8	55.9	59.5	66.7	47.2
Processes (Equip.)	45.1	45.1	34.8	34.8	7.8	7.8	7.8	7.8
Hg (g)								
Mat'l. Production								
100% Bitumen	5.15	4.67	4.43	4.07	4.55	4.55	4.57	4.52
50% Bitumen	2.58	2.34	2.22	2.04	2.28	2.28	2.29	2.26
0% Bitumen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mat'l. Transportation	0.07	0.06	0.07	0.06	0.10	0.10	0.10	0.10
Processes (Equip.)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb (g)								
Mat'l. Production								
100% Bitumen	244.7	220.3	210.6	192.3	217.8	218.2	218.9	216.6
50% Bitumen	125.0	111.8	107.7	97.8	112.8	113.1	113.9	98.30
0% Bitumen	5.22	3.22	4.70	3.22	7.70	8.00	8.80	6.40
Mat'l. Transportation	3.33	2.68	3.09	2.61	4.56	4.56	4.56	4.78
Processes (Equip.)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table C-1 (Con't.) PaLATE Results for Total Emissions and Environmental Effects

Emission / Environmental Effect	Treatment							
	CIPR-4-AS	CIPR-4	CIPR-3-AS	CIPR-3	MF-1.5	MF-2	MF-3	TCO
RCRA Hazardous Waste (kg)								
Mat'l. Production								
100% Bitumen	51,640	46,726	44,409	40,723	45,685	45,763	45,918	45,423
50% Bitumen	25,972	23,458	22,342	20,456	23,163	23,241	23,396	22,901
0% Bitumen	303	190	275	190	641	719	874	379
Mat'l. Transportation	713	575	663	560	978	978	978	1,025
Processes (Equip.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HTP Cancerous (g)								
Mat'l. Production								
100% Bitumen	374,530	365,272	372,216	365,272	730,545	730,545	730,545	730,545
50% Bitumen	200,141	190,883	197,826	190,883	381,766	381,766	381,766	381,766
0% Bitumen	25,751	16,493	23,436	16,493	32,986	32,986	32,986	32,986
Mat'l. Transportation	2,122	1,712	1,973	1,665	3,610	3,843	4,310	3,050
Processes (Equip.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HTP Non-Cancerous (kg)								
Mat'l. Production								
100% Bitumen	306,366	189,491	277,148	189,491	378,982	378,838	378,982	378,982
50% Bitumen	306,294	189,419	277,076	189,419	378,838	378,766	378,838	378,838
0% Bitumen	306,221	189,347	277,004	189,347	378,694	378,694	378,694	378,694
Mat'l. Transportation	2,603	2,100	2,420	2,043	4,429	4,715	5,288	3,742
Processes (Equip.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

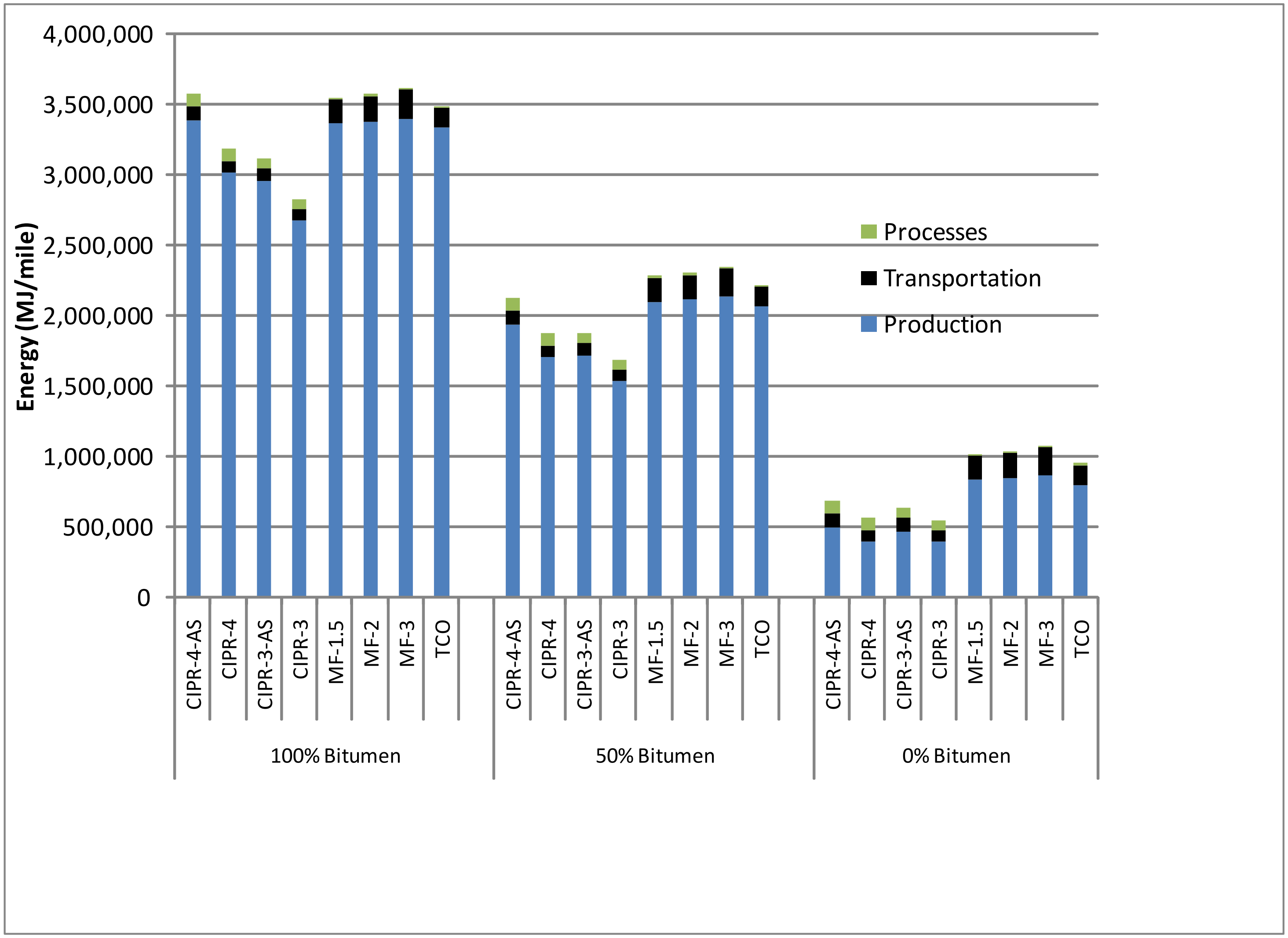

Figure C-1. Energy consumed by each treatment.

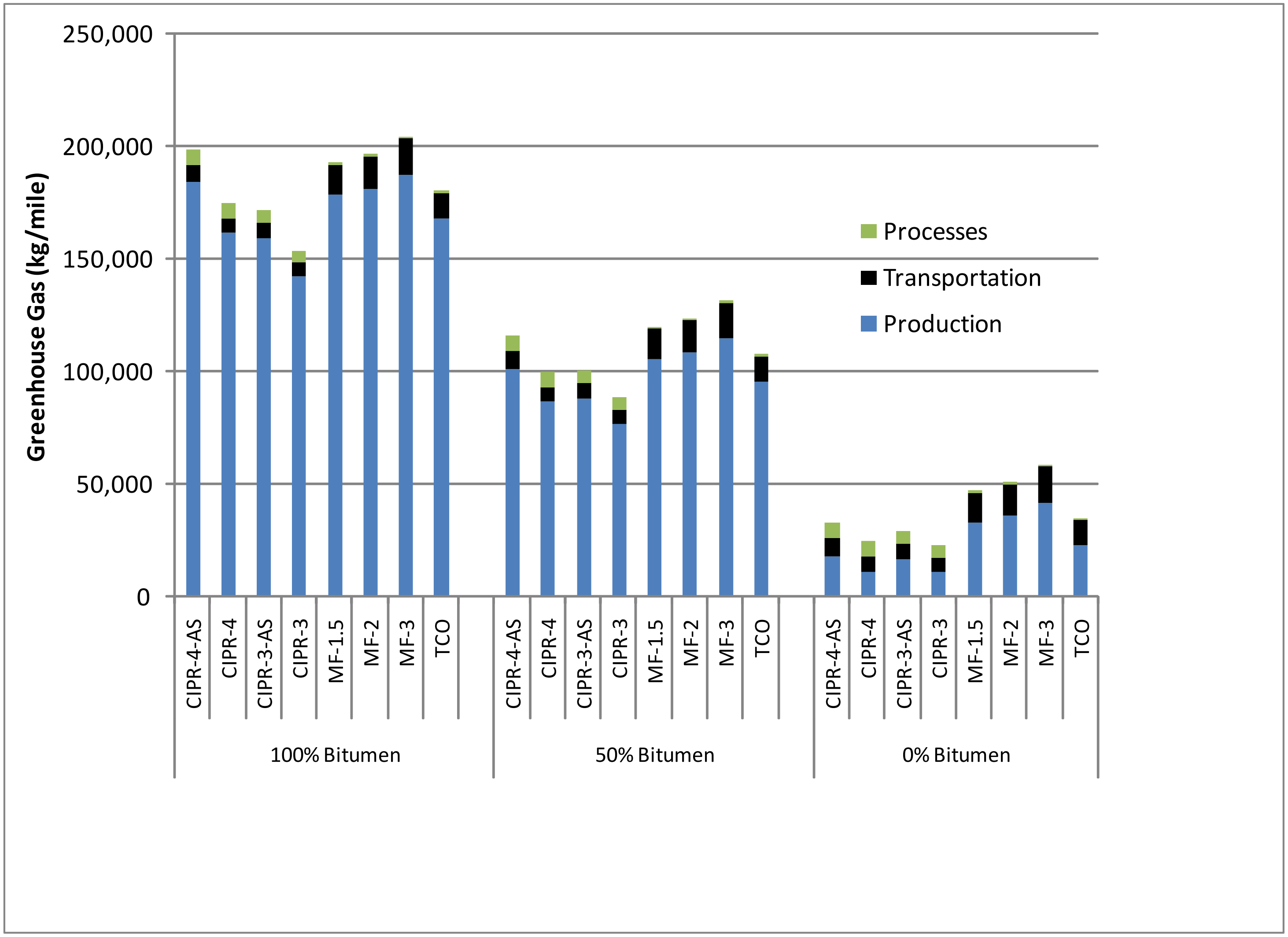

Figure C-2. Total greenhouse gas emissions.

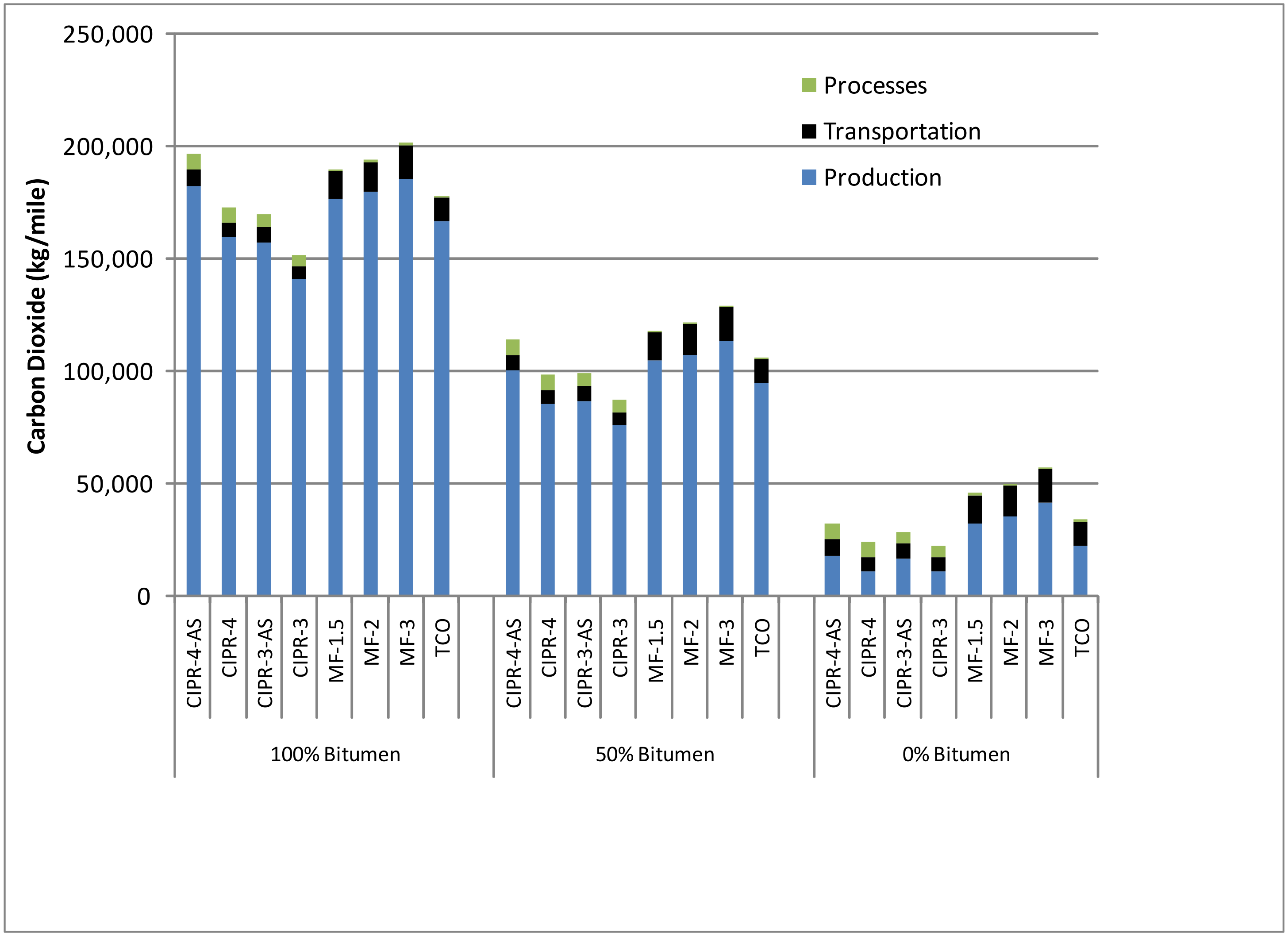

Figure C-3. Total CO_2 emissions.

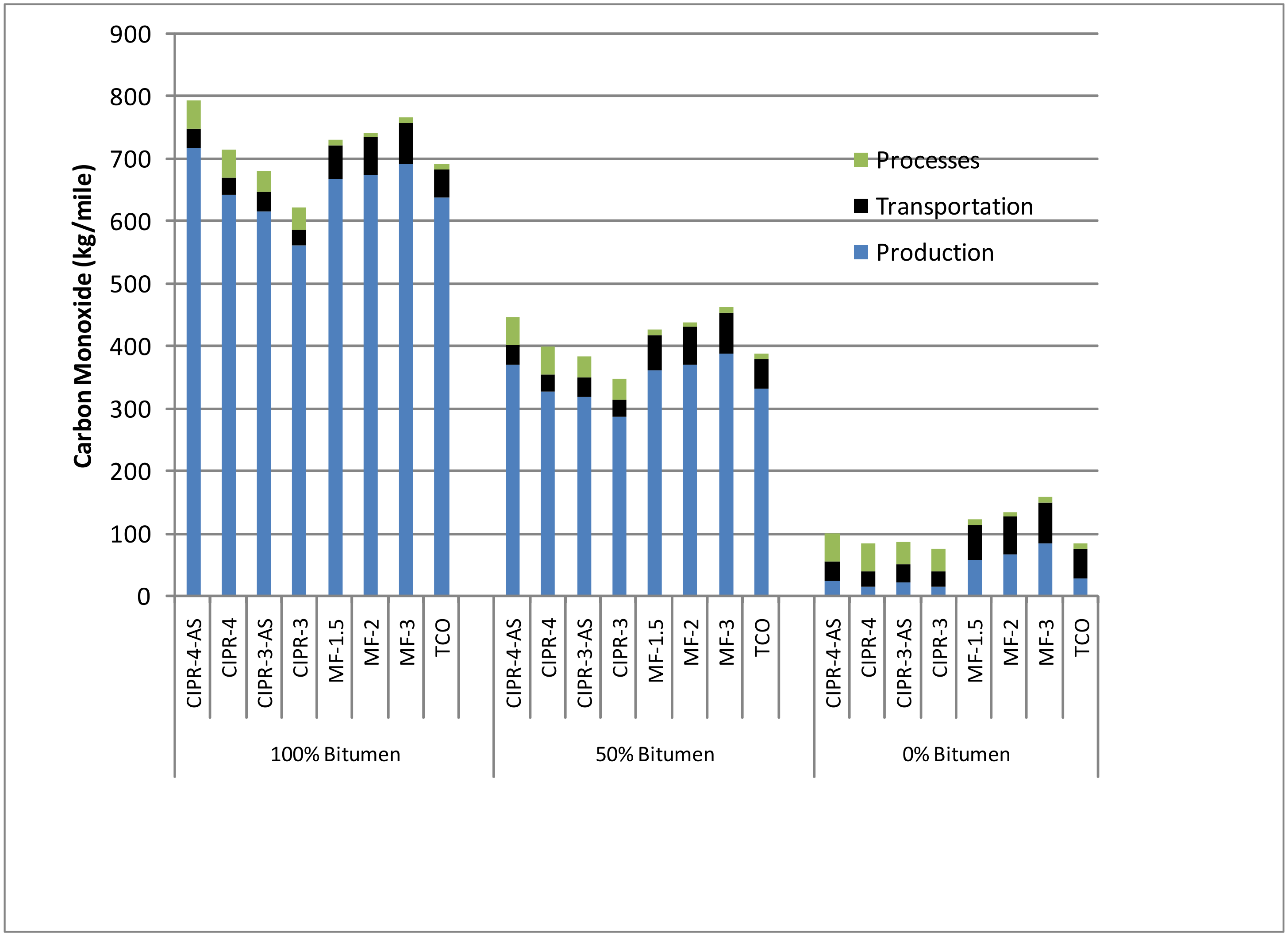

Figure C-4. Total CO emissions.

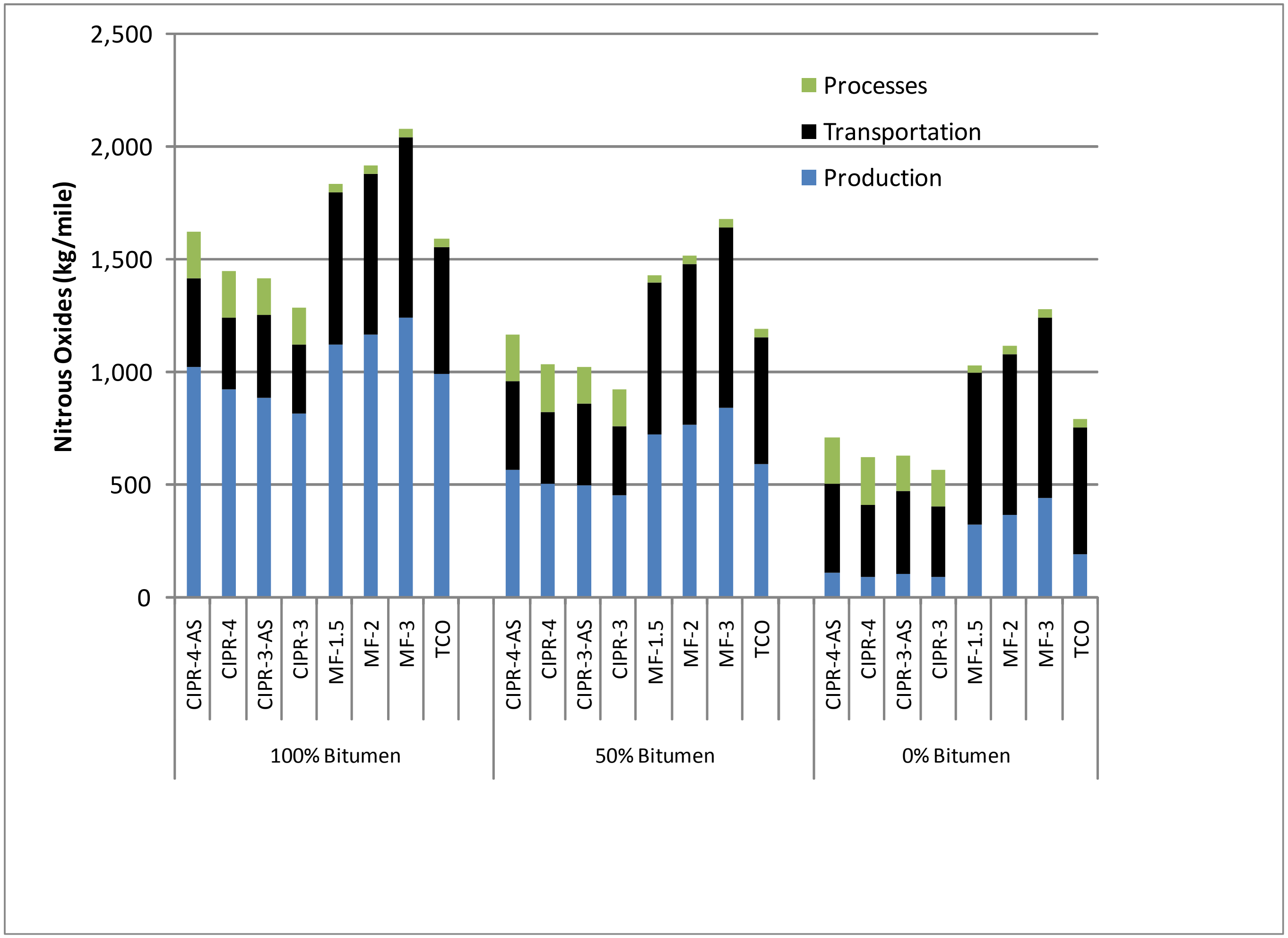

Figure C-5. Total NO_x emissions.

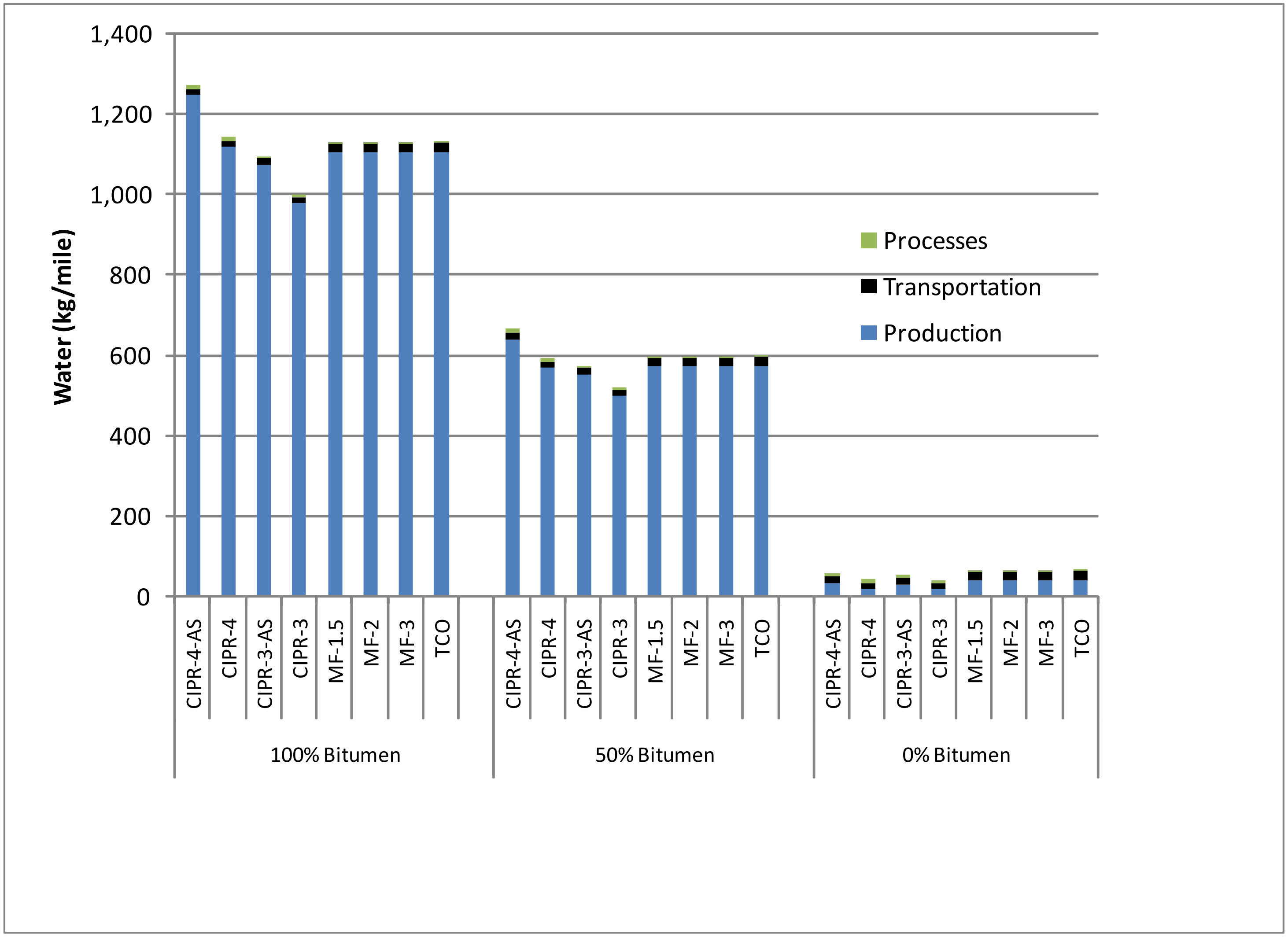

Figure C-6. Water consumption by treatment.

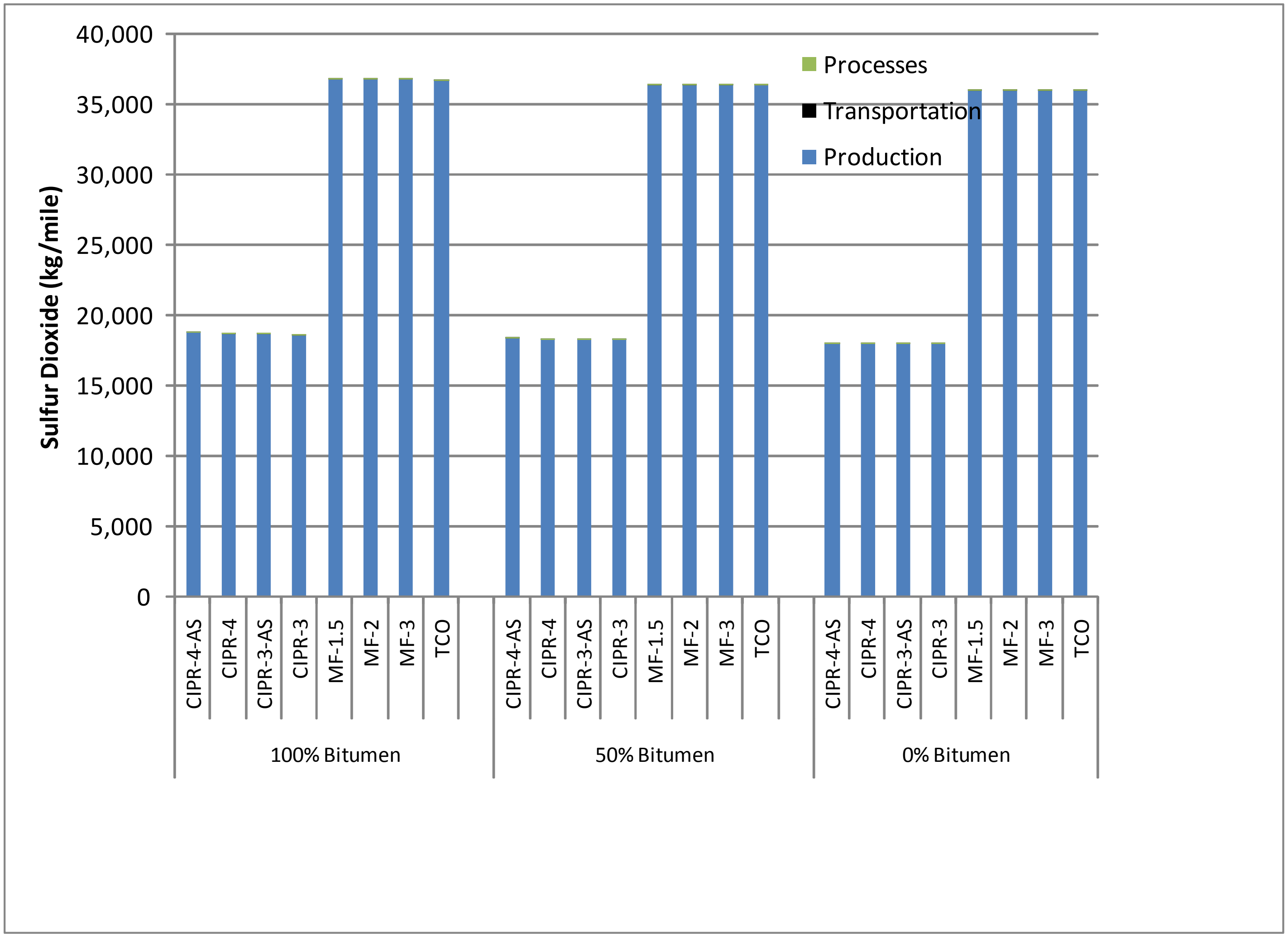

Figure C-7. Sulfur dioxide by treatment.

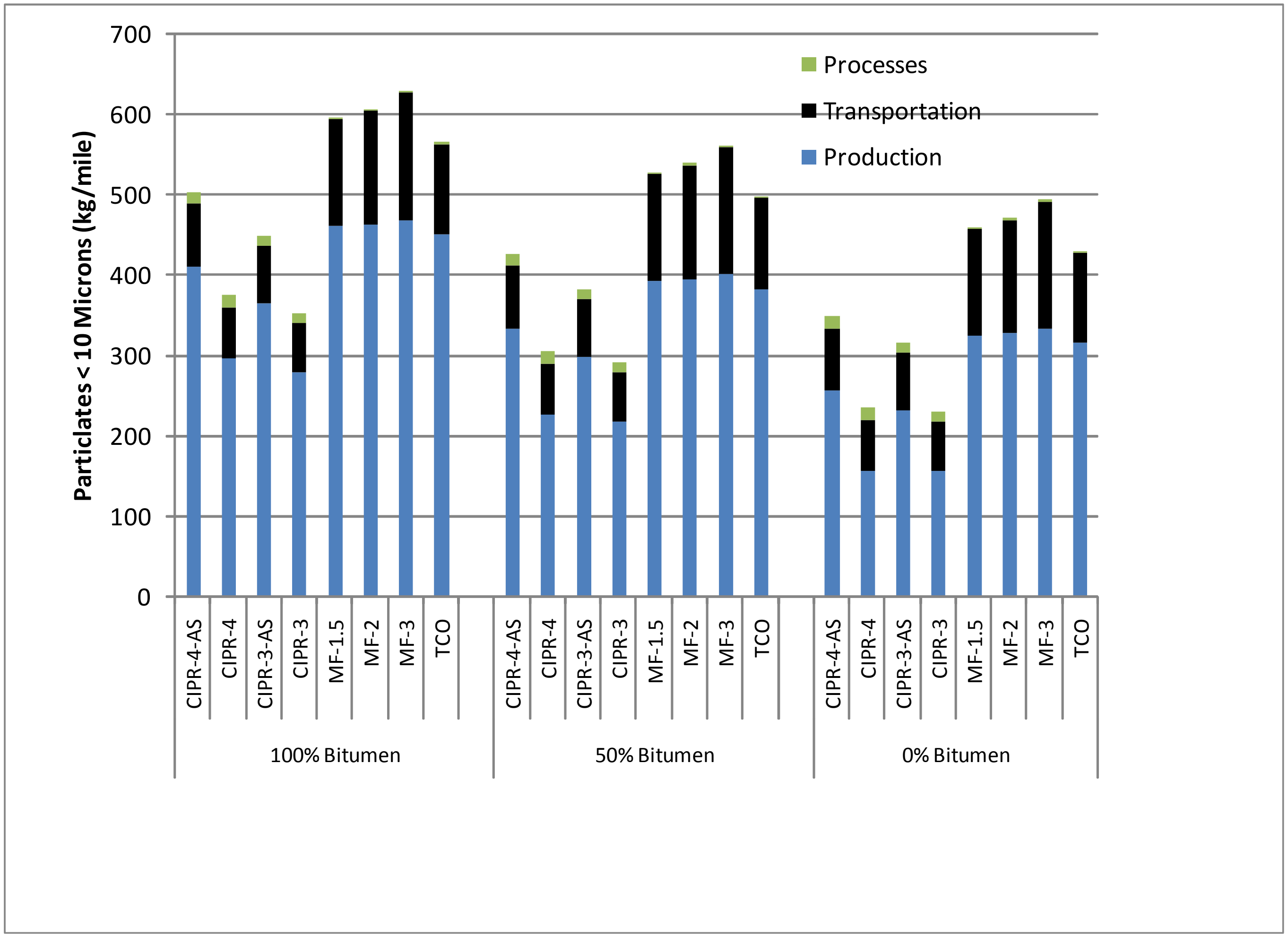

Figure C-8. Particulate matter less than 10 microns (PM_{10}) by treatment.

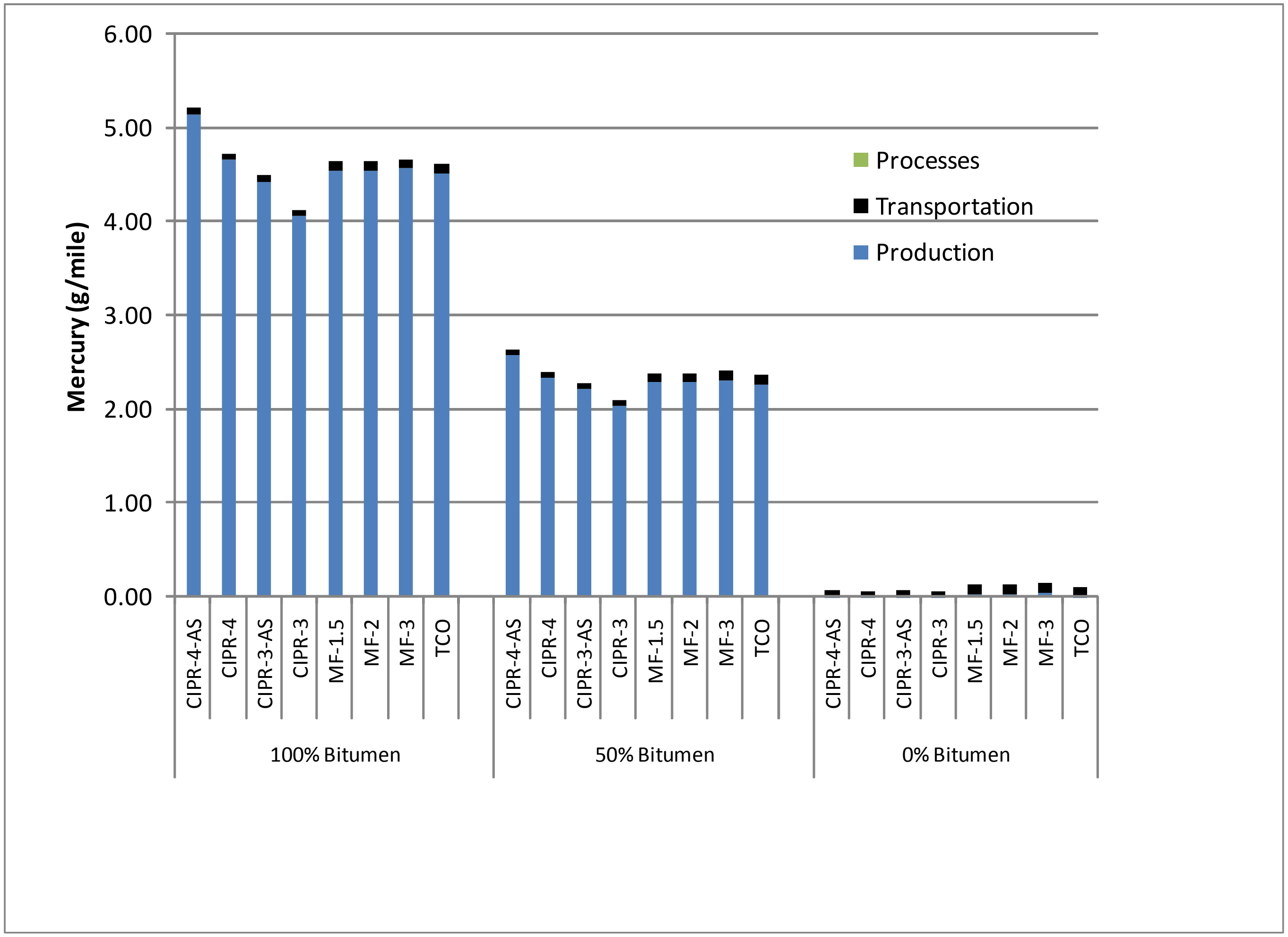

Figure C-9. Mercury emissions by treatment.

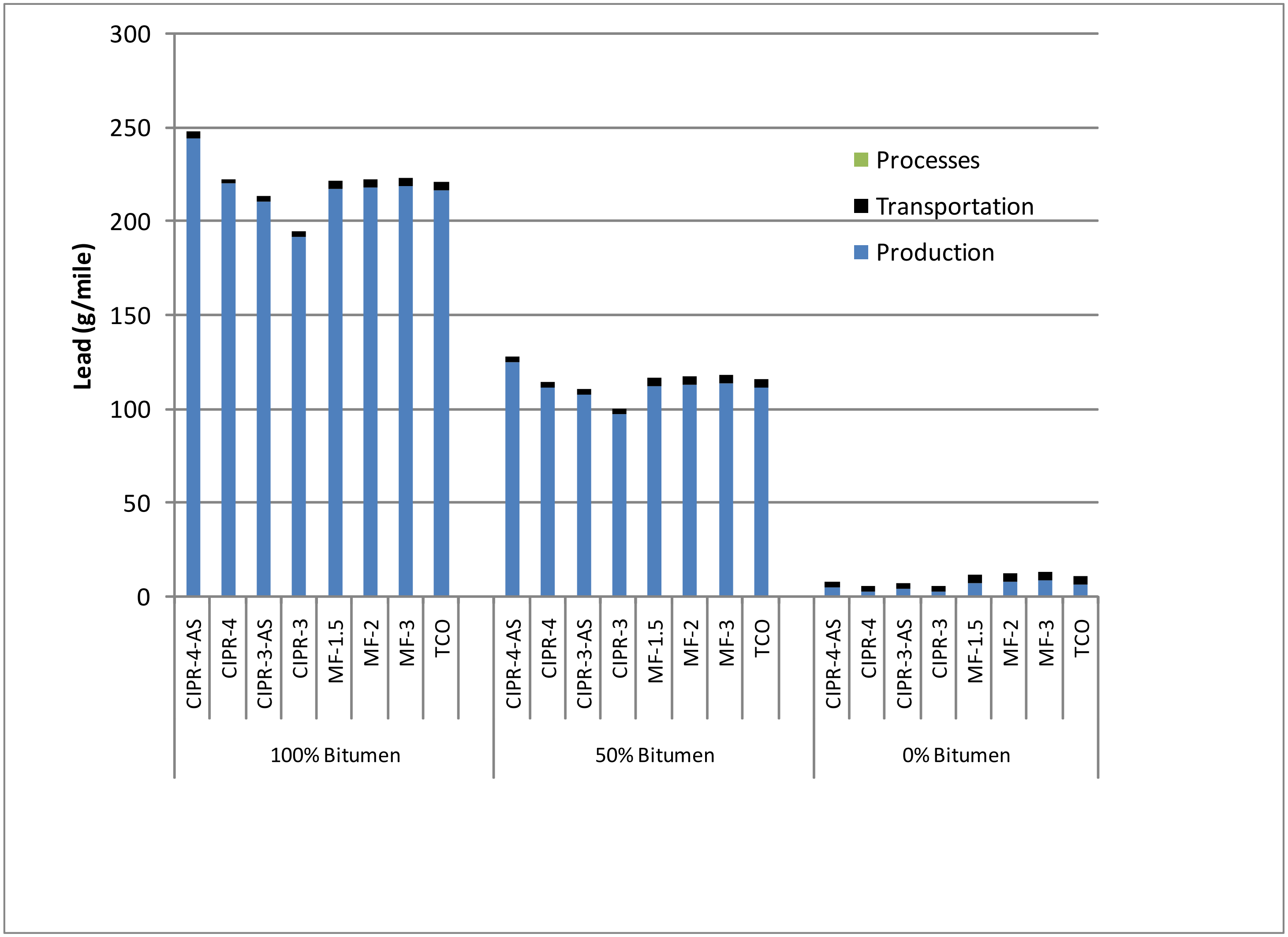

Figure C-10. Lead emissions by treatment.

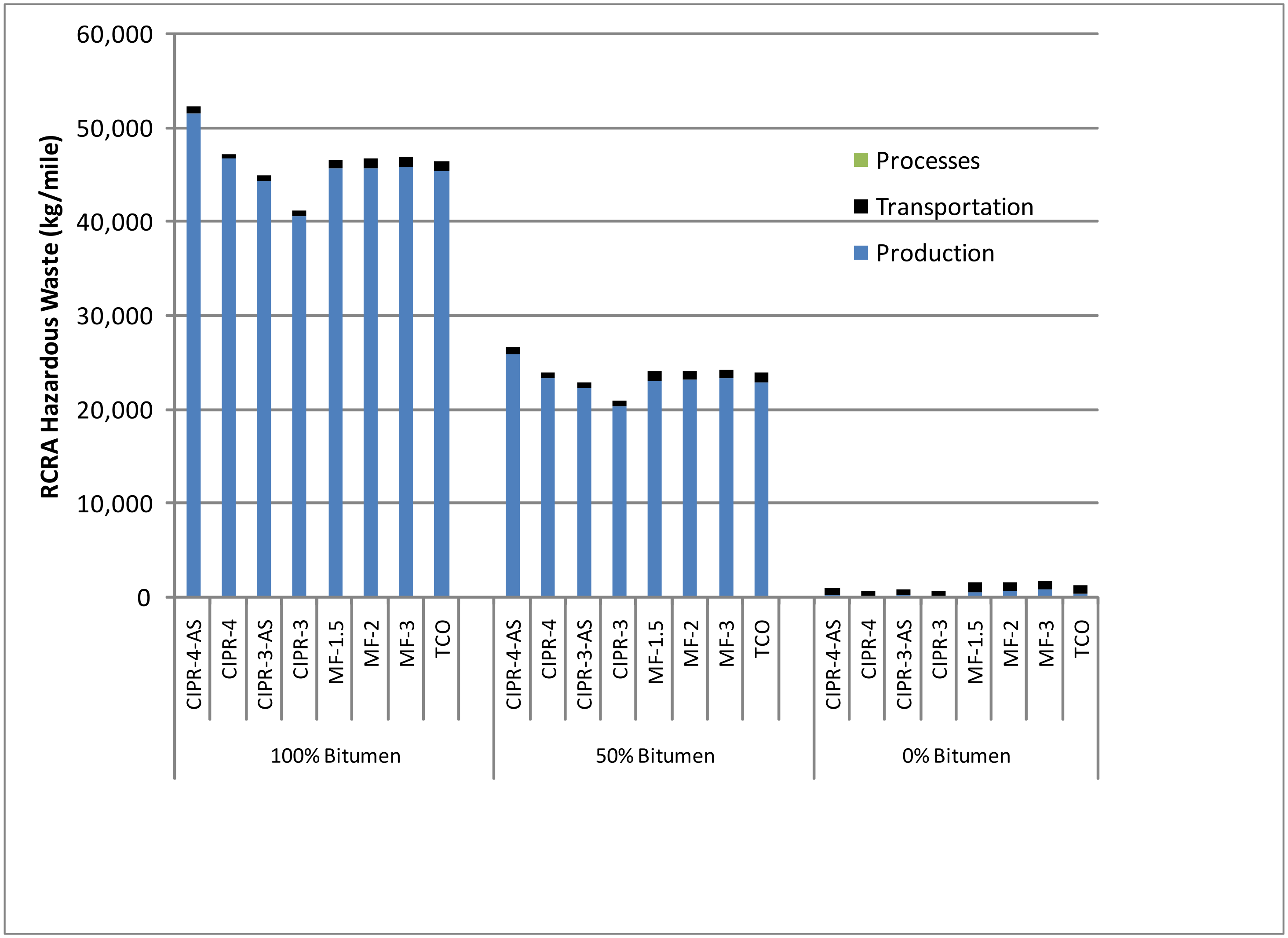

Figure C-11. RCRA hazardous waste generated by treatment.

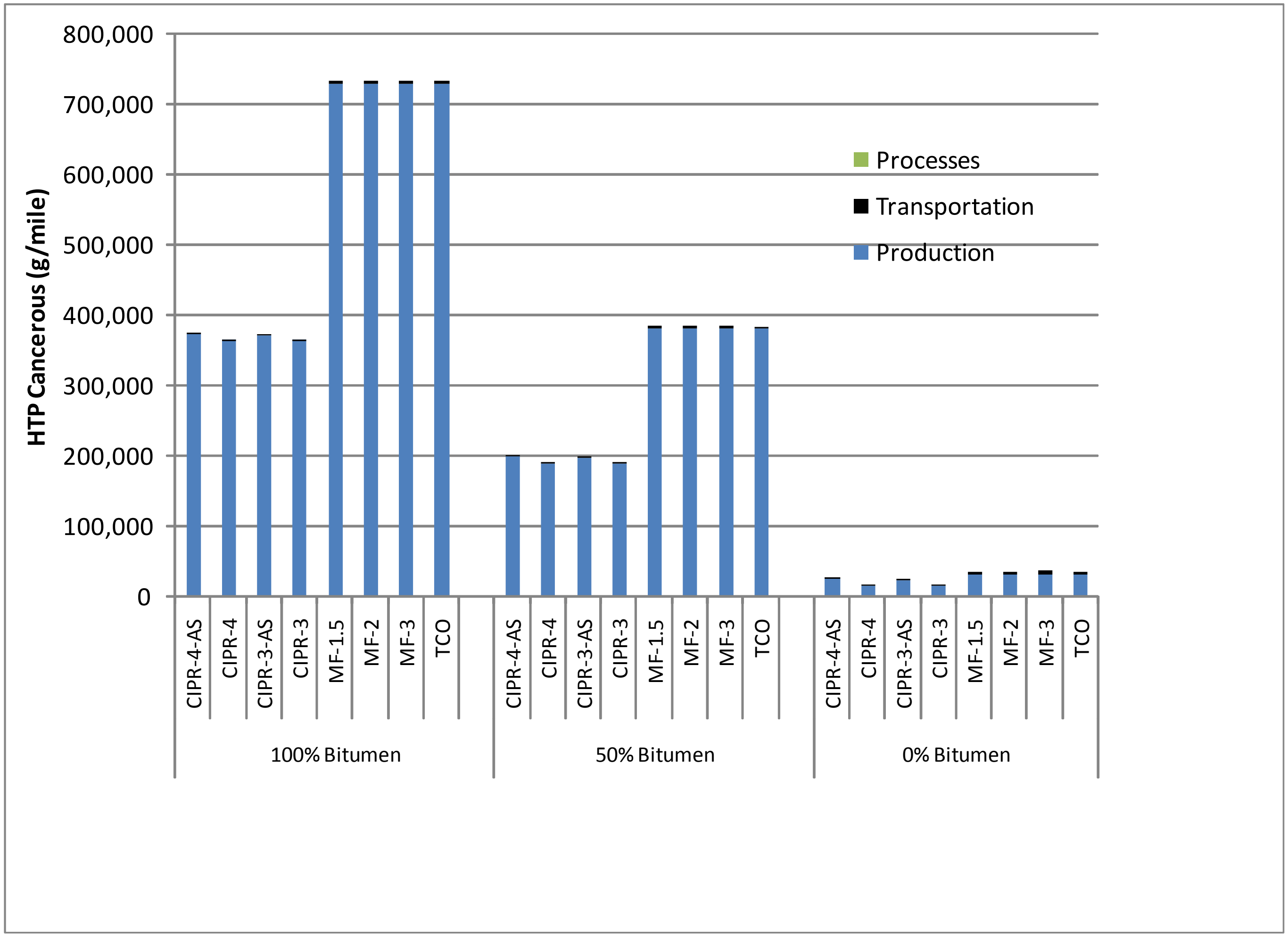

Figure C-12. Human toxicity potential (cancerous) by treatment.

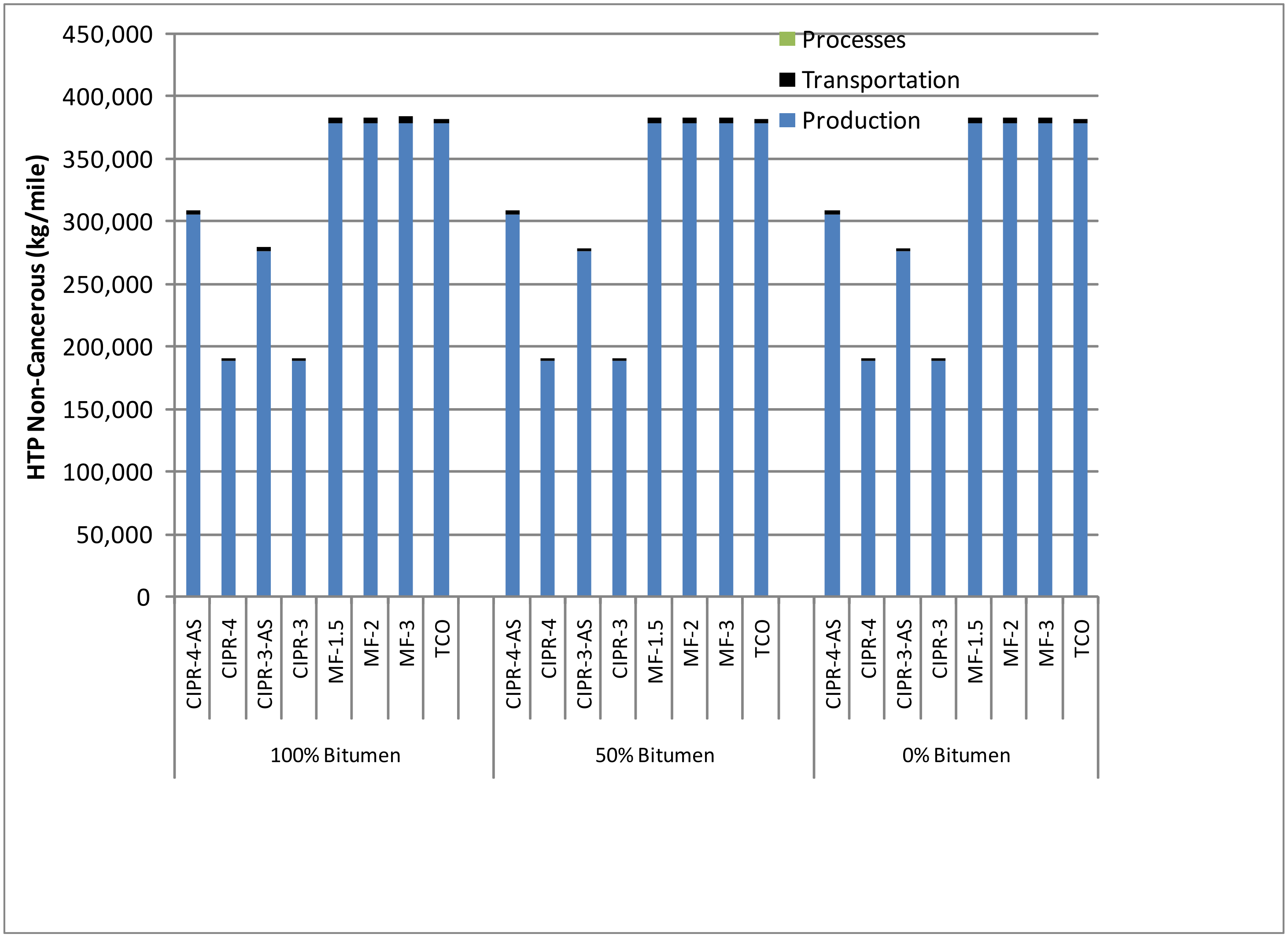

Figure C-13. Human toxicity potential (non-cancerous) by treatment.

APPENDIX D: Asphalt Bitumen Burden Assumptions: Option Assessment

It is of note that PaLATE attributes the major fraction (well over 90%) of the environmental burden of asphalt concrete and emulsion mixes used in roadway construction to the presence of asphalt bitumen.

The data and figures presented in Appendix C reflect the fact that as the environmental burden attributed to asphalt bitumen use is reduced there is a significant reduction in overall resource use and environmental emissions.

Figure D-1 is a graphical representation of the quantity of asphalt bitumen used by each of the maintenance options examined in the report. The total new asphalt bitumen shown below is the sum of the asphalt cement in the HMA overlays and residual asphalt in the asphalt emulsion from the CIPR.

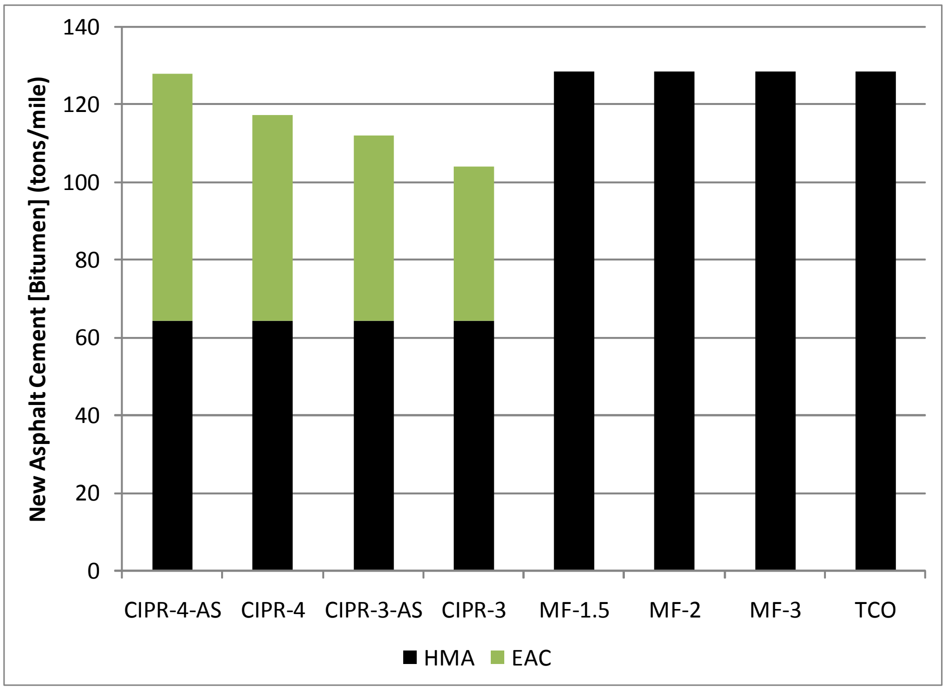

Figure D-1 Total asphalt bitumen consumed by each treatment.

When the CIPR options are compared to the MF and TCO options, the data reveal that

- The MF and TCO options use the same quantity of asphalt bitumen (asphalt cement) per mile of pavement (each option in the analysis uses two, 1.5 inch HMA overlays).
- CIPR-4-AS requires the same total amount of asphalt bitumen (asphalt cement and residual asphalt from asphalt emulsion) as the three MF options and TCO.
- CIPR-3, CIPR-3-AS and CIPR-4 use the least amount of asphalt bitumen (approximately 19, 13 and 9% less, respectively than the three MF options, TCO and CIPR-4-AS).

The impact of reducing the environmental burden of asphalt bitumen projected by PaLATE, as presented in Appendix C, can be examined by developing a relative ranking table for each environmental factor to assess the degree to which each respective maintenance option is relatively effected by the magnitude of the asphalt bitumen environmental burden.

Table D-1 provides a listing of the relative ranking of each maintenance option as a function of the asphalt bitumen burden. The lowest environmental burden receives a ranking of one and the highest a ranking of eight. The sum of the individual rankings yields a total ranked score. The total ranked scores and the order of the scores are presented in Table D-2.

Table D-1. Relative Ranking of Asphalt Bitumen Burden Effects

Treatment	CIPR-4-AS			CIPR-4			CIPR-3-AS			CIPR-3			MF-1.5			MF-2			MF-3			TCO		
Bitumen Burden (%)	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**	**100**	**50**	**0**
Energy	5	4	4	3	3	2	2	2	3	1	1	1	6	6	6	7	7	7	8	8	8	4	5	5
Water	8	8	4	7	3	1	2	2	3	1	1	1	3	4	5	3	4	5	3	4	5	3	4	5
CO2	7	5	4	3	2	1	2	3	3	1	1	1	5	6	6	6	7	7	8	8	8	4	4	5
NOx	5	4	4	3	3	2	2	2	3	1	1	1	6	6	6	7	7	7	8	8	8	4	5	5
PM10	4	4	4	2	2	1	3	3	3	1	1	1	6	6	6	7	7	7	8	8	8	5	5	5
SO2	4	4	4	3	3	1	2	2	3	1	1	1	6	6	6	7	7	7	8	8	8	5	5	5
CO	8	6	4	4	3	1	2	2	3	1	1	1	5	5	6	6	7	7	7	8	8	3	4	5
Hg	8	8	1	7	7	1	2	2	1	1	1	1	4	4	1	5	5	1	6	6	1	3	3	1
Pb	8	8	4	7	4	1	2	3	3	1	1	1	4	5	6	5	6	7	6	7	8	3	2	5
RCRA Waste	8	8	4	7	7	1	2	2	3	1	1	1	4	4	6	5	5	7	6	6	8	3	3	5
HTP-C	4	4	4	1	1	1	3	3	3	1	1	1	5	5	5	5	5	5	5	5	5	5	5	5
HTP-NC	4	4	4	1	1	1	3	3	3	1	1	1	5	5	5	5	5	5	5	5	5	5	5	5
TOTALS	73	67	45	48	39	14	27	29	34	12	12	12	59	62	64	68	72	72	78	81	80	47	50	56

1. Note: Greenhouse gas is not included in the ranking table due to the redundancy with the individual greenhouse gas components (primarily CO2)

Table D-2. Total Score Rankings

	Total Score			Ranking		
Bitumen Burden (%)	**100**	**50**	**0**	**100**	**50**	**0**
CIPR-4-AS	73	67	45	7	6	4
CIPR-4	48	39	14	4	3	2
CIPR-3-AS	27	29	34	2	2	3
CIPR-3	12	12	12	1	1	1
MF-1.5	59	62	64	5	5	6
MF-2	68	72	72	6	7	7
MF-3	78	81	80	8	8	8
TCO	47	50	56	3	4	5

The data in Tables D-1 and D-2 reveal the following:

- CIPR-3 generates the least environmental burden regardless of the asphalt bitumen-related burden (CIPR-3 ranks 1 in all environmental burdens and in the total score for all conditions). This is due to the lower asphalt bitumen content, compared to the other options (see Figure D-1).
- As the environmental burden associated with asphalt bitumen is reduced, the CIPR options have the lowest environmental effect and the environmental burden of TCO increases. The environmental impact of the MF options increases as the asphalt bitumen burden is reduced.

In general, adjustments made to the asphalt bitumen-related environmental burden did not significantly affect the report conclusions. The CIPR options, relatively speaking, rank higher than the MF options and are similar to the TCO option. As the asphalt bitumen related environmental burden is reduced, however the CIPR-4 and CIPR-4-AS options improve in rankings relative to TCO, and MF.

COLD-IN-PLACE RECYCLING IN NEW YORK STATE

Attachment F: CIPR Service Life Projections

Prepared for

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Contract No. 6764F-2

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Table of Contents

1. Introduction

In New York State Cold-In-Place Recycling (CIPR) is one of a series of asphalt pavement rehabilitation options, which are designed to extend the service life of pavements. The CIPR option typically involves recycling the existing pavement to construct a 4-inch recycled base with a 1.5-inch new asphalt overlay.

Using a graphical and numerical model described herein, projections were made to determine how long CIPR pavements could be expected to last before additional treatment is required.

NYSDOT tracks the condition of State pavements and defines maintenance and rehabilitation needs by use of a pavement rating scale known as NYSDOT Sufficiency Ratings (SR). The SR scale is a 10 to 1 point scale (10 being the best condition) based on the prevalence of surface related pavement distresses. An SR value of six (6) is a pavement rating that is used to indicate that corrective action is required.

Projections of the expected increase in service life were made by developing a model to describe the relationship between NYSDOT Sufficiency Ratings (SR) and Pavement Age (Age). The Age at which the pavement SR value dropped to six (6) was used to define the extended service life of the pavement.[1]

The model was developed by analyzing scatter plots of NYSDOT Sufficiency Ratings (SR) versus Pavement Age for CIPR pavements, and determining from these data the best-fit model. The best-fit model or regression line was selected by comparing four options: 1) a linear model, 2) a power model, 3) an exponential model, and 4) a log model. Additional studies were undertaken to assess whether other variables, which included daily traffic, truck traffic, base thickness, base plus subbase thickness, or total pavement thickness might influence the pavement service life.

A description of the development of the model, the results of the analysis and the conclusions are presented in subsequent sections of this document.

[1] Age is meant to represent the time-period in years since the last CIPR rehabilitation activity.

2. Data Sources and Analysis

The NYSDOT Pavement Management Unit supplied 2008 CIPR-SR data used in the analysis. This data was extracted from the 2008 NYSDOT Highway Sufficiency Ratings Database. The 2008 data included CIPR pavements installed during the period from 1992 through 2008,which included a total of 163 projects, 604 pavement segments, 1240 individual SR data points covering a pavement distance of 756 miles.[2]

The SR-Age data was compiled in a Microsoft Access Data Base, which was used in concert with Microsoft Excel and the SOLVER function associated with Excel to generate the regression models and statistical data presented herein. Data was compiled and analyzed to produce regression lines and upper and lower 90% confidence intervals (CI) using methods most suitable for non-linear regression analysis.[3]

In the NYSDOT Highway Sufficiency Ratings Database, a single pavement project consists of multiple pavement segments. Each segment contains an annual Sufficiency Rating (SR) or data point for that segment. Project SR ratings, as a function of Age, were calculated by averaging the SR values of all segments within a project for a given year. These average SR values for each respective project were used in the regression analysis. Only values from the reported year of last work to the most recent data were used for each project.

The initial scatter plot analysis included a combined analysis of all available "ungrouped" CIPR-SR data. These data were used to select the preferred model type. The data was subsequently divided into selected sub-groupings to "inquire" whether such sub-groupings might reveal unique relationships between the sub-groupings and the extended service life. Sub-grouping inquiries were made for the following variables:

- Average Annual Daily Traffic (AADT)
- Equivalent Single Axle Load (ESAL)
- Base Thickness (BT)[4]
- Base Plus Sub-base Thickness (BSBT)[5]
- Total Pavement Thickness (TPT)[6]
- Regional Project Distribution (RPD)
- Rehabilitation Sufficiency Rating (RSR).

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[2] An additional 11 segments in the 163 projects were submitted in the 2008 CIPR-SR data but were excluded from all analysis because of potential discrepancies in the reported year of last work. Of the 163 projects used in the analysis 16 were excluded from the pavement thickness sub-grouping analysis, presented below because no thickness data was reported. These 16 projects represent 61 pavement segments.

[3] Brown, A.M. A step-by-step guide to non-linear regression analysis of experimental data using a Microsoft Excel spreadsheet., Computer Methods and Programs in Biomedicine, 65 (2001) 191-200, Elsevier Science

[4] "Base Thickness" is the thickness of the material between the pavement layer and the subbase. Base could be asphalt treated or Portland cement treated permeable base or cement stabilized base.

[5] "Subbase" is the underlying structure of the pavement. Types include gravel, stone, select soils or graded and drained natural soils.

[6] "Total pavement thickness" is the combined thickness of the Pavement, Base and Subbase courses.

A listing of the sub-group conditions that were used to analyze the CIPR-SR database is presented in Table 1. Sub-groups were selected to provide similar ranges (magnitude) within each range, while at the same time ensuring that a sufficient number of projects and segments were available in each respective range to provide a large number of data points.[7] An analysis of variance (ANOVA) test was subsequently run on each of the independent sub-groups listed in Table 1 to provide the means to determine whether differences observed between the sub-group data were significant.[8]

Table 1. Data Grouping Chart

Grouping Parameter	Sub-groupings
1. Ungrouped	All Data
2. AADT Grouping (vehicles per day)	<2000 2000-4000 >4000
3. ESAL Grouping (equivalent single axle loads per year)	<50,000 50,000-100,000 >100,000
4. Base Thickness Grouping (in)	<4.5 4.5-5.5 >5.5
5. Base and Sub-base Thickness Grouping (in)	<9 9-11 >11
6. Total Thickness Grouping (in)	<10 10-13 >13
7. Regional Project Distribution	Region 7 and Essex County (Region 1, County 2) Remaining Regions
8. Rehabilitation Sufficiency Rating	<5.5 5.5-6.5 >6.5

[7] Available data from CIPR pavements are those associated with low-volume traffic roads as defined by NYSDOT Comprehensive Pavement Manual, Design Division & Technical Services Division, April 2005 rev. Low-Volume Traffic refers to 2-3 lane highways with a design-year, two-way AADT less than 8000.
[8] ANOVA tests were run at a Level of Significance of 0.05.

3. Model Selection

As noted above, four models were evaluated to determine the best-fit model. These included 1) a linear model, 2) a power model, 3) an exponential model, and 4) a log model. A comparative analysis of these four options is presented in Appendix A.

The log model in the form of $y = a \log(x) + b$ (where y represents the value of SR, x represents the pavement age and b represents the y-intercept) was determined to be the best regression model. The log curves displayed the highest regression coefficients and provided the most rational representation of the data. A more detailed discussion of model rationale is presented in Appendix A.

A graphical representation of all of the data (ungrouped data) used in the analysis and the log regression line is presented in Figure 1. The ungrouped database included 163 projects, 604 segments and 1204 SR data points. Upper and lower ninety percent confidence interval lines are also depicted. The upper and lower 90% confidence lines were generated using the derived equation for each regression analysis and adding or subtracting the calculated 90% confidence interval value.[9]

A linear representation of the log model on a semi-log coordinate system, shown in Figure 2 provides a convenient method for projecting the graphical intersection of the Pavement Age with an SR value of six.

[9] See footnote 2.

Figure 1. Log Model Results (Linear Coordinates): All Sufficiency Rating (SR) Data

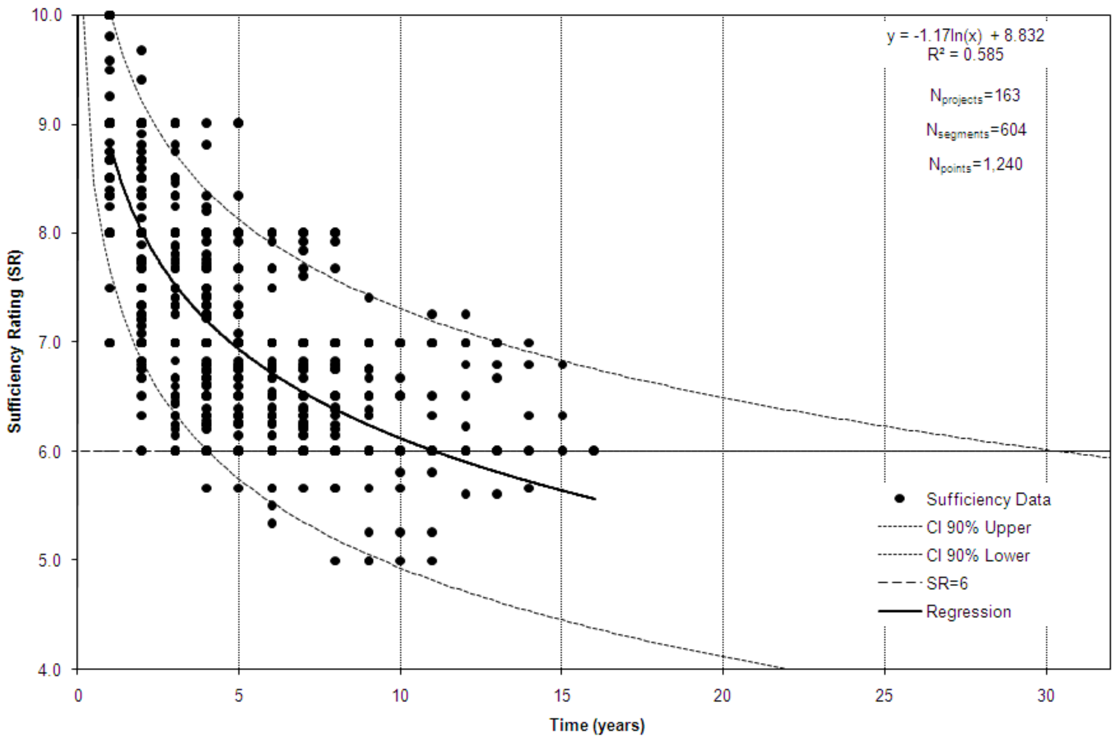
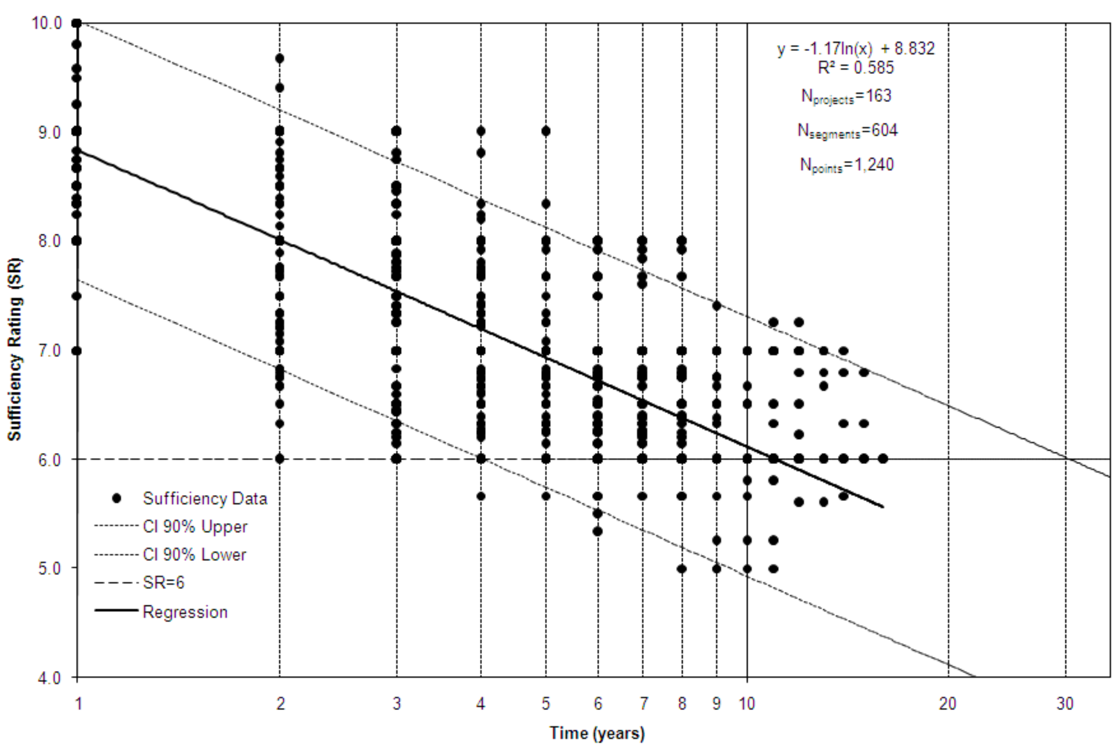


Figure 2. Log Model Results (Semi-Log Coordinates): All Sufficiency Rating (SR) Data



4. Ungrouped Data Results

The ungrouped data are presented in Figures 1 and 2. There is a considerable scatter in the SR data shown in Figures 1 and 2. This is somewhat expected since there are numerous variables that can affect the SR value with age. Some of the more prominent variables include vehicular traffic (AADT), truck traffic (ESAL), base thickness, total pavement thickness, drainage conditions, construction quality, weather conditions and scheduled routine maintenance activities.[10]

A summarized listing of the expected increase in service life along with the upper and lower 90% confidence limits, respectively are presented in Table 2.

Table 2. Ungrouped Data
Expected Service Life Extension (yrs)

Expected Service Life	11
Upper 90% confidence limit	4
Lower 90% confidence limit	30

The ungrouped regression data suggest that the expected extended service life for a CIPR rehabilitation is 11 years.

[10] In some cases, the initial SR values, which are based on a condition survey usually taken during the first year after rehabilitation, were recorded as less than 8. This suggests that these pavements experienced rapid deterioration after CIPR installation, probably due to existing conditions or improper construction procedures. Such data will increase generate more widespread scatter.

5. AADT Grouping Results

A listing of the AADT sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 3. A graphical presentation of the respective regression models by group is depicted in Figure 3.

Table 3. AADT Sub-Groupings

Sub-Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<2,000	61	216	487	11.08	0.534
2,000-4,000	59	190	432	9.47	0.661
>4,000	41	198	321	13.27	0.595

The data showed an inconsistent pattern with 11 year, 9.5 year and 13.3 yr extended service lives for pavements with < 2000, 2000-4000, and > 4000 AADT, respectively.

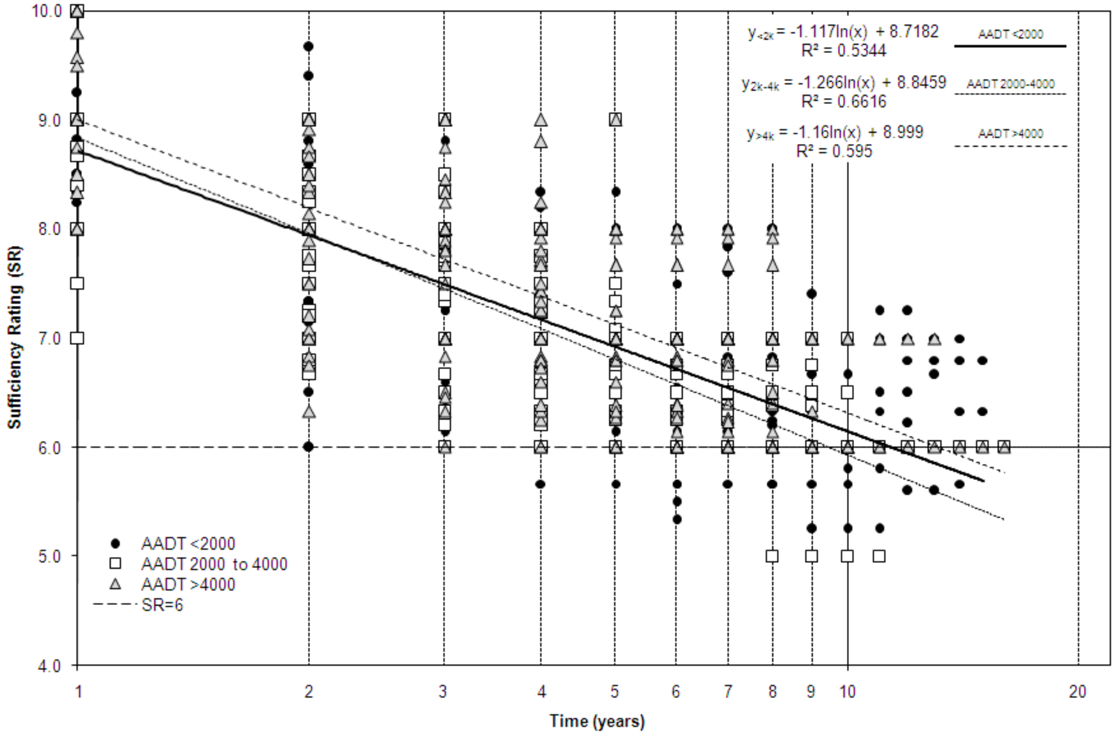
Descriptive results of ANOVA testing of three sub-groups listed in Table 3 are summarized in Table 4. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with AADT values <4000 and for CIPR pavements with AADT values >4000, and that CIPR pavements with values of AADT > 4000 can be expected to last an additional 2-4 years longer than CIPR pavements with AADT <4000.

Table 4. Descriptive AADT ANOVA Results[1, 2,3]

Sub-Group	<2000	2000-4000	>4000
<2000	---	No difference	Difference
2000-4000	No difference	---	Difference
>4000	Difference	Difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

Figure 3. Log Model Results: All Sufficiency Rating (SR) Data Grouped by AADT Range



6. ESAL Grouping Results

A listing of the annual ESAL sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 5. A graphical presentation of the respective regression models by group is depicted in Figure 4.

Table 5. ESAL Sub-Groupings

Sub-Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<50,000	90	296	692	10.67	0.560
50,000-100,000	39	148	289	12.98	0.734
>100,000	32	160	259	14.11	0.581

The data show a consistent pattern with increasing extended service lives of 10.7 years, 13.0 years and 14.1 years for pavements with < 50,000, 50,000-100,000, and > 100,000 annual ESALs, respectively.

Descriptive results of ANOVA testing of three sub-groups listed in Table 5 are summarized in Table 6. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with ESAL values <50000 and for CIPR pavements with ESAL values >50000, and that CIPR pavements with values of ESAL > 50000 can be expected to last an additional 2-4 years longer than CIPR pavements with ESAL values <50000.

Table 6. Descriptive ESAL ANOVA Results[1, 2,3]

Sub-Group	<50000	50000-100000	>100000
<50000	---	Difference	Difference
50000-100000	Difference	---	No difference
>100000	Difference	No difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

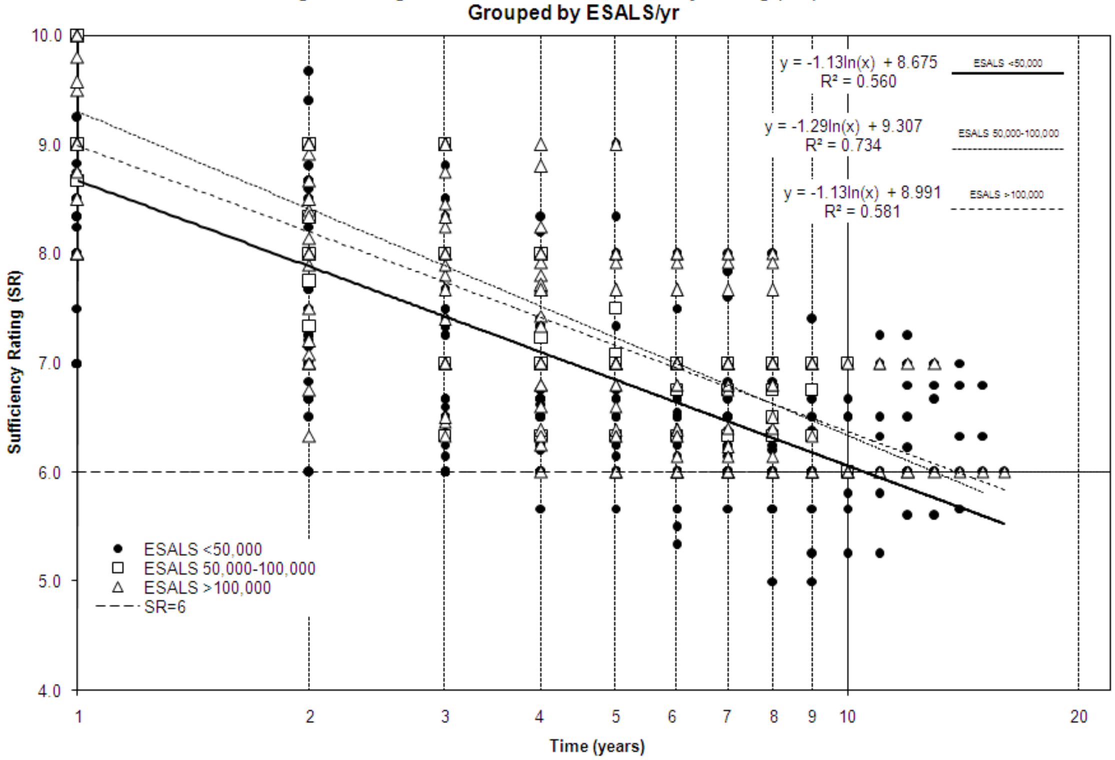


Figure 4. Log Model Results: All Sufficiency Rating (SR) Data Grouped by ESALS/yr

7. Base Thickness Grouping Results

A listing of the base thickness sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 7. A graphical presentation of the respective regression models by group is depicted in Figure 5.

Table 7. Thickness Sub-Groupings (Base)

Sub-Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<4.5	32	112	232	10.64	0.518
4.5-5.5	53	206	413	11.26	0.579
>5.5	60	225	437	11.29	0.602

The data show a pattern of slightly higher expected extended service lives for pavements having a base thickness > 4.5 inches.

Descriptive results of ANOVA testing of three sub-groups listed in Table 7 are summarized in Table 8. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with a base thickness of <4.5 inches and those with a base thickness >5.5 inches, and that CIPR pavements with a base thickness >5.5 inches can be expected to last approximately 0.75 years longer than CIPR pavements with a base thickness <4.5.

Table 8. Descriptive Base Thickness ANOVA Results[1, 2,3]

Sub-Group	<4.5	4.5-5.5	>5.5
<4.5	---	No difference	Difference
4.5-5.5	No difference	---	Difference
>5.5	Difference	Difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

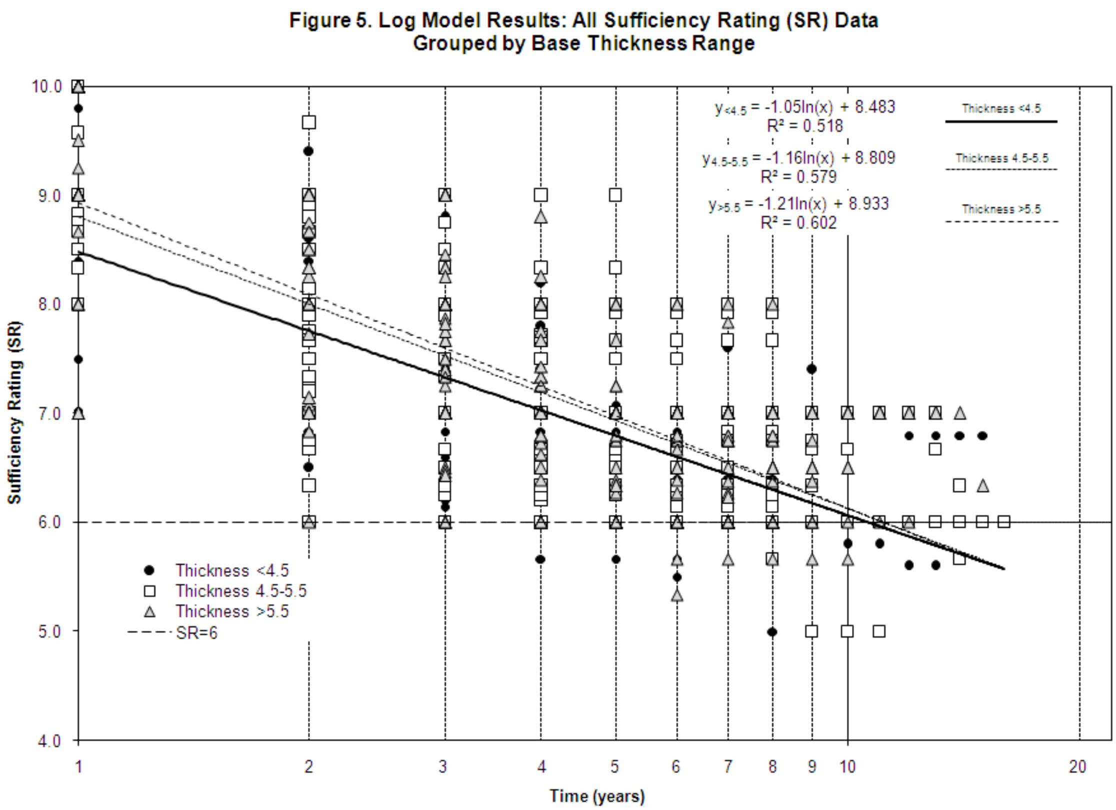


Figure 5. Log Model Results: All Sufficiency Rating (SR) Data
Grouped by Base Thickness Range
$y_{<4.5} = -1.05\ln(x) + 8.483$
$R^2 = 0.518$
$y_{4.5-5.5} = -1.16\ln(x) + 8.809$
$R^2 = 0.579$
$y_{>5.5} = -1.21\ln(x) + 8.933$
$R^2 = 0.602$
Thickness <4.5
Thickness 4.5-5.5
Thickness >5.5
Thickness <4.5
Thickness 4.5-5.5
Thickness >5.5
SR=6
Sufficiency Rating (SR)
Time (years)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
1
2
3
4
5
6
7
8
9
10
20

8. Base Plus Subbase Thickness Grouping Results

A listing of the base thickness sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 9. A graphical presentation of the respective regression models by group is depicted in Figure 6.

Table 9. Thickness Groupings (Base Plus Subbase Thickness)

Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<9	42	168	332	10.77	0.558
9-11	87	322	627	10.87	0.598
>11	16	53	123	15.02	0.508

The data show a pattern of increasing extended service lives of 10.8 years, 10.9 years and 15.0 years for pavements with total thickness of < 9 inches, 9-11 inches, and >11 inches, respectively.

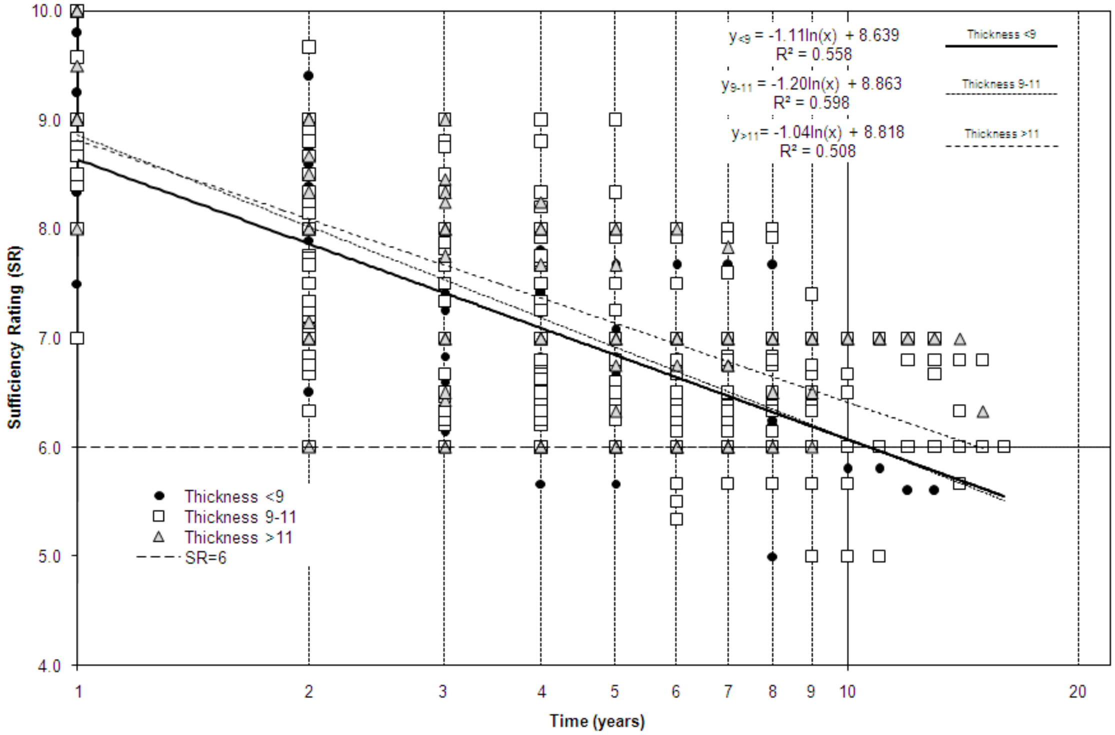
Descriptive results of ANOVA testing of three sub-groups listed in Table 9 are summarized in Table 10. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with a base plus sub-base thickness of <9 inches and those with a base plus sub-base thickness >11 inches, and that CIPR pavements with a base plus sub-base thickness >11 inches can be expected to last more than 4 years longer than CIPR pavements with a base plus sub-base thickness <9 inches.

Table 10. Descriptive Base Plus Subbase Thickness ANOVA Results[1,2,3]

Sub-Group	<9	9-11	>11
<9	---	No difference	Difference
9-11	No difference	---	No difference
>11	Difference	No difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

Figure 6. Log Model Results: All Sufficiency Rating (SR) Data Grouped by Base+Subbase Thickness Range



9. Total Pavement Thickness Grouping Results

A listing of the base thickness sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 11. A graphical presentation of the respective regression models by group is depicted in Figure 7.

Table 11. Thickness Sub-Groupings (Total Thickness)

Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<10	16	60	126	9.37	0.563
10-13	111	419	818	11.03	0.584
>13	18	64	138	14.6	0.532

The data show a consistent pattern with increasing expected extended service lives of 9.4 years, 11.0 years and 14.6 years for pavements with total thickness of < 10 inches, 10-13 inches, and > 13 inches, respectively.

Descriptive results of ANOVA testing of three sub-groups listed in Table 11 are summarized in Table 12. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with a total pavement thickness of <10 inches, and those with a total pavement thickness between 10-13 inches and > 13 inches. CIPR pavements with a total pavement thickness between 10-13 inches and those with a total pavement thickness >13 inches can be expected to last approximately 1.6 and 5.2 years longer, respectively, than CIPR pavements with a total pavement thickness <10 inches.

Table 12. Descriptive Base Plus Subbase Thickness ANOVA Results[1, 2,3]

Sub-Group	<10	10-13	>13
<10	---	Difference	Difference
10-13	Difference	---	No difference
>13	Difference	No difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

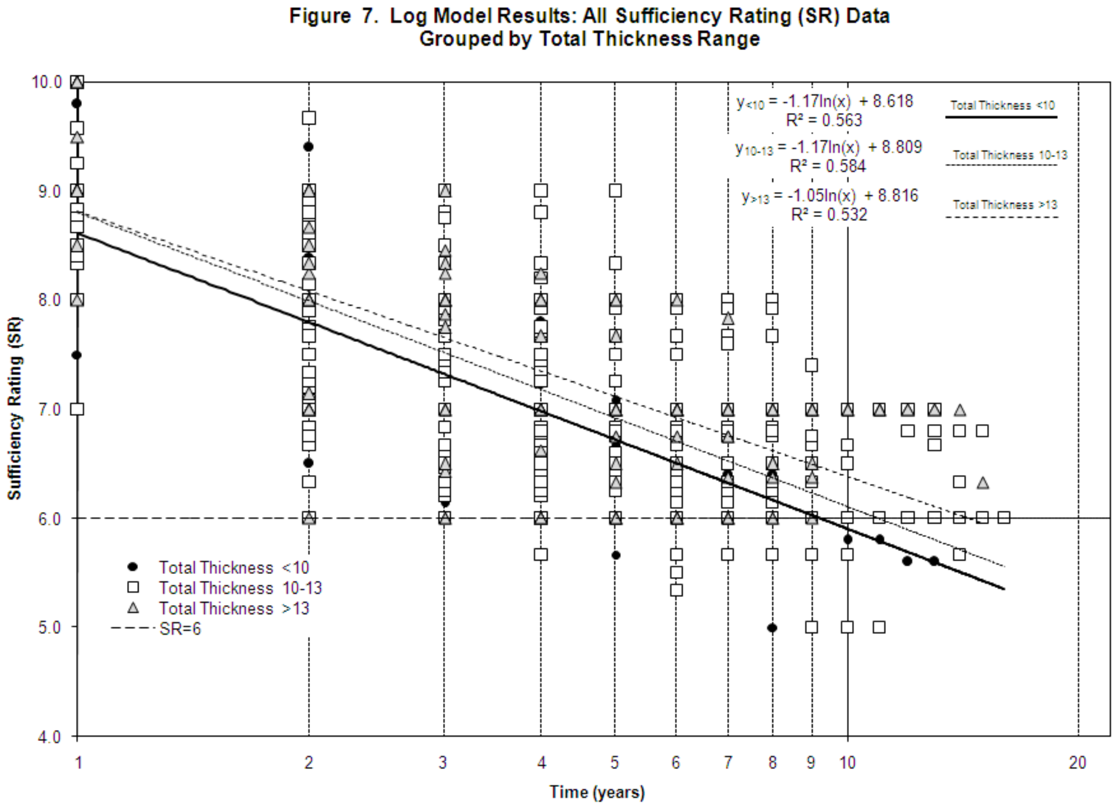


Figure 7. Log Model Results: All Sufficiency Rating (SR) Data
Grouped by Total Thickness Range
$y_{<10}$ = -1.17ln(x) + 8.618
R² = 0.563
y_{10-13} = -1.17ln(x) + 8.809
R² = 0.584
$y_{>13}$ = -1.05ln(x) + 8.816
R² = 0.532
Total Thickness <10
Total Thickness 10-13
Total Thickness >13
Total Thickness <10
Total Thickness 10-13
Total Thickness >13
SR=6
Sufficiency Rating (SR)
Time (years)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
1
2
3
4
5
6
7
8
9
10
20

10. Regional Project Distribution Grouping Results

A listing of the regional sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 13. A graphical presentation of the respective regression models by group is depicted in Figure 8.

Table 13. Regional Project Distribution

Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
Regions 1,2,7	94	331	765	11.17	0.533
All Others	67	273	475	11.02	0.677

The sub-groups presented in Table 13 were selected because pavements in Region 7 and Essex County (represented by Regions 1, County 2) are subjected to a harsher environment, with more pronounced freeze/thaw cycles and the affects of increased salts, chemicals and plowing, compared to that of the remaining regions.

The data presented in Table 13 show expected extended service lives of approximately 11.0 years for both Region 1 and County 2 and all other Regions.

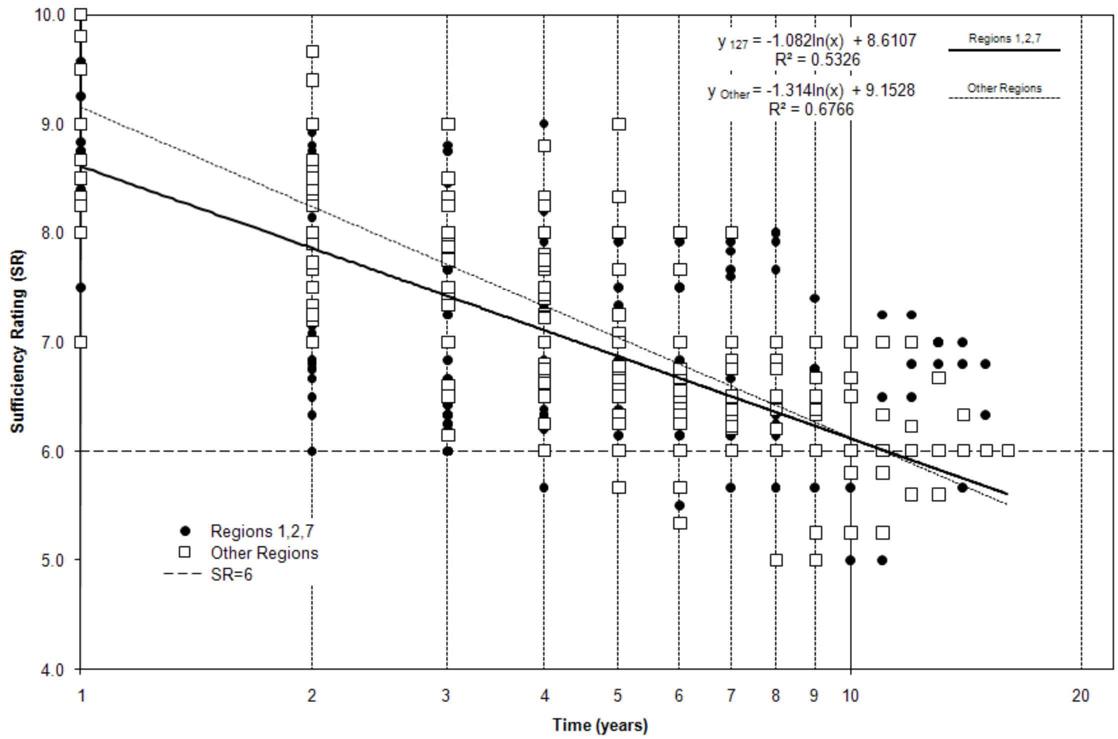
Descriptive results of ANOVA testing of three sub-groups listed in Table 13 are summarized in Table 14. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements in Regions 1,2 and 7 and the remaining regions. An examination of Figure 8, however, suggests that that differences in the data are primarily due to the initial SR values of the pavements, which skew the data during the initial years after treatment. SR values in Region 1,2,7 tend to be lower after the first year than the remaining regions. After a period of 6-7 years, the SR values tend to merge and ultimately result in similar SR 6 values, as shown in Table 13.

Table 14. Descriptive Regional Distribution ANOVA Results[1, 2,3]

Sub-Group	Regions 1,2,7	All Others
Regions 1,2,7	---	Difference
All Others	Difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

Figure 8. Semi-Log Model Results: All Sufficiency Rating (SR) Data Region



11. Rehabilitation Sufficiency Rating Grouping Results

The Rehabilitation Sufficiency Rating (Rehab SR) represents the Sufficiency Rating (SR) of the pavement segment in the year prior to rehabilitation. For example, the Rehab SR value for a given pavement segment will typically range from a value of 4 to 8. This is illustrated in the example below, which lists the condition history for a pavement segment from 1997 through 2007.

Year:	97	98	99	00	01	02	03	04	05	06	07
Rating:	6	5	9	8	8	7	7	7	7	7	6

From the data above, the pavement was rehabilitated in 1998 and the prior year or rehabilitation SR value or Rehab SR (in 1998) was 5. The rehabilitation sufficiency subgroup analysis undertaken was designed to determine the affects on performance based on the initial condition of the pavement. For example, one might assume that if a CIPR project was placed on a pavement rated 7 (Good condition), it would last longer and perform better than one placed on a 5 (poor condition).

A listing of the regional sub-groupings selected for analysis and the SR 6 intercept (expected extended service life) is presented in Table 15. A graphical presentation of the respective regression models by group is depicted in Figure 9.

Table 15. Regional Project Distribution

Group	$N_{projects}$	$N_{Segments}$	N_{Data}	SR6 Intercept (yrs)	R^2
<5.5	50	180	350	10.45	0.586
5.5-6.5	95	355	740	10.35	0.596
>6.5	18	69	150	17.0	0.644

The data show expected extended service lives of approximately 10.35 and 10.45 years for pavements with Rehab SR values 6.5 or less, but 17 years for pavements with Rehab SR values greater than 6.5.

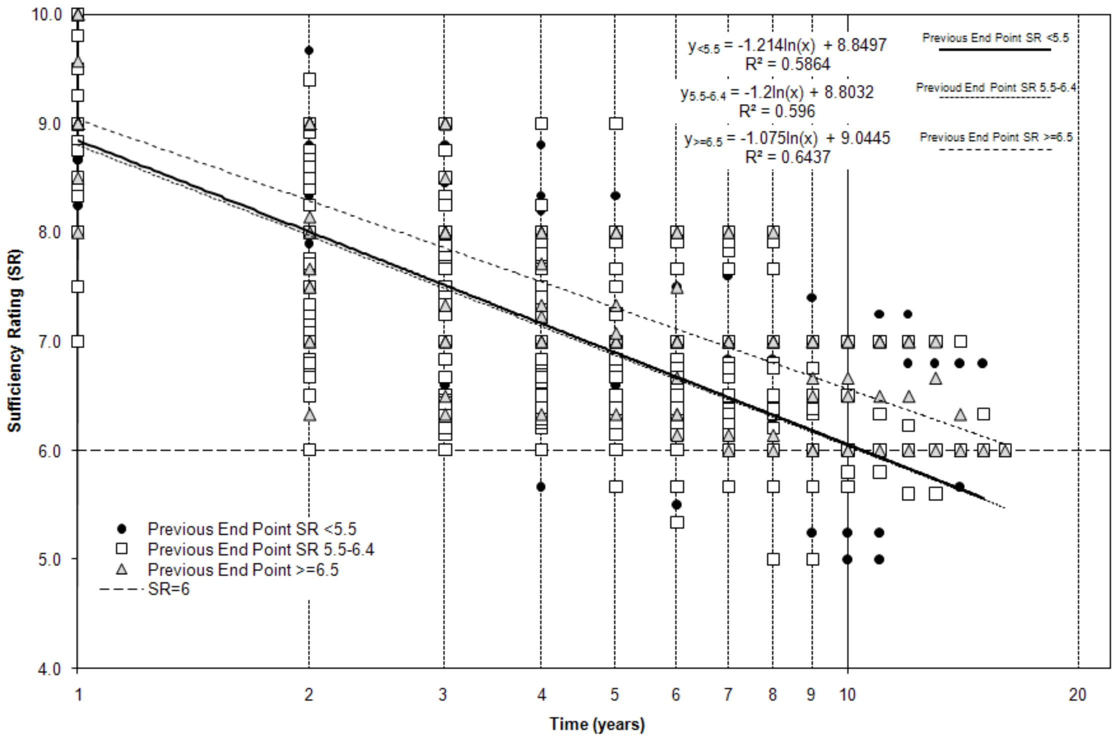
Descriptive results of ANOVA testing of three sub-groups listed in Table 15 are summarized in Table 16. Detailed results are tabulated in Appendix B. The ANOVA results suggest that there is a significant difference between SR data for CIPR pavements with SR Rehab values greater than 6.5 and those with SR Rehab values 6.5 or lower. CIPR pavements with an SR Rehab value greater than 6.5 can be expected to last approximately 6-7 years longer, than CIPR pavements with Rehab SR values of 6.5 or lower.

Table 16. Descriptive Base Plus Subbase Thickness ANOVA Results[1, 2,3]

Sub-Group	<5.5	5.5-6.5	>6.5
<5.5	---	No difference	Difference
5.5-6.5	No difference	---	Difference
>6.5	Difference	Difference	---

1.ANOVA - Level of Significance: 0.05
2. No difference: implies that the Null Hypothesis was not rejected and the sub-grouping data are part of the same distribution.
3. Difference: implies that the Null Hypothesis was rejected and the sub-grouping data are not part of the same distribution.

Figure 9. Semi-Log Model Results: All Sufficiency Rating (SR) Data Previous End Point SR



12. Findings and Conclusions

The results of the analysis suggest the following:

1. It is expected that on average when CIPR is used for pavement rehabilitation the service life of the pavement will be extended by approximately 11 years.

2. Pavements subjected to higher AADT and higher truck traffic can be expected to exhibit longer extended service lives.

3. Pavements constructed with thicker pavement base, base plus sub-base and total pavement thickness can be expected to exhibit longer CIPR service lives.

4. The environment and climate for CIPR rehabilitated pavements, examined in this study, did not significantly affect the expected extended service life of the pavement.

5. Pavements that employ CIPR as a rehabilitation strategy prior to severe deterioration (Rehab SR value of 6.5 or less) can be expected to extend the service life of the pavement by approximately 50 percent when compared to pavements that are rehabilitated after severe deterioration.

It is of note that the general policy when employing CIPR as a pavement preservation strategy has been to limit CIPR to pavements that are subjected to low AADT and low truck traffic (i.e., CIPR has typically been characterized as a pavement option for lightly traveled pavements). Findings 2 and 3 above, for the ranges of low volume traffic density for the sub-groupings examined in this study, support the opposite conclusion. CIPR tends to last longer if applied on pavements with higher AADT and higher levels of truck traffic. Since such pavements tend to be designed with greater thickness, enhanced support is provided to the CIPR section, thereby increasing the extended service life of the pavement.

It is concluded that

1. When CIPR is used on better-designed pavements that have thicker supporting bases and sub-bases, CIPR performance will benefit and the service life of the pavement will be extended. This could significantly expand the locations that CIPR can be employed.

2. Pavement rehabilitation implemented as soon as possible after the pavement SR value drops below 6.5 (to avoid continuous deterioration of the pavement structure) will significantly increase the extended service life of the pavement after CIPR rehabilitation is employed.

APPENDIX A – MODEL DEVELOPMENT

The best-fit model was selected by comparing four options: 1) a linear model, 2) a power model, 3) an exponential model, and 4) a log model.

The results of this comparison, show that a log model (in the form of y = a log (x) + b relationship) was the best line of fit in all graphs generated during the analysis; where y = SR, x = Age and b = SR intercept at Age = 0.

The log curve displayed the highest regression coefficient. The log regression line also provided the most rational presentation of SR vs. Age data. This can be deduced by examining the SR rating criteria and how one might expect such a rating to such rating to vary with Age.

A description of the rating criteria used to establish the quantitative SR rating scale criteria is presented in Table A-1. An examination of the rating criteria reveals that numeric SR values ranging from 10 to 7 can be expected to occur with normal surface deterioration, due to weather and traffic, during the first few years of pavement service. SR values below 7 reflect more severe surface deterioration that could be the result of base and sub-base distress. The nature of this rating scale is such that one would expect a rapid decay of SR values early after the pavement treatment (decreasing rapidly from 10 to 7), followed by a leveling off of SR values.

This type of relationship can be represented by the conceptual graphical model presented in Figure A-1. This model when plotted on semi-log paper results in a straight line as shown in Figure A-1.

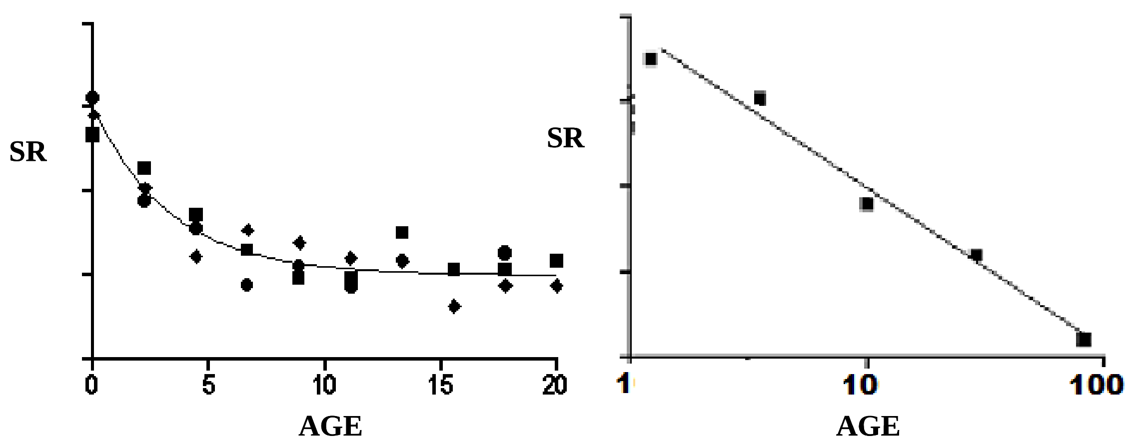


Figure A-1. Expected Model Configuration

Table A-1
2008 NYSDOT Sufficiency Rating
(Source: Training for Regional Materials Personnel, June 9-11, 2008

Pavement Distress Rating Warrants					
	Rating	General Description	Warrants		
			Frequency	Severity	Appearance
Flexible/Overlaid	10	No Distress Recently Constructed or Rehabilitated	No distress is present.		New pavement, dark black and neat. Typically one year old or less.
Flexible/Overlaid	9	No Distress	No distress is present.		Surface is typically oxidized to gray color. Typically one to three years old.
Flexible/Overlaid	8	Infrequent Distress, Very Slight Severity	Most of the pavement is free of cracking. Easy to count number of cracks at highway speed.	Cracks are tight and very widely spaced. No secondary cracking. No Dominant Distresses present.	Surface looks uniform and neat. May or may not be crack sealed.
Flexible/Overlaid	7	Infrequent to Occasional Distress with Slight Severity	Much of the pavement is free of cracking. More difficult to count number of cracks but still possible.	Cracks are mostly less than 1/8" wide. Cracks may have secondary cracking. No to very little connected cracking. May have isolated Dominant Distresses.	Looks fairly good but cracking is noticeable. Additional cracking has developed since last crack seal. Too many cracks to effectively crack seal- good candidate for single course overlay.
Flexible/Overlaid	6	Occasional to Frequent Distress with Moderate Severity	Much to most of the pavement is cracked. Cracks are spaced only a few feet apart or less.	Cracks vary in width from tight to greater than 1/8" wide. Most cracks have secondary cracking. Cracks extend to connect with adjacent cracks. Dominant Distresses may be common.	Condition looks "Fair." Needs work, likely more than a single course overlay.
Flexible/Overlaid	5	Distress is Frequent and Moderate to Severe	Nearly all the pavement or wheel paths have multiple, well developed cracks.	Cracks are wide and/or well developed with secondary cracking. Many cracks are interconnected. Pieces of pavement are dislodged or have been patched.	Condition looks "Poor." Needs major work.
Flexible/Overlaid	4	Distress is Frequent and Severe	Pavement is mostly cracked. Travel on the pavement is impaired.	Cracks are wide and connected. Potholes and/or patches are common. Patches on patches.	Beyond repair.

Graphical and numerical presentations of each type of model type examined are presented below. A summary of the regression coefficients and lower and upper 90% confidence limits predicted by each model are presented in Table A-2.

Table A-2. Model Statistics

Model	Equation	R^2	SR6 Intercept	Lower CI_{90} SR 6 Intercept	Upper CI_{90} SR 6 Intercept	y-intercept (@Age = 0)
Linear	$y = -0.2416x + 8.4148$	0.4353	10	4.25	15.8	8.41
Power	$y = 8.365x^{-0.156}$	0.5726	12	3.80	48.5	NA
Exponential	$y = 8.3808e^{-0.032x}$	0.4387	10.45	4.05	18.5	8.38
Log	$y = -1.178\ln x+8.8327$	0.5853	11.05	4.05	30.5	8.83

All models predicted expected service lives (SR 6 Intercept) in a tight range of 10 to 12 years. The Power and Log Models both exhibited highest regression coefficients and similar SR 6 intercepts. The log model was chosen because of its slightly higher regression coefficient, and the fact that it can be converted to a linear plot on semi-log coordinates. The power model cannot predict a y-intercept and breaks down as x approaches zero.

Figures A-2, A-3, A-4, and A-5, respectively provide graphical representations of the regression lines for each model. The upper and lower 90% confidence intervals as well as the SR 6 ordinate line are highlighted.

Figure A-2. Linear Model Results: All Sufficiency Rating (SR) Data

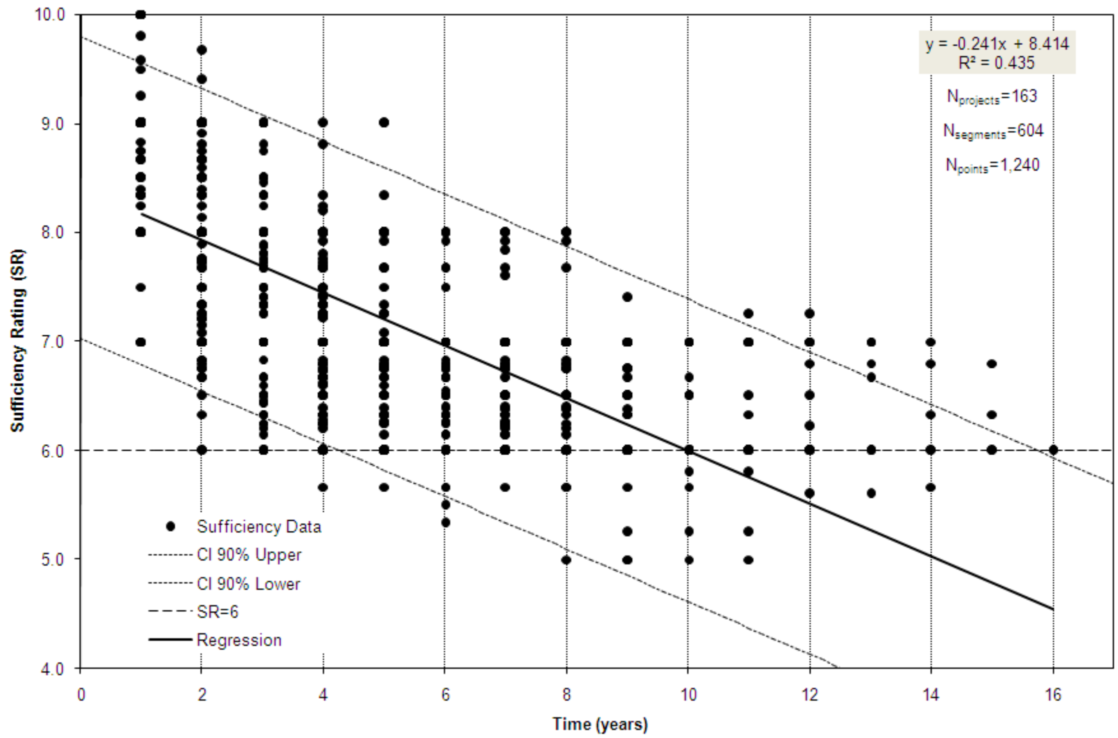


Figure A-3. Power Model Results: All Sufficiency Rating (SR) Data

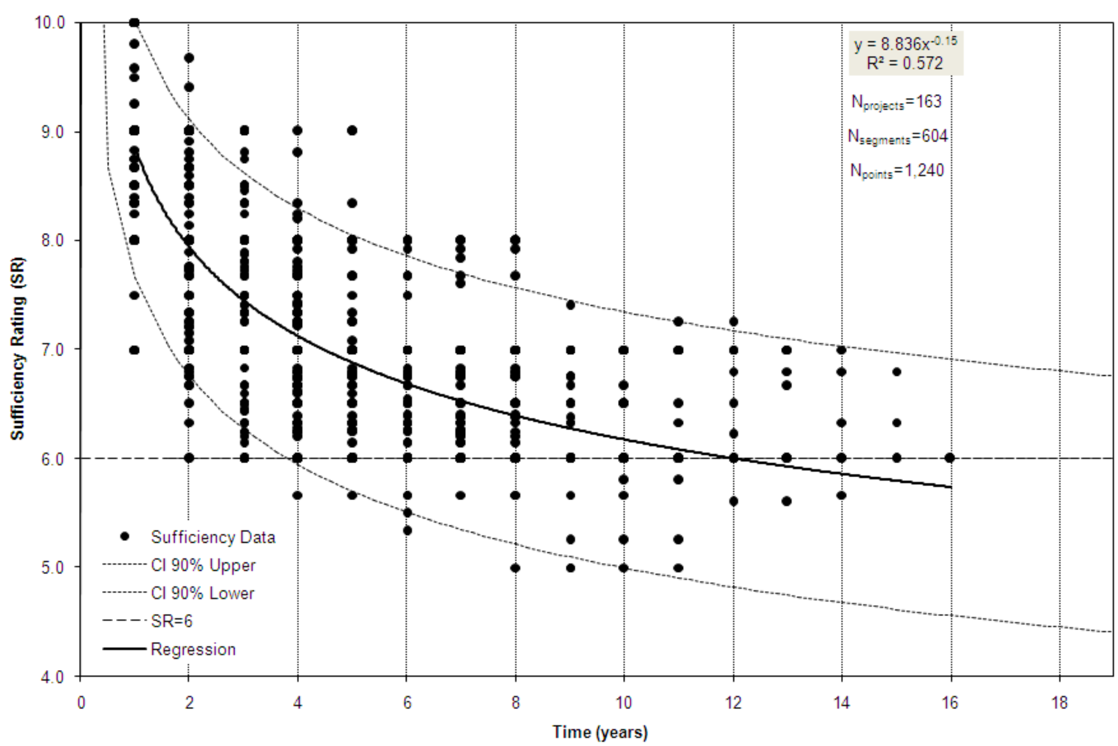


Figure A-4. Exponential Model Results: All Sufficiency Rating (SR) Data

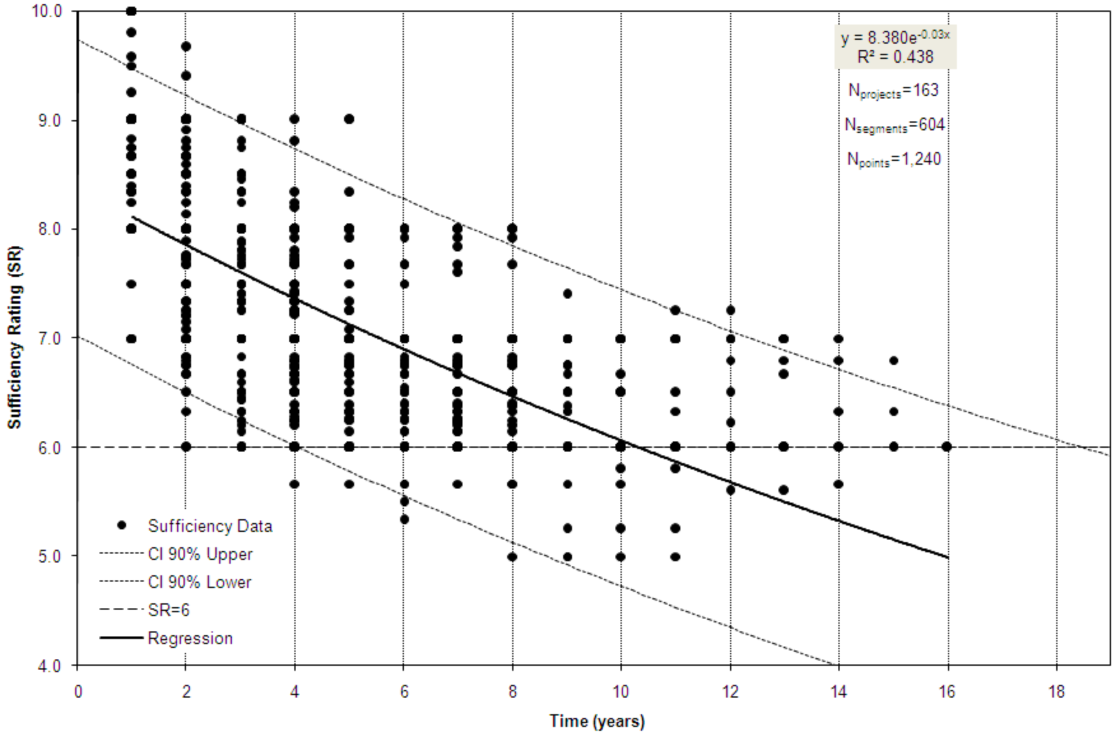
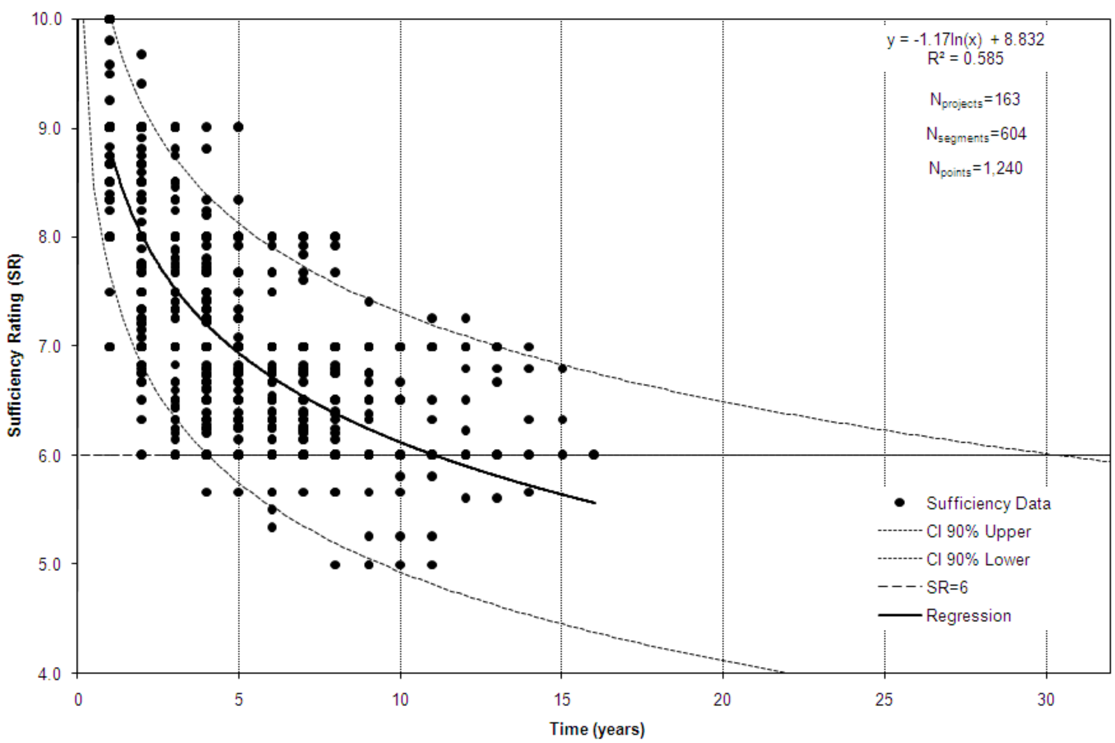


Figure A-5. Log Model Results: All Sufficiency Rating (SR) Data



APPENDIX B – ANOVA TEST DATA

1. AADT Sub-Groups

Anova Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<2000	487	3488.921	7.16411	1.305462
2000-4000	432	3094.264	7.162647	1.249028
>4000	321	2380.421	7.415641	1.153092

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	15.13454	2	7.567269	6.071387	0.002377	3.002999
Within Groups	1541.775	1237	1.246382			
Total	1556.91	1239				

SUMMARY

Groups	Count	Sum	Average	Variance
<2000	487	3488.921	7.16411	1.305462
2000-4000	432	3094.264	7.162647	1.249028

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00049	1	0.00049	0.000383	0.984394	3.851619
Within Groups	1172.786	917	1.278937			
Total	1172.786	918				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
2000-4000	432	3094.264	7.162647	1.249028
>4000	321	2380.421	7.415641	1.153092

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.78731	1	11.78731	9.756497	0.001856	3.853871
Within Groups	907.3206	751	1.20815			
Total	919.1079	752				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
>4000	321	2380.421	7.415641	1.153092
<2000	321	2279.655	7.101728	1.274911

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	15.81591	1	15.81591	13.02792	0.000331	3.856029
Within Groups	776.961	640	1.214001			
Total	792.7769	641				

2. ESAL Sub-Group Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
<50	692	4928.03	7.12143	1.270451
50-100	289	2114.896	7.31798	1.270805
>100	259	1920.68	7.415753	1.138402

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19.32839	2	9.664195	**7.774946**	0.000441	3.002999
Within Groups	1537.581	1237	1.242992			
Total	1556.91	1239				

Anova: Single Factor < 50 and 50-100

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
<50	692	4928.03	7.12143	1.270451
50-100	289	2114.896	7.31798	1.270805

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.875529	1	7.875529	**6.198495**	0.012951	3.850975
Within Groups	1243.873	979	1.270555			
Total	1251.749	980				

Anova: Single Factor 50-100 and >100

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
50-100	289	2114.896	7.31798	1.270805
>100	259	1920.68	7.415753	1.138402

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.305732	1	1.305732	**1.080689**	0.299004	3.858546
Within Groups	659.6996	546	1.208241			
Total	661.0053	547				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
>100	259	1920.68	7.415753	1.138402
<50	259	1851.005	7.146737	1.3966

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.37189	1	9.37189	**7.393992**	0.006765	3.859543
Within Groups	654.0304	516	1.267501			
Total	663.4023	517				

3. Base Thickness Sub-Group

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<4.5	232	1643.401	7.083623	1.174707
4.5-5.5	413	2971.124	7.194004	1.294311
>5.5	437	3213.927	7.354524	1.215648

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	12.2533	2	6.126648	4.953151	0.007223	3.004065
Within Groups	1334.636	1079	1.236919			
Total	1346.889	1081				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<4.5	232	1643.401	7.083623	1.174707
4.5-5.5	413	2971.124	7.194004	1.294311

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.809962	1	1.809962	1.446416	0.229547	3.855961
Within Groups	804.6134	643	1.251343			
Total	806.4234	644				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
4.5-5.5	413	2971.124	7.194004	1.294311
>5.5	437	3213.927	7.354524	1.215648

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.471007	1	5.471007	4.363311	0.037019	3.852448
Within Groups	1063.278	848	1.253866			
Total	1068.749	849				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
>5.5	437	3213.927	7.354524	1.215648
<4.5	232	1643.401	7.083623	1.174707

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.1215	1	11.1215	9.256588	0.002439	3.855438
Within Groups	801.3797	667	1.201469			
Total	812.5012	668				

4, Base + Sub Thickness Sub-Group

Anova Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<9	332	2373.012	7.147628	1.12876
9-11	627	4547.996	7.253582	1.314454
>11	123	907.4426	7.377582	1.189916

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.251486	2	2.625743	2.11173	0.121528	3.004065
Within Groups	1341.638	1079	1.243408			
Total	1346.889	1081				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<9	332	2373.012	7.147628	1.12876
9-11	627	4547.996	7.253582	1.314454

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.436832	1	2.436832	1.949111	0.163006	3.851194
Within Groups	1196.468	957	1.250228			
Total	1198.905	958				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
9-11	627	4547.996	7.253582	1.314454
>11	123	907.4426	7.377582	1.189916

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.581086	1	1.581086	1.221726	0.269378	3.853921
Within Groups	968.0179	748	1.294142			
Total	969.599	749				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
>11	123	907.4426	7.377582	1.189916
<9	332	2373.012	7.147628	1.12876

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.745871	1	4.745871	4.14403	0.042363	3.862068
Within Groups	518.7895	453	1.145231			
Total	523.5354	454				

5. Total Thickness Sub-Group Anova Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<10	126	879.8839	6.983205	1.361844
10-13	818	5931.75	7.251528	1.235757
>13	138	1016.818	7.368244	1.141482

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.66192	2	5.330961	4.304738	0.013737	3.004065
Within Groups	1336.227	1079	1.238394			
Total	1346.889	1081				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<10	126	879.8839	6.983205	1.361844
10-13	818	5931.75	7.251528	1.235757

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.860777	1	7.860777	6.276128	0.012405	3.851349
Within Groups	1179.844	942	1.252488			
Total	1187.705	943				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
10-13	818	5931.75	7.251528	1.235757
>13	138	1016.818	7.368244	1.141482

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.608553	1	1.608553	1.316093	0.251582	3.851225
Within Groups	1165.997	954	1.222219			
Total	1167.605	955				

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
>13	138	1016.818	7.368244	1.141482
<10	126	879.8839	6.983205	1.361844

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.764583	1	9.764583	7.832867	0.005512	3.877196
Within Groups	326.6136	262	1.246617			
Total	336.3782	263				

6. Regional Distribution Sub-Group						
			Anova: Single Factor			
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
ALL	1240	8963.605986	7.228714505	1.256585556		
127	765	5436.594289	7.106659201	1.163792779		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.048262192	1	7.048262192	5.771625848	0.016377461	3.846105389
Within Groups	2446.047187	2003	1.221191806			
Total	2453.095449	2004				
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
127	765	5436.594289	7.106659201	1.163792779		
Other	475	3527.011697	7.425287782	1.346035305		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	29.75108567	1	29.75108567	24.11789349	1.02726E-06	3.848980956
Within Groups	1527.158418	1238	1.233568997			
Total	1556.909504	1239				
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Other	475	3527.011697	7.425287782	1.346035305		
ALL	1240	8963.605986	7.228714505	1.256585556		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.27089244	1	13.27089244	10.35706664	0.001313918	3.846892886
Within Groups	2194.930238	1713	1.281336975			
Total	2208.201131	1714				

7. Rehabilitation SR Sub-Group			Anova: Single Factor			
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
<5.5	350	2532.138	7.23468	1.406983		
5.5-6.4	740	5310.637	7.176536	1.214985		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.80330156	1	0.803302	0.629264	0.427798	3.85002
Within Groups	1388.911	1088	1.276573			
Total	1389.7143	1089				
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
5.5-6.4	740	5310.637	7.176536	1.214985		
>=6.5	150	1120.832	7.47221	1.054214		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10.9033366	1	10.90334	9.177826	0.002521	3.851952
Within Groups	1054.9517	888	1.188009			
Total	1065.85504	889				
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
>=6.5	150	1120.832	7.47221	1.054214		
<5.5	350	2532.138	7.23468	1.406983		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.92417048	1	5.92417	4.552027	0.033368	3.860199
Within Groups	648.114927	498	1.301436			
Total	654.039098	499				