CFIRE

Cost-Effective Means of Managing Pavements in Poor Condition

Final Report

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16. Abstract

Tight budgets and dwindling state and federal revenue hinder efforts of transportation agencies to resurrect pavements in poor condition. As a “stop-gap” measure, some agencies simply allow roads to deteriorate to gravel. However, this approach can be costly over the long-term and often results in dissatisfied users.

This research project will identify construction treatments and/or materials that can be used to extend the service life of pavements in poor condition. These treatments are intended to be economical and practical “stop-gap” measures until permanent and affordable solutions are available. They are not an “alternative” to reconstruction.

New emerging pavement rehabilitation strategies are being developed and tested at the Recycled Materials Resource Center (RMRC) at University of Wisconsin-Madison using superior properties of recycled materials (e.g., fly ash stabilized reclaimed asphalt pavement and recycled concrete aggregate) to extend service lives of roadways. Efforts are underway to evaluate their performance by comparative economic and environmental life cycle analyses. These methods show great promise as cost-effective measures to treat poor pavements to achieve stop-gap or longer life cycle results.

The research will create tools for selecting and analyzing strategies for pavements in poor condition. The tools, created for Minnesota, will support future decision-making based on cost effectiveness by providing a synthesized method of life cycle cost analysis (LCCA) and life cycle assessment (LCA). This research will illustrate design strategies that offer Minnesota greater economic and environmental sustainability in resurrecting dead roads, resulting in maintaining a healthy road system.

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Overview

This report relates to *Task 6: Spreadsheet Tools for Evaluating Cost-Effectiveness and Environmental Impacts* and includes the following deliverables:

- Spreadsheet tools for evaluating and comparing the cost effectiveness and environmental impacts of treatments for pavements in poor condition.
- User Guide for the Spreadsheet Tool that includes a description of the tool and instructions for modifying existing selection criteria and calculation values as well as adding new treatments.

Description of Work

- The spreadsheet tool and this user guide were developed based on the Task 3 deliverables which included a spreadsheet tool for selecting technically feasible HMA treatments based on project characteristics and a corresponding user manual. See pages 3 and 4 of the Task 3 deliverable for detailed explanations of logical flow for determining treatment availability and service life projects. Much of the functionality of that tool is also described here as that work has been fully integrated with additional functions.
- The final tool adds the following to the Task 3 tool:
    - Agency costs based on the methodology described in the Task 4 deliverable.
    - Environmental impacts of treatments developed under Task 5 of the project.
    - Agency benefits due to reduced maintenance of pavements in poor condition.
    - User costs due to delays related to work zone speed and congestion changes due to maintenance activities.
    - Safety benefits of increased surface friction after treatments.
- Inputs and results are located on the first page of the workbook. Additional worksheets contain variables and calculations. General users only need to interact with one sheet.
- Key outputs are: treatment availabilities, annualized costs of treatments, total costs of treatments and qualitative values for safety and environmental qualities.

Summary of Treatments Considered

Table 1 contains a list of treatments considered.

Table 1: Treatments Considered

Treatment	Coverage Area
Chip Seal	Surface
Double Chip Seal	
Thin (2”) Overlay	
Mill and Thin (2”) Overlay	

Treatment	Coverage Area
Micro-surfacing	
Cape Seal	
Ultra-thin Bonded Wearing Coat (UTBWC)	
Crack Seal	Localized
Mastic	

Summary of Inputs

- Project Name and Year
- Existing Pavement Distress
  - Distresses Considered (4): Rutting, Cracking, Raveling, Roughness
  - Distress Levels Considered (4): None, Low, Medium, High
- Constraints (4): Curb and Gutter, Maintain Ditch Slope, Variable Pavement Widths, ADA Requirements
- Roadway Geometry
  - Lanes during Normal Operation and During Treatment with Work Zone Restrictions
  - Terrain Type
  - Segment Lengths
  - Lane Widths
- Traffic Characteristics
  - AADT, Single Unit, and Combination Truck Percent AADT
  - Normal and Work Zone Speed Limit
  - Traffic Distribution Type (Urban, Rural)
  - Traffic Direction (Inbound, Outbound, Both)
  - Maximum Queue Length
- Daily Work Zone Activity Times (inbound and outbound work zone times
- Agency Cost Source
  - Selection of research results or manually entered values
  - Table to provide cost values
- Safety Benefit Source – Friction Number
  - Selection of default value or agency inputs entered for different existing pavement condition by HMA Tool administrators.

Summary of Outputs

- Feasibility and Monetary Decision Factors
  - Treatment availability: Yes, No, Engineer Decision
  - Annualized Cost
  - Minimum and maximum expected service life
  - Expected Net Monetary Costs
- Qualitative Decision Factors
  - Safety Benefits
  - Environmental Factors (water, energy, CO_2, hazardous waste)
- Information for Total Project Costs and Benefits
  - 95 percent Confidence Interval for Agency Cost
  - Agency Benefits from reduced maintenance
  - User Costs of construction work zones

User Manual–General Users

Introduction

This user manual supports use of the included Excel worksheets intended to facilitate the process of selecting a treatment for maintenance of pavements in poor condition. The Excel tool identifies viable treatment alternatives for an existing roadway based on the existing distresses and constraints. It then calculates expected agency cost of materials for each treatment, agency benefits from reduced annual maintenance, and user benefits due to delays related to construction zones. Safety and environmental benefits are presented as qualitative values.

Most users of the spreadsheet only need to interact with the worksheet named “User Interface.” All additional worksheets contain constants and variables as well as look-up tables necessary for the selection tool, none of which need to be modified frequently. This section of the User Manual contains information for users of the decision tool interface located under “User Interface.” Information for modifying data and other features of the supporting worksheets can be found in the section of this report containing the User Manual for Administrators.

NOTE: Upon opening the workbook an entry will appear in the information bar at the top of the page giving the option to enable macros. Select “Enable” prior to proceeding with the worksheet.

Instructions for Inputs

The left side of the “User Interface” worksheet contains fields for inputting relevant data to evaluating to availability, costs, and qualitative impacts of treatments. All white fields should be filled in unless otherwise noted. Other than these white input fields other cells will be protected to avoid accidental changes to the worksheet. Fields in which values are selected from lists or dropdown menus only allow for only one entry.

1. **Existing Pavement Distress**: For each distress type, select the appropriate distress level (none, low, medium, high) by clicking above the correct value in the list. Distress levels selected are qualitative; engineering judgment is required for determination of existing pavement distress and how to differentiate between the categories available.
2. **Constraints**: The presence of the constraints listed above is identified in the spreadsheet tool by use of check boxes. If the constraint is present, check the box by left-clicking on it with the mouse. If the constraint is not present, leave the check box blank.
3. **Project Segment Geometry:** Geometry inputs are used for calculation of treatment area and user costs.
    a. **Number of Lanes:** This information is used to calculate the treatment area and is important to the calculation of user cost. Note that only the number of lanes in **one** direction should be entered. For a two-lane facility, enter 1 for “lanes in each direction during normal operations.” On two-lane facilities, entering 0.5 for the “number of lanes in each direction during treatment” variable can represent traffic control that restricts flow to one lane over all via flagging operations.
    b. **Segment Length and Lane Width by Section:** Segment length and lane width are used to calculate treatment area. The tool assumes that the number of lanes is constant within the project segment but allows the project to be broken up into three sections. Not all sections must be used (blank cells or 0 will be ignored).

c. **Terrain Type:** Terrain type is used to calculate capacity, which is needed for user cost calculations. Terrain type affects the number of passenger car equivalents heavy trucks represent.

    i. **Level** terrain consists of grades less than 2 percent and for short distances.

    ii. **Rolling** terrain represents grades and distances that may cause heavy vehicles to reduce their speed below passenger cars.

    iii. **Other** by default represents more challenging grades over extended distances that further challenge heavy vehicles. This could be repurposed by MnDOT to represent a more specific case to MN.

4. **Traffic Characteristics:** Traffic Characteristics are important to the calculation of user costs and also in determining treatment availability based on an AADT cutoff.

    a. **AADT:** Enter the Annual Average Daily Traffic, which represents the whole project segments average.

    b. **Trucks % of AADT:** The user cost calculation can handle single unit and combination trucks differently. The passenger vehicle share is determined automatically by subtracting the truck share. If only overall truck counts are available, enter 0 for single unit and the whole percentage under combination trucks.

    c. **Speed Limits:** The RealCost user cost methodology relies on normal and work zone speed limits by default, but actual free flow speed during normal operations and in the work zone could also be used.

    d. **Hourly Traffic Distribution Type:** The tool contains two sets of default values to distribute AADT throughout the hours of the day (Urban, Rural). These distribution values could be updated by MnDOT admin to reflect more specific circumstances but generally are not expected to be changed on a project-by-project basis.

    e. **Traffic Direction:** If the treatment is only being considered for one direction of travel select that direction. “Both” should be selected for projects considering the whole facility.

    f. **Maximum Queue Length:** This value represents the queue length at which travelers will take an alternate route rather than entering the queue to pass through the work zone. It most likely is the distance between the beginning of the work zone and the exit/intersection, which would provide the next viable detour.

5. **Daily Work Zone Activity Times:** The calculation of user costs allows for inbound and outbound work zones to be put in place at different times. These work periods are used to model work zone queuing throughout the day and also to calculate the number of days that would be required to complete a project.

    a. The methodology requires work zones to be entered using a 24-hour clock beginning at midnight (0). This makes entering overnight activities slightly complicated as the activity period must be split up and entered in two parts. The portion occurring after midnight of the next day must be placed in the table first, followed by any daytime activity periods and then the other part of the overnight work.

    b. Not all three available periods need to be used. For example, if work was to take place between 9am and 3pm, under First Period of Work enter 9 for the “Start” and 15 for the “End.” Enter zeros for “Second” and “Third” period start and end times.

6. **Agency Cost Source:** The research team analyzed cost data for 2010-2013 using the methodology described in the Task 4 Technical Memo. This data can be used to calculate agency costs. If the user has more relevant or more recent data, there is an option to select manual entry of average treatment cost. This table can be left blank if using research results.
   a. **Standard Deviation** is a common measure of variability and essential for estimating ranges. If this statistic is not available enter *zeros* in this column rather than using another measure of variability. Not including this factor will not significantly impact the outcomes of the analysis.
7. **Safety Benefit Source:** The research team chose the Friction Number as measured by the Locked Wheel Skid Trailer as the parameter to assess the safety benefits of the various treatments used in this study. The safety benefit, expressed as a percentage, is defined as the increase in Friction Number for a given treatment relative to the Friction Number of the existing pavement prior to treatment. The user has the option of selecting between a default Friction Number of 30, based on published research results, or agency inputs for minimum Friction Number based on existing pavement conditions.

Description of Outputs

The right side of the “User Interface” worksheet contains information organized to assist users with selection of the optimal treatment for the project. No user manipulation of these fields is necessary. Following is a description of the outputs.

1. **Definition of Overall Existing Pavement Condition:** The overall condition of the existing pavement is determined from the pavement distresses entered by the user and provided at the top of the Treatment Selection table in Column I:J. The three levels of existing pavement condition are defined below and depicted in Table 2:
   a. Moderate: The maximum allowable distress is one occurrence of “medium” severity.
   b. Poor: The maximum allowable distress is one occurrence of “high” severity or two occurrences of “medium” severity.
   c. Very Poor: This rating applies to any segment where distress severity is greater than or equal to 1) two occurrences of “high” distress, 2) three occurrences of “medium” distress, or 3) two “medium” and one “high” distress.

Table 2: Summary of Existing Pavement Condition Results Based on Distress Severity

Occurrence of Medium Severity	Occurrence of High Severity				
	0	1	2	3	4
0	Moderate	Poor	Very Poor	Very Poor	Very Poor
1	Moderate	Poor	Very Poor	Very Poor	
2	Poor	Very Poor	Very Poor		
3	Very Poor	Very Poor			

Occurrence of Medium Severity	Occurrence of High Severity				
	0	1	2	3	4
4	Very Poor				

2. **Feasibility and Monetary Decision Factors**
   a. **Identification of Treatments Availability**: All treatments are provided in Column I, treatment availability is provided in Column J of the worksheet and is identified by the following categories.
      i. **Yes, in green:** Treatment is available for selection and cost analysis has been applied.
      ii. **No, in red:** The treatment is not available for selection, because it does not meet agency-defined requirements, and consequently no analysis results are reported.
      iii. **Engineer's Decision:** The treatment is available for use at the discretion of the engineer based on selection of certain project constraints.
   b. **Annualized Cost:** This is the most important monetary factor which should be used for making decisions. Annualizing the net monetary value of each treatment allows comparison despite differing expected service lives.
   c. **Service Life:** Minimum and maximum service lives for each treatment are provided based on existing pavement condition. Like all other information they are not reported for treatments which are not available for this project.
   d. **Expected Net Monetary Costs:** This value provides a perspective on what total costs and benefits might be for each treatment. **Note:** This does not represent expected upfront financial costs to the agency as it includes factors such as user benefits and future maintenance savings.
3. **Qualitative Decision Factors**
   a. **Safety:** Safety improvements are reported as a percentage increase in the segments friction number due to treatment compared to an expected friction number based on existing pavement condition. Conditional formatting shows the greatest increase in friction in dark green, while treatments that provide minimum improvement are shown in lighter shades and white.
   b. **Annualized Environmental Impacts:** Four environmental factors are reported. Conditional formatting is again used to highlight which treatments have the greatest negative environmental impact (red) and which are relative beneficial to the environment (green). Values are reported on an annual basis for comparison across treatments.
      i. **Water:** Water use is reported in gallons. A significant amount of water is used in the production and application of treatments and may have negative environmental impacts on water resources.
      ii. **Energy:** Energy use is reported in megajoules. Energy production has significant negative side effects and minimizing energy use will have positive effects.
      iii. **Carbon Dioxide:** Carbon dioxide is the most common greenhouse gas contributing to global climate change. This variable is reported in kilograms of

carbon released. Production of materials as well as the significant energy use of treatments contributes to this factor.

iv. **RCRA Haz. Waste:** This category, reported in kilograms, refers to a number of harmful materials categorized as hazardous waste under the Resource Conservation and Recovery Act. They are byproducts of production and application of treatments and are a cause of cancers and other chronic disease.

4. **Information for Total Project Costs and Benefits**

   a. **Agency Cost (95% Confidence):** A range of expected costs for each treatment are provided. Given the research results or manually entered standard deviations, the ranges have been constructed in order that roughly 95 percent of treatment material purchases should fall within the given range. This data can be used to assess the risk of a project being drastically over- or under-budget compared to the estimate used to calculate the annualized cost.

   b. **Agency Benefit:** Applying treatment to the poor condition pavements should significantly reduce future year needs for maintenance activities. MnDOT project coordinators provided estimates of the varying effectiveness of different treatments in reducing annual patching. Those percent reductions in patching are expected to be effective for each year during the service life of the treatment, after which there are no additional agency benefits.

   c. **User Cost:** Work zones cause system users to face some costs that are often ignore in the construction planning process. These costs mainly arise from speed changes when entering the work zone and queuing if traffic levels exceed the number of vehicles that can pass through the work zone in a given time period. These costs are calculated using a methodology deployed by FHWA’s RealCost Lifecycle Cost Analysis tool.

User Manual–Administrators

The spreadsheet tool consists of one worksheet that is accessed regularly by general users and numerous worksheets that work in the background to automate the handling of data related to different decision factors. The following manual provides a more detailed overview of the tool's worksheets, instructions on how to manage how general users interact with the tool, and instructions for modification of various modules of the tool.

Detailed Overview

This portion of the manual provides a description of the worksheets used for data input, data output, and processing contained within the spreadsheet tool. The information provided should allow administrators to have a general understanding of how the tool works overall. A detailed walkthrough of each worksheet is not provided because this would occupy many dozen pages. A description of each worksheet is provided in Table 3.

Table 4 provides a more detailed review of the main worksheet, which contains tables used for calculations. Table 5 provides more detail on some of the functions used in the tool, which may not be familiar to administrators.

Table 3: Summary of Worksheets in Treatment Selection Tool

Worksheet Title	Worksheet Type	Description
User Interface	User Interface	The user enters project-level information into this worksheet. It also presents the output of the decision factor analysis tool. This sheet is discussed in detail in the User Manual for General Users.
Supplemental Data	Data Tables	This worksheet contains many essential values for the calculations carried out by the tool. Administrators can update these data tables as more recent or more accurate information becomes available. These values are not expected to change on a project-by-project basis, nor to be entirely familiar to all general users. Detailed information on the data contained in these tables can be found in Table 4 below.
Environmental Data	Data Tables (Static, but some dynamic adjustment factors)	This worksheet contains the results of Task 5 analysis of the environmental impacts of various treatments. Research results produced environmental impacts per 12-ft lane mile of treatments, with the thickness of each treatment assumed for calculations. Results in the main table are adjusted to square yards and the assumptions on treatment thickness can be modified in the "Supplemental Data" worksheet. Localized treatments adjust for the existing pavement condition. Additional tables report annualized

Worksheet Title	Worksheet Type	Description
		environmental impacts based on the expected service life of the treatment.
RealCost Sheets – Multiple	Calculation Table	One sheet exists for each treatment. These sheets contain the user costs modules of FHWA’s RealCost Lifecycle Cost Analysis tool. RealCost is a much larger program that was not entirely applicable to this project but provided a well-developed user costs calculation methodology. Worksheets are linked to values defined on the User Interface worksheet, and user cost results for each treatment are reported back to that sheet. The RealCost module’s core functionality is based on queuing algorithms and delays due to speed changes.
Distress Data	Data Table (Static)	This worksheet provides all possible combinations of pavement distress type and level (i.e., Rutting – High) in column A. All treatments considered are listed in subsequent columns. Cells are populated with “Yes” and “No” as indicators as to whether a treatment is available for a given distress level.
Distress Evaluation	Look-Up Table (Dynamic)	This worksheet provides the connection between user inputs for existing pavement distress and agency established treatment application criteria (Distress Data worksheet). User inputs are used for evaluation of treatment availability by a combination of Excel “IF” and VLOOKUP functions. The final row accumulates information related to individual distresses to provide an overall assessment of treatment availability.
Constraint Evaluation	Look Up Table (Dynamic)	This worksheet identifies all constraints to treatment selection defined by MnDOT in original scoping of the project. The same Yes/No format used in the Distress Evaluation worksheet is used here, with “Yes” indicating that the treatment is available regardless of the presence of the constraints. Only certain treatments are affected by constraints; these cells are highlighted in yellow and include an “IF” statement to change availability of the treatment based on the presence of a constraint. Cells unaffected by constraints are not highlighted and simply contain “Yes” to indicate that the treatment is available. Similar to the Distress Evaluation worksheet, the final row of this worksheet provides a summary of treatment availability based on constraints. There are three possible outcomes, “Yes,” “No,” and “Engineer Decision.” These outcomes are

Worksheet Title	**Worksheet Type**	**Description**
		determined using a simple "IF/OR" statement.
Service Life Input	Data Table (Static)	This worksheet summarizes the minimum and maximum service life for each treatment and various levels of existing pavement condition. The treatments and their applications (i.e., localized vs. surface) are provided in Columns A and B. Columns C-E present the minimum service life for different conditions of the existing pavement, ranging from moderate to very poor. Similar information for maximum service life is provided in Columns F-G. Existing pavement condition is determined based on the distresses entered by the user.
Form Control	Look Up Table (Dynamic)	This worksheet controls the list, combo, and check boxes used for data input on the User Interface worksheet. It controls both the options available to select in the boxes and translates the user input into numerical or Boolean values required for manipulation of data elsewhere in the tool. For list boxes numerical values (ex. 1-4) are assigned to possible choices based on the order they appear. Combo boxes function much like list boxes but with dropdown menus rather than showing all options. They again return numeric values based on the order of entries. For check boxes, "TRUE" or "FALSE" is reported based on user input. To edit the values displayed in boxes, right-click the box you want to change and select "Form Control…" IF statements are used to translate output of list, combo, and check boxes to the text used in other spreadsheets. Overall existing pavement condition is defined based on levels of distress entered by the user and evaluated using IF statements nested with the AND or OR functions.
Safety Benefits	Data Table (Static) with Dynamic Tool to Address Different Input	The worksheet includes a static data table that lists the maximum, minimum, and average Friction Numbers for each treatment based on literature review. References are available in the Task 4 memo. Safety benefit is calculated as the increase in Friction Number due to a given treatment relative to the Friction Number of the existing pavement. Two options for existing pavement Friction Number are available: 1) Default Friction Number of 30 that applies to all existing pavement conditions, 2) Agency Input – Friction Number for each pavement condition as determined by HMA Tool administrators.

Table 4: Summary of Supplemental Data Tables

Table Name	Source	Description
Added Time and Vehicle Running and Idling Costs	FHWA Technical Bulletin, August 1996 via RealCost	This table supports the calculation of user costs. Dollar amounts are in 2014 dollars and may need to be updated in the future to account for inflation. FHWA used the Consumer Price Index (CPI) to escalate the values from 1996 amounts.
Traffic Distributions	RealCost Defaults	This table is used to distribute AADT on an hourly basiss in order to match up demand and capacity for calculation of user costs. These values should be updated by administrators if more relevant figures for Minnesota are available. The final row allows for checking that total distributions account for 100 percent of traffic.
Inputs for Capacity Calculations	Life-Cycle Cost Analysis Procedures Manual, updated 2013 from Caltrans	This data assumes “normal” lane and shoulder widths, which is an important simplifying assumption. Consequently for some situations capacity estimates may be suboptimal and it may be worthwhile to decrease capacity estimates for major projects with narrow lanes or no shoulders. Note that the order of PCE values are in a different order than in the input menu and form control due to requirements of the VLOOKUP used for capacity calculations. Level and Rolling values come directly from the Highway Capacity Manual, however the Other value should be adapted to best fit the needs of the agency.
Average Cracking Per Road Station (Per Lane)	Research assumptions	These values are based on researcher’s assumptions. They are used to determine the costs and environmental impacts of crack sealing as a local treatment. They should be updated with current estimates from MnDOT.
Pavement Requiring Annual Patching	Research assumptions based on information provided by MnDOT	These values are based on some correspondence with MnDOT but are not especially well defined. They should be modified as soon as MnDOT can articulate a better understanding of how annual patching costs are related to road condition.

Table Name	Source	Description
Percent Reduction in Patching Post-Treatment	Correspondence with MnDOT	This table was provided by MnDOT and should be updated if the conceptualization of treatments effects on annual patching needs is updated.
Research Results for Material Cost of Treatment	Research results based on Task 4 of current project	This table contains the default material prices for each treatment. Except for overlays this data is reported as the average cost and variable of each treatment based on data provided. The overlay data provides an additional level of assessment based on the characteristics of this material and the amount of data available. These values vary based on the size of the project due to economies of scale achieved in large HMA purchases. They are also divided into large and small projects based on non-linearity in material purchases data.
Discount Rate	MnDOT guidelines for BCA	Discount rates are essential for annualizing values and valuing the present value of future costs or benefits. This should be updated if MnDOT decides a different value should be employed for Benefit-Cost Analysis.
Patching Cost Per Sq. Yd.	Placeholder	This information is not available to the researchers at this time and should be updated by MnDOT as soon as possible.
Treatment Productivity Rates	Researchers summary of various sources	Researchers compiled this data for use in calculating the user costs. Productivity affects the number of days which a work zone will need to be in place in order to complete a project. Estimates are drawn from a number or sources and should be updated if MnDOT has more accurate information available based on department expertise.
Value of Time	MnDOT guidelines for BCA	MnDOT currently only provides BCA guideline values for passenger vehicles and heavy trucks. The single unit truck value of time was extrapolated from the heavy truck value to align with the default values used by RealCost.
AADT Cutoff Point	Correspondence with MnDOT	This variable controls the cutoff traffic level for some treatments and is currently defined as 10,000 AADT by MnDOT.

Table Name	Source	Description
Existing Pavement Friction Numbers	Research results and administrator inputs	A Friction Number of 30 represents the minimum friction number for which rehabilitation is needed. Researchers have insufficient information to make assumptions regarding actual friction numbers for pavements by pavement condition. An option is included for HMA tool administrators to input Friction Numbers based on existing pavement condition if they are available. The User Inputs sheet includes a list box to select the source of Safety Benefit Data as "Default" or "Agency Input."
Treatment Thickness Assumptions	Researcher assumptions	These values are used to calculate environmental impacts. Researchers did not have access to specific thickness information but felt that these were reasonable approximations. The administrator can adjust these to reflect more accurate values in order to make sure environmental outputs are as close to reality as possible.
Total Daily Work Zone Hours	Calculation based on user inputs	CALCULATION. Modification should be unnecessary. This value is used to determine the number of days that would be required to complete the project using each treatment. This is a factor of the number of hours based on the input work zone times. It is combined with treatment productivity rates for use in the RealCost sheets.
Segment Capacity	Life-Cycle Cost Analysis Procedures Manual, updated 2013 from Caltrans based on Highway Capacity Manual 2010	CALCULATION. Modification should be unnecessary. These capacity estimates are based on simplifications of HCM formulas as described by Caltrans' guidelines for using RealCost.
Values Selected for Agency Cost Calculations	User inputs or research results	CALCULATION. Modification should be unnecessary. This table is contains the values used in calculations. It is set as a separate table to that it is populated correctly based on user input directing the use of research results or manual values. This format greatly increases the readability of agency cost calculations in the "User Interface" worksheet.

Treatment selection was automated by using a variety of formulas to support the Look Up Tables through identifying which tables are appropriate for a given set of user inputs and establishing relationships between information listed on separate worksheets. The following is a description of the base functions used, for operation of the spreadsheet many of the functions were combined or nested. The functions described in Table 5 are used in the dynamic look-up tables and other worksheets to automate the treatment selection process.

Three custom functions are defined for the workbook. They can be accessed by going to Developer > VisualBasic. This opens the Visual Basic editor. In the portion of the window at the top left expand the folder called Modules found under VBAProject (HMATool_5_2014). Double-click CustomFunctions to see the code. Defining custom functions greatly increased readability of some workbook sheets as well as allowing the researchers to manipulate data that would have been nearly impossible with normal single line Excel commands.

Table 5: Summary of MS Excel Functions Used in Spreadsheet Tool

Function	Description
IF	Logical test that returns different values based on whether the user-defined condition is met. The format is *IF(logical_test, [value if true], [value if false]).* Can be nested with additional IF statements or other functions for evaluation of multiple conditions.
OR	Used when multiple conditions exist for evaluating one multiple test. If any of the conditions defined are true the test is considered true. The format is *OR(logical1, logical2, logical3….).*
AND	Used when multiple conditions must be met for a given test. All conditions must be true in order for the test to be considered true. The format is *AND(logical1, logical2, logical3….).*
VLOOKUP and HLOOKUP	Searches the first column of a range of cells and returns a value from any cell on the same row within the range defined by the user. The format is, *VLOOKUP(look_up value, table array, col_index_number, [range lookup]).* The look_up value is the value to search in the first column of the data range identified. The table array defines the cells that contain the data for the look up function. The column index number identifies which column the output data from which the matching output must be returned. In the spreadsheet numbers are sequential based on a starting value of 1 for Column A. The range look up defines whether an approximate or exact match is required. For this application an exact match is necessary, so the range format is always defined as "FALSE." HLOOKUP works exactly the same as VLOOKUP except it searches across rows instead of columns.
LOOKUP	Similar function as VLOOKUP function, with the data organized in rows rather than columns. The format is, *LOOKUP(look_up value, look_up vector, [result_vector]).*

Function	Description
CALC	Custom Function. This function greatly increases the readability of the output portion of the User Interface. This function determines if a value should be calculated based on whether it is available or not. If it is unavailable “N/A” is returned rather than potentially returning errors due to treatments not being available. The format is *CALC(Available, [Function])*.
TotHours	Custom Function. Calculates the total hours of the day which a work zone will be in place through simple addition or subtraction but avoids numerous command line cell references. This function would need to be modified to allow for more than three periods of work in a day. (Two with an overnight work period.) The format is *TotHours([Work Zone Times as a 2x3 range of cells]).*
IsWorkZone	Custom Function. Replaces a custom function from RealCost, which was not available for use in the tool development. Also would need significant modification if additional work zones or time periods were needed. This function takes a large number of inputs but organizes them in a way that would take dozens of nested IF statements to perform in the command line.
PMT	This formula is employed to calculate Annualized Cost values in the output portion of the User Interface. It provides the annual payment for spreading a present value over a given number of periods. The format is *PMT(rate,nper,pv,[fv],[type]). Rate* should be the discount rate, *nper* is the expected service life of the project, and *pv* is the expected net monetary cost.
PV	Agency benefits occur throughout the service life of the project. These values need to be summed in current dollars for comparison with other immediate costs. This formula works in the opposite direction of PMT and is in the form: *PV(rate,nper,pmt,[fv],[type]).*

Managing Tool Access

The tool has been developed so that users only need to interact with one worksheet of the tool. The tool contains a total of 19 worksheets as of the time it was delivered by the research team. Of these 19 worksheets, 17 are expected to be hidden from the general user, 1 is expected to be completely locked to editing, and 1 is expected to be partially protected from change to cells that carry out calculations. This section of the manual covers how to maintain this workbook structure while still allowing administrators the flexibility to review and update/modify the tool.

The worksheet named User Interface is password protected to lock cells from editing. However, cells in which users adjust inputs for calculations have been unlocked. If users attempt to change a cell which is locked, a notice will pop-up explaining that the cells are locked for editing and how the worksheet can be unprotected to allow editing of those cells using a password.

The worksheet named Supplemental Data is password protected to lock cells from editing. All cells are locked, which makes this data visible to the user but does not allow them to edit it.

The remaining 17 worksheets are hidden. A password protects them from being unhidden. This is accomplished using a feature called Protect Workbook Structure that allows the workbook structure to be protected. Hidden worksheets are not individually protected like the User Interface and Supplemental Data worksheets. The tool administrator may decide that the Supplemental Data worksheet should also be hidden in this manner rather than protected if users do not need to reference the values stored in it.

Table 6 provides walkthroughs for using the various types of protection tools provided my Excel to maintain this access management structure or to change the visibility and protection of worksheets.

Table 6: Access Management Task Walkthroughs

Task	Instructions
Protecting and Unprotecting the Workbook Structure	Protecting the workbook structure prevents adding, deleting, or moving worksheets. This also affects the hiding of worksheets, which is an important part of the researchers' attempt to make the tool easy to interact with for general users. The workbook structure will need to be unlocked by administrators in order to unhide worksheets to make changes. Re-protect it after hiding those worksheets again. The prompt for protecting and unprotecting workbook structure is a simple password entry box in both cases and can be accessed two different ways. • On the Windows ribbon, select Review, and then click Protect Workbook. Enter the password. Researchers used and recommend continuing to use CFIRE4ADMIN. • Or, under the File menu, select Protect Workbook and then Protect Workbook Structure. • This either locks or unlocks the workbook.
Hiding and Unhiding Worksheets	Worksheets can be hidden by right-clicking the tab in the bottom of the workbook and selecting Hide. Worksheets can be unhidden by right-clicking some other unhidden worksheet's tab at the bottom of the workbook and selecting Unhide. This will pop-up a window where you can select what worksheet you want to unhide. Only one worksheet can be unhidden at a time, so an administrator identify which worksheets need to be unhidden ahead of time. Hide worksheets again after making changes.
Unprotecting Worksheets	Worksheets will need to be unprotected to make any changes to them. Worksheets protected by the researchers include User Interface and Supplemental Data. 1. Use one of these multiple ways to access the workbook protection function:

Task	Instructions
	a. Right-click on the worksheet's tab at the bottom of the workbook window and select Unprotect Sheet… b. In the ribbon, open the Review tab and click Protect Sheet. c. From the File menu, under Protect Workbook, find the name of the sheet that you wish to unprotect and select the options. 2. Enter the password. a. The password used by researchers is CFIRE4ADMIN.
Protecting Worksheets	If additional sheets are made visible they should be protected in order to prevent accidental editing of the workbook that could cause errors to the results. These steps should also be used to re-protect a workbook, which has been unprotected to make changes. 1. To protect an unprotected workbook: a. Right-click on the worksheets tab at the bottom of the workbook window and select Protect Sheet… b. In the ribbon, open the Review tab and click Protect Sheet c. From the File menu, select Protect Workbook, then Protect Current Sheet. 2. Enter a password. The researchers recommend continuing to use the CFIRE4ADMIN password. This will insure other administrators maintain access to the workbook and that there is a record of the password so it will not be lost. 3. Default settings should be sufficient for the management restrictions desired. Press OK. 4. Reenter the password. 5. NOTE: Do not protect the Form Control worksheet without unlocking all cells that are linked to input Form Controls.
Unlocking Cells for Editing in Protected Worksheets	Cells may need to be unlocked when edits are made to the workbook, although when new rows are added they should match the protection settings of the row above them. In most cases no changes to protection settings should be needed. Administrators may also decide to give users more control over the workbook, for example by allowing them to edit some portions of the Supplemental Data tables. This can be accomplished by unlocking the cells using the following steps. 1. Unprotect the worksheet. 2. Highlight the cell(s) for which you wish to change protection

Task	Instructions
	settings. 3. Right-click on the selection and choose Format Cells… 4. Open the Protection tab of the Format Cells window. 5. Uncheck the checkbox next to Locked to allow users to edit this sell when the worksheet is locked. Check this box in order to make a cell for which editing was previously allowed unavailable for changes when the worksheet is locked. 6. Click OK to close the window. 7. Protect the worksheet. (Locking or unlocking cells only changes their behavior when the worksheet is locked!)

Tool Modifications

Possible changes to the spreadsheet tool identified include modification of existing criteria or adding of new criteria to the following:

- Service life range based on existing pavement condition inputs.
- Pavement distress levels that determine existing pavement condition.
- Treatment selection based on existing levels of pavement distress.
- Constraints including traffic level
- Available Treatments
- Modifying default values on the Supplemental Data worksheet.

A qualitative ranking system was used to provide an initial assessment of the amount of work required to perform each modification. For this system the stars at the end of the modification descriptions denote initial author assessment of difficulty. The scale is from one star to four stars, with one star denoting minimal effort and four stars denoting extensive effort.

The tool accounts for three levels of existing pavement condition: moderate, poor, and very poor. These three levels are expected to capture all scenarios within the scope of the project. This factor affects the expected service life for each treatment. Refer to Table 2 and the corresponding section of the User Manual for descriptions of the default parameters for assigning pavement condition.

Table 7: Instructions for Modifications of *Existing Pavement Condition* Determination

Modification	Instructions
Modify expected service life for a given distress. *	1. Open the Service Life Input worksheet and modify the expected minimum and maximum service life for each treatment by entering the new number in the appropriate cell.

Modification	Instructions
Modify distress level rules for determining existing pavement condition*	1. Open the Form Control worksheet and locate the Pavement Distress table. The Number of Occurrences column aggregates the number of occurrences of each distress level input by the user. The Pavement Condition column contains nested IF, OR and AND statements. The formula is provided below: *=IF(AND(G7<=1,G8=0),"Moderate",IF(OR(AND(G7=2,G8=0),AND(G7=0,G8=1),AND(G7=1,G8=1)),"Poor",IF(OR(AND(G7>=2,G8<=1),G7>=3,G8>=2),"Very Poor")))*. 2. Cells G7 and G8 correspond to occurrences of medium and high distress respectively. Each AND statement captures one or more combinations of medium and high distress. Each OR statement (color-coded for readability) captures all combinations which would cause a classification as one type of condition. The IF statements assign the distress name in the case that one of the combinations resulting in that condition classification is true. Otherwise it tests for the next condition level. For more on IF, OR and AND statements see Table 5. 3. Cases can be modified by changing the AND statements to represent different combinations of stress or by adding or removing AND statements from the OR groups.

Table 8: Instructions for Modifying Distress Data (Thresholds, Labels, New Distresses)

Modification	Instructions
Modify distress thresholds for which treatments are considered viable.*	1. Open the Distress Data worksheet. If a treatment should start or stop being considered available at a given severity of a specific stress, change that criteria by deleting the existing criteria and replacing it with a “Yes” or “No” as appropriate.
Modify distress label (i.e. change cracking to thermal cracking)*	1. Open the User Interface worksheet and modify the appropriate label located in cells C3:F3. 2. Open the Distress Data worksheet and modify the appropriate label for each level of distress for all traffic levels. 3. Open the Distress Evaluation worksheet and modify the appropriate label.
Adding a new distress (i.e. fatigue cracking)****	1. Open the Form Control worksheet. Add a row underneath the Pavement Distress table. In the Distress Column, name the new distress. 2. Open the User Interface worksheet and rearrange the sheet in order to add a distress input field like those found in C6:F10. Insert a List Table by selecting Developer > Insert > List Table. Right-click the list table and select Format Control.

Modification	Instructions
	3. In the Control tab of the window press the button to interactively fill the Input Range field. Navigate to the Form Control worksheet and select the appropriate distress levels to consider from the Distress Levels column of the Pavement Distress table. 4. Remaining in the Control tab, press the button to interactively select the Cell Link cell. Navigate to the Form Control worksheet and select the cell in your new row under the List Box Output column. 5. Open the Distress Data worksheet and insert the new distress/levels selected at the end of the distress data table for each traffic level. Populate the Yes/No selection criteria in the corresponding rows and columns for each combination of treatment/distress level. 6. Return to Form Control. In the Distresses Based on List Box Output, use nested IF statements to report the list box output. Based on the number of distress levels selected (3 or 4) two or three nested IF statements are required. The IF statement is of the form, *=IF(B18=1,[Cell in Distress Data worksheet Corresponding to lowest level of distress], IF(B18=2,Cell in Distress Data worksheet corresponding to 2nd level of distress], IF(B18=3, [Cell in Distress Data worksheet corresponding to 3rd level of distress], [Cell in Distress Data worksheet corresponding to highest level of distress])).* 7. Open the Distress Evaluation tab and insert a row above Row 7. Enter the new distress in column A. 8. Highlight B6:J6, copy, and paste in B7:J7. 9. Modify the formulas to reflect the new distress range in the VLOOKUP function for the distress table that corresponds to each traffic level. The VLOOKUP function is in the form *VLOOKUP([Distress Output from Form Control Worksheet], [Range of Evaluation in Column A of Distress Data Table]).* The only modification necessary is to ensure this range is changed to reflect the location of the new distress and levels in the Distress Data worksheet, the location of this in the formula is highlighted in red. 10. The end of the Distress Evaluation worksheet evaluates if the treatment is viable by ensuring that “Yes” is identified for all modes of distress. The formula is a simple IF/OR statement that requires the treatment to be deemed unavailable if it fails the selection criteria for any of the selected distresses. Modify the IF/OR statement to include evaluation of the new distress data presented in row 7. Example: for the Cape Seal Treatment (Column G), the modification to the existing formula is highlighted in Red, *=IF(OR(G3=”No”, G4=”No”, G5=”No”, G6=”No”, G7= ”No”), ”No”, “Yes”)).* This step needs to be repeated for all treatments.

A total of six constraints that eliminated some treatments were identified in the original selection criteria provided by MnDOT as follows 1) high traffic level, 2) very poor existing pavement condition, 3) presence of curb and gutter, 4) presence of variable lane widths, 5) requirement to maintain existing ditch slopes, and 6) requirement to meet Americans with Disability Act (ADA) provisions. Two possible changes were considered for constraints, modifying the treatments for which constraints apply and adding new constraints to the spreadsheet tool. In the existing spreadsheet tool, constraints are coded into the Constraints worksheet, cells corresponding to combinations of constraints and treatments that require consideration are highlight in yellow. All other cells include only “Yes” indicating that the treatment is available regardless of the presence of a constraint.

Table 9: Instructions for Modifications of Availability Constraints

Modification	Instructions
Remove existing constraints from selection of available treatments *	1. Open the Constraint Evaluation worksheet and modify the constraints for a given treatment. For the treatment and constraint of interest, delete the formula in the highlighted cell and replace with “Yes.” Remove the highlighting.
Add treatments for which existing constraints apply.**	1. Open the Constraint Evaluation worksheet and select the combination of treatment and constraint of interest. Delete “Yes.” 2. Enter an IF statement to define the new criteria in the following form: = *IF([“Form Control sheet, Summary of Constraints table, Constraint row, Check Box Output column] = TRUE, [Either “No” or “Engineer Decision”], “Yes”).* Do not use quotation marks around TRUE in the formula.
Add a new constraint. ***	1. Open the Form Control worksheet. Add a row under the Summary of Constraints table. Enter the new constraint in column Constraint below the existing constraints. 2. Open the User Interface worksheet. Insert the check box near the other constraints by selecting Developer > Insert > Check Box. 3. Enter the label for the new constraint next to the check box. 4. Right-click the new check box and select Format Control from the drop down menu. In the Control tab, select the button to interactively fill the Cell Link box. Select the cell in the Form Control worksheet that is adjacent (in the Check Box Output column) to the text from Step 1. 5. Open the Constraint Evaluation worksheet and insert a new row above the Treatment Available row. 6. Enter “Yes” in the cells that correspond to all treatments for which the new constraint does not apply. 7. Enter an IF statement to define the new criteria for treatments it will apply to in the following form: = *IF([“Form Control sheet, Summary of Constraints table, Constraint row, Check Box Output column] = TRUE, [Either “No” or “Engineer Decision”], “Yes”).* Do not use quotation marks around TRUE in the formula. 8. Modify the Treatment Available formula in column B. If one constraint is added to the existing spreadsheet this will be cell B10. The formula is written to consider all possibilities, so the only modification is adding the

Modification	Instructions
	new constraint. Assuming one constraint is added, the modifications to the existing formula is highlighted in red, *=IF(OR(B3="No",B4="No",B5="No",B6="No",B7="No",B8="No",B9=”No”)," No",IF(OR(B3="Engineer Decision",B4="Engineer Decision",B5="Engineer Decision",B6="Engineer Decision",B7="Engineer Decision",B8="Engineer Decision", B9=”Engineer Decision”),"Engineer Decision","Yes")).* 9. Place the cursor in the cell that contains the formula modified in Step 8 and highlight columns B-J. Fill right (CTRL+R) to extend the formula to all possible treatments.
Modify current traffic thresholds. **	1. Open the Supplemental Data worksheet and modify the value corresponding to AADT Cutoff Point. 2. If this new cutoff affects which treatments are available at a given distress level, see Table 8 for modifications of treatment availability considering this new threshold.
Add new traffic thresholds. ****	1. Open the Supplemental Data worksheet and add another cutoff value. 2. In the Distress Data worksheet, copy and paste an existing table and add the selection criteria for the new traffic level. To maintain order, the location of the new data table should reflect where the new traffic level input is relative to existing inputs. 3. In the Distress Evaluation worksheet the look up formulas for each combination of treatment and distress need to be modified to reflect the new traffic level using nested if statements. For three traffic levels, the format is: *IF(‘User Interface’!C34 < [Cutoff 1], VLOOKUP(Input Distress, Distress Data Range Traffic Level 1, Column of Treatment, FALSE), IF(‘User Interface’!C34 < [Cutoff 2], VLOOKUP(Input Distress, Distress Data Range Traffic Level 2, Column of Treatment, FALSE), VLOOKUP Distress Data Range Traffic Level of Treatment, FALSE).* Changes to existing formulas are highlighted in Red.

Table 10: Instructions for Modifications to Available Treatments

Modification	Instructions
Remove an Available Treatment*	1. Open the Distress Data worksheet and delete the column associated with the treatment selected for removal in all Distress Data tables. 2. Open the Distress Evaluation worksheet and delete the column associated with the treatment selected for removal. 3. Open the Constraint Evaluation worksheet and delete the column associated with the treatment selected for removal. 4. Open the Service Life Input worksheet and delete the row associated with the treatment selected for removal. 5. Open the User Interface worksheet and delete the cells associated with

Modification	Instructions
	the treatment selected for removal. 6. Delete the associated RealCost worksheet. 7. Open the EnvironmentalData worksheet and remove the associated row from all 5 datas. If removing a local treatment delete the associated dedicated table.
Add an Available Treatment ****	1. Open the Distress Data worksheet. a. Insert a column for the new treatment. If it is a full surface treatment, insert it to the left of the Crack Seal treatment in the existing spreadsheet. If it is a localized treatment insert it to the right of the Mastic treatment. b. Add the treatment label in the new column in the row adjacent to existing treatment labels. c. Populate the Distress Data table for each traffic level with selection criteria for availability of the new treatment. For a given distress level “No” indicates that the treatment is not available, and “Yes” indicates that the treatment is available. 2. Open the Distress Evaluation worksheet. a. Insert a column to add the new treatment. The ordering of the treatments in the Distress Evaluation worksheet must match the order in the Distress Data worksheet. b. Drag the cursor to highlight each cell in the column to the left of the inserted column and the new (blank) column. Use CTRL+R to copy the existing formulas to the empty cell. c. For each distress modify the formula to adjust the VLOOKUP function to the appropriate cells in the Distress Data worksheet. Assuming that the new treatment is located in Column I the formula will be modified as follows, changes to the copied formula are highlighted in red. *=IF('Form Control'!$C$3='Form Control'!$A$3,VLOOKUP('Form Control'!$C$14,'Distress Data'!$A$3:$I$6,9,FALSE),VLOOKUP('Form Control'!$C$14,'Distress Data'!$A$21:$I$24,9,FALSE)).* Repeat for all distresses. d. If the column was inserted within the current Distress Evaluation table and not at the end, the column reference in the VLOOKUP function needs to be increased by one for all columns to the right of the inserted column. Otherwise, no further action is needed. In the example code above, this number is the red 9. 3. Open the Constraint Evaluation worksheet. a. Insert the new treatment at the appropriate location in the Constraint Evaluation table. If none of the constraints apply to the new treatment enter the text “Yes” in the cells for each constraint. If constraints apply follow guidance in Table 9 for adding a new constraint.

Modification	Instructions
	b. In the Treatment Available row of the Constraint Evaluation table, copy the formula from the adjacent column to the inserted column. 4. Open the Service Life Input worksheet. a. Insert a row and enter the label for the new treatment in Column A. Maintain consistency in the order of the treatments between this worksheet and all other worksheets (Distress Data, Distress Evaluation, and Constraint Evaluation). Enter the minimum and maximum service life for each existing pavement condition in the appropriate cells. 5. Open the Safety Benefits worksheet. a. Insert the new treatment at the appropriate location. Input minimum and maximum friction numbers for the treatment. b. Drag the formulas from the Average and %Improvement columns to apply to the new treatment. 6. Open the User Interface worksheet. a. Insert rows for the new treatment. Remember to maintain consistency with previous worksheets for the ordering of treatments. The following tables must be modified: i. If it is a localized treatment, add a row of cells to the Localized Treatments table with the appropriate labels. Drag down the summation function in the Total column. ii. On the inputs portion of the sheet add a row for manual entry of price information. iii. On the outputs portion of the sheet add a row to the Feasibility and Monetary Decision Factors table. 1. The Available column evaluates if the treatment is available. Highlight the cell above the inserted row and copy the formula into the new cell. Modify the formula to reference the appropriate columns in the Distress Evaluation and Constraints Evaluation worksheets. The modifications to the copied formula are highlighted in Red. *=IF(OR('Distress Evaluation'!I$7="No",'Constraint Evaluation'!I$9="No"),"No",IF('Constraint Evaluation'!I$9="Engineer Decision","Engineer Decision","Yes")).* 2. Copy formulas for Minimum and Maximum Service Life from the row above into the appropriate cells. The formula is written such that it will update upon copying or filling down from an existing cell that provides minimum or maximum service life. For example, if the new treatment is in row 21, the correct formula is, the cells that change in the formula with location in the spreadsheet are highlighted in red: *=CALC(J21, Lookup(FormControl'!C8,'Service Life Input'!$C$2:$E$2,*

Modification	Instructions
	'Service Life Input'!C13:E13)). iv. Add a row to the Qualitative Decision Factors table. v. Add a row to the Information for Total Project Costs and Benefits table. 7. Open the Supplemental Data worksheet. a. Add a row to the Percent Reduction in Patching Post-Treatment table. Enter values in the Moderate, Poor, and Very Poor. Drag down the formula in the Current Project column or fill down by highlighting the entire column including the new treatment and pressing CTRL-D. b. Add a row to the Research Results for Material Cost of Treatment table. Note that this is a new treatment and the date it was entered when entering the treatment name in the Treatment column. Enter average costs and standard deviations as appropriate. Adding to this table is necessary to maintain usability of the other research results. c. Add a row to the Treatment Productivity Rates table. Enter the appropriate rate. d. Add a row to the Values Selected for Agency Cost Calculations table. Drag down the formulas in the columns or use CTRL-D. 8. Open the EnvironmentalData worksheet. If no data is available this step still needs to be carried out in order to maintain consistency across the workbook. Simply leave cells blank or enter 0 or FALSE. a. Add a row to the Total Environmental Results (Per Square Yard) worksheet. Input values of environmental impacts per sq. yd. in each columns corresponding units. b. Add rows to each of the annualized results tables. Drag the formulas to apply to the new treatment. Formulas reference the Service Life Input worksheet and the Total Environmental Results table. 9. Add a RealCost sheet. a. Right click on an existing RealCost sheet's tab at the bottom of the workbook. Select "Move or Copy…" and place the sheet in the appropriate location based on the order of treatments added so far. Select Create a copy. Find the new sheet and rename it according to the naming convention used for the other RealCost sheets. b. Open the new RealCost sheet. i. Enter the name of the treatment in the top left. ii. In cell B14, modify the part of the formula highlighted in red below to correspond the new treatment's productivity data in Supplemental Data table Treatment Productivity Rates. *=ROUNDUP(('User Interface'!$M$6)/'Supplemental Data'!U10/'Supplemental Data'!$AB$4, 1)*

Modification	Instructions
	10. Return to the User Interface worksheet. a. In the Information for Total Project Costs and Benefits table: i. Apply the formulas for minimum and maximum Agency Cost. For a localized treatment, drag the formulas from another localized treatment. For a global surface treatment drag that appropriate formula to apply. ii. Apply the formula for Agency Benefit in the same way by dragging the corresponding formula or using CTRL-D. iii. Copy a formula from User Cost and paste it into the new treatment's row. Correct the reference so that it points to the new treatment's RealCost sheet. *=CALC(J13,'RealCost-DblChip'!$B$11*1000)* b. In the Qualitative Decision Factors table: i. Drag the formula in the Friction Improvement Affecting Safety column to apply to the new treatment. ii. Drag the formula for each of the environmental impact factors to apply to the new treatment. If environmental data was not added black out the new treatment's environmental factor boxes. c. In the Feasibility and Monetary Decision Factors table: i. In Expected Net Monetary Costs, drag the formula to apply. ii. In Annualized Cost, drag the formula to apply.

Modifying Default Values in Supplemental Data Worksheet

Default values were determined to provide baseline calculations for the following aspects of the selection tool. Details related to the assumptions driving these calculations are available in the Task 4 and 5 reports.

- Agency Cost: Extent of cracking and patching required based on existing pavement condition.
- Agency Benefit: Reduction in patching required with each treatment based on existing pavement condition.
- User Cost: Production rates for treatments.
- Safety Benefit: Improvement in Friction Number associated with each treatment.
- Treatment Environmental Impact: Treatment thickness. Analysis tool used (PALATE) requires all quantities in units of CY.

All of these factors are summarized in clearly labeled data tables in the Supplemental Data worksheet. Administrators have the capability of editing these values to better reflect MnDOT practices or to update cost information with time.

Appendix 1: Tools for Recommending Treatments for Pavements in Poor Condition

This report relates to Task 3: Tools for Recommending Treatments for Pavements in Poor Condition and includes the following deliverables:

- Spreadsheet Tool for recommending treatments for poor pavements based on technical considerations (HMA only).
- User Guide for the Spreadsheet Tool that includes a description of the tool and instructions for modifying existing selection criteria and adding new treatments.

Description of Work

- MnDOT submitted treatments and selection criteria for in-service HMA pavements.
- The information was converted into an Excel-based selection tool through use of lookup tables and if/then statements. There are currently three outputs of the tool.
    - Identification of viable treatments based on traffic level, existing pavement distress, and geometric or access related constraints.
    - Range of anticipated service life based on existing pavement condition.
    - Overall assessment of existing pavement condition.
- The Excel tool is formatted to allow for addition of cost, environmental, and safety information as the project progresses.
- The user only has to view two sheets identified as User Input and Supplemental Data. All other sheets in the workbook are hidden from users as they support look up tables and define selection criteria. Administrators have access to these sheets if a treatment needs to be added or selection criteria changes are necessary.

Table 11: Summary of Treatments Considered

Treatment	Coverage Area
Chip Seal	Surface
Double Chip Seal	
Thin (2") Overlay	
Mill and Thin (2") Overlay	
Micro-surfacing	
Cape Seal	
Ultra-thin Bonded Wearing Coat (UTBWC)	
Crack Seal	Localized
Mastic	

Both full surface and localized treatments are considered in the selection tool. If existing pavement condition and distress warrant use of a localized treatment, it is at the discretion of the engineer if a localized treatment is the most viable alternative. Future task reports will add agency/user cost, safety benefits, and environmental impacts to the spreadsheet tool to provide supporting information for the engineer to use in the decision-making process.

Summary of Inputs

- Traffic Level (2): <10,000 AADT or >10,000 AADT.
- Distresses Considered (4): Rutting, Cracking, Raveling, Roughness.
- Distress Levels Considered (4): None, Low, Medium, High.
- Additional Constraints (4): Curb and Gutter, Maintain Ditch Slope, Variable Pavement Widths, ADA Requirements (urban area, signalized area with Ped Xing, can add much cost).
- Constraint Classifications (2): Not Applicable (N/A), Present.

Summary of Outputs

- Available treatments based on levels of distress in the existing pavement and any applicable constraints.
- Overall existing pavement condition: Determined based on distress levels using the criteria provided in Table 12.
- Maximum and minimum expected treatment life based on existing pavement condition.

Definition of Existing Pavement Condition based on Distress Severity

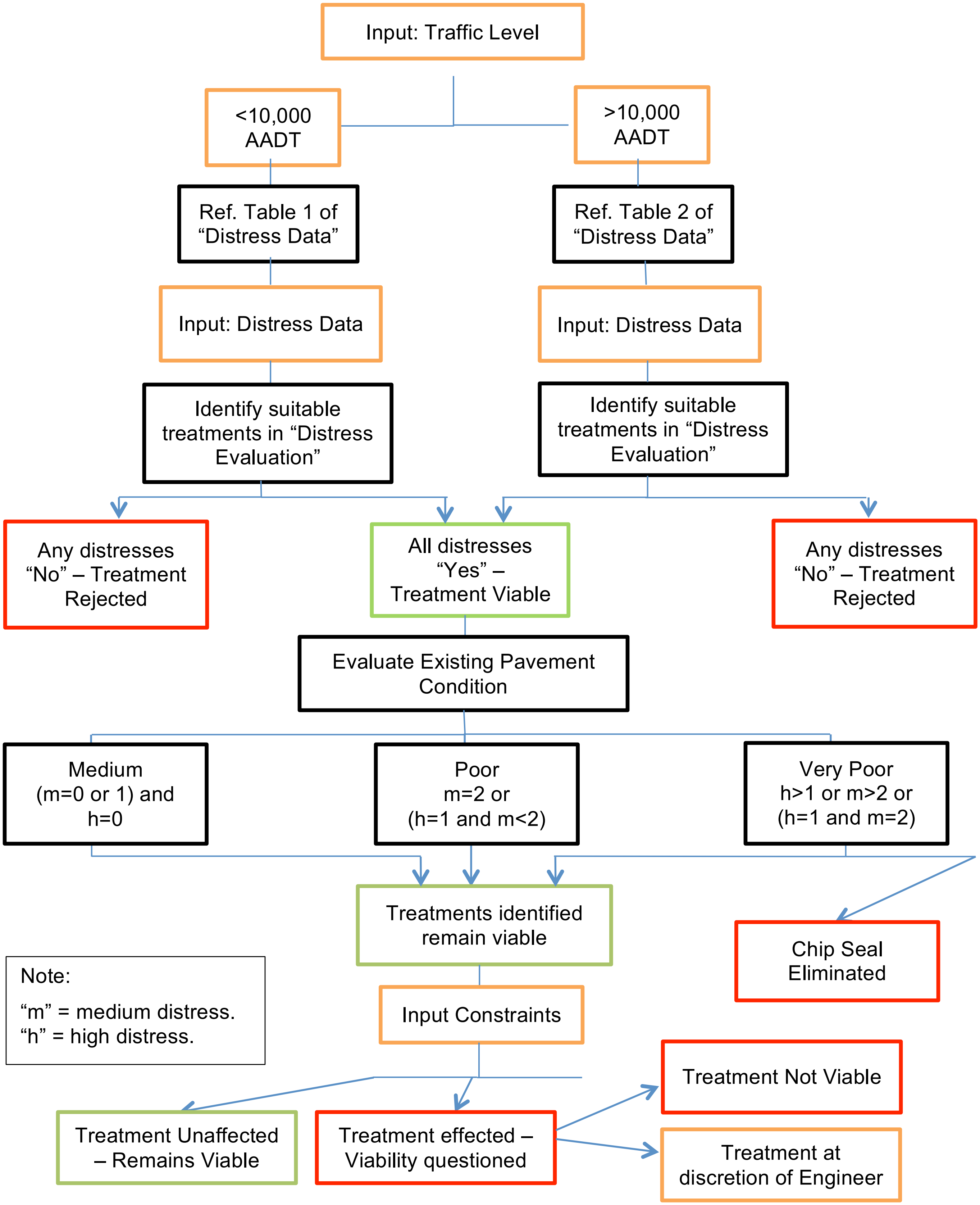
A relationship was established between the overall condition of the existing pavement and the severity of the distresses observed. Three general rules were established to define existing pavement condition:

1. **Moderate Condition:** All distress severities designated as “none” or “low.” Also a maximum of one occurrence for moderate distress severity is allowed.
2. **Poor Condition:** At least two distress severities classified as “medium” or one classified as “high.” If three distresses are classified as “medium” existing pavement condition is downgraded to “very poor.”
3. **Very Poor Condition:** Three or more distress severities designated “medium” or two or more distresses classified as “high.”

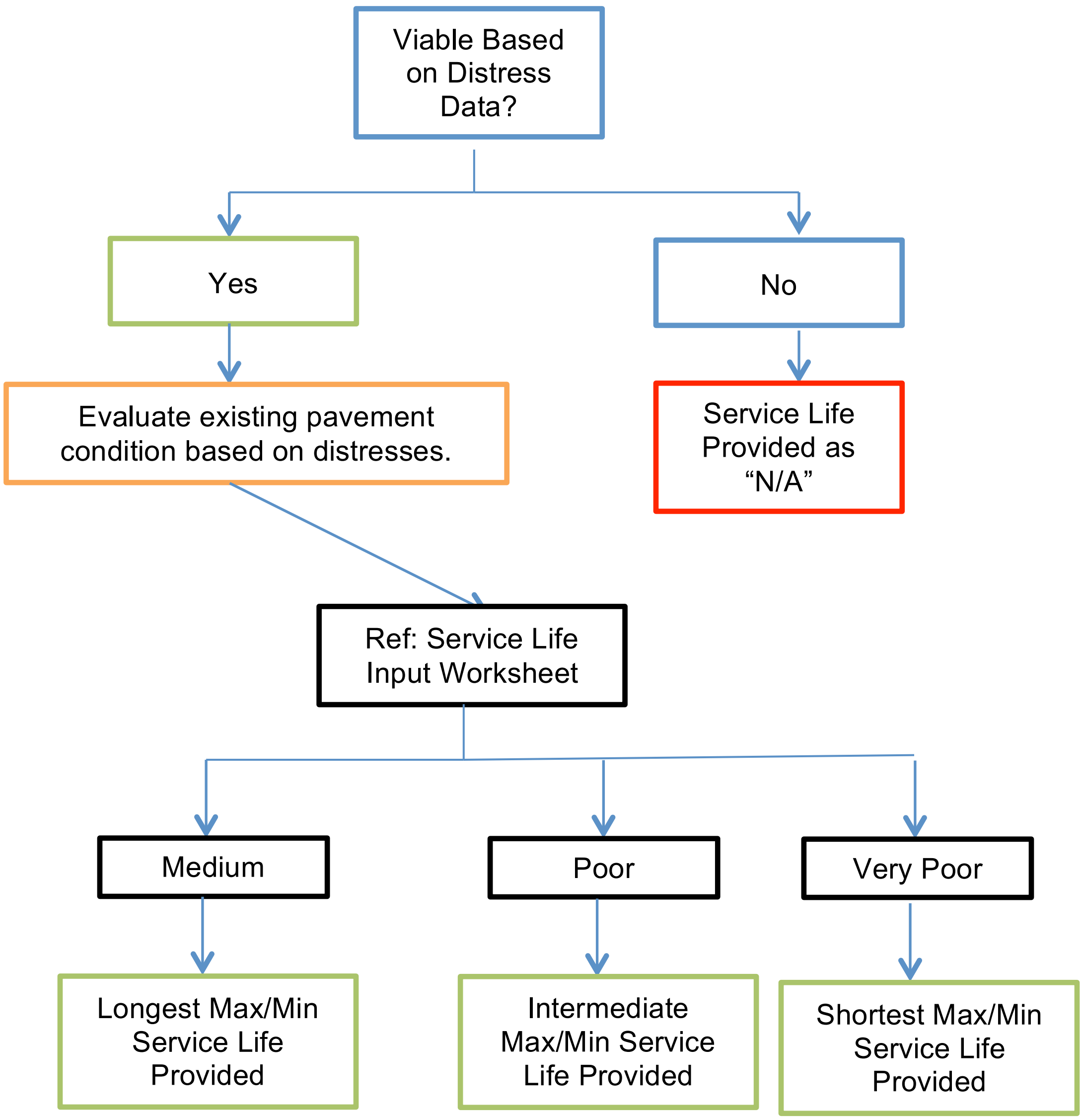
Table 12: Summary of Criteria used for Defining Existing Pavement Condition based on Distress Severity

Occurrence of Medium Severity	Occurrence of High Severity				
	0	1	2	3	4
0	Moderate	Poor	Very Poor	Very Poor	Very Poor
1	Moderate	Poor	Very Poor	Very Poor	
2	Poor	Very Poor	Very Poor		
3	Very Poor	Very Poor			
4	Very Poor				

Summary of Identification of Viable Surface Treatments



Summary of Definition of Service Life for Viable Treatments



Appendix 2: Procedure for Assessing Treatment Cost-Effectiveness

The Minnesota Department of Transportation (MnDOT) provided a list of stopgap treatments for consideration as well as extensive information regarding the costs of the materials used for these treatments. The researchers have analyzed this cost data to determine the average cost for different treatment alternatives. Material costs from several sources were adjusted to a common format in order to make comparisons across treatments and years. Once unit costs of each treatment are determined, total project cost can be calculated based on project characteristics. Total project costs must be converted to equivalent annualized costs to the agency, because alternatives have different service lives.

Analysis Steps

Agency costs of construction will be the largest component of the cost-effectiveness analysis. Agency benefits result from reduced spending on localized maintenance during the service life of the treatment. The researchers use a module of FHWA's RealCost lifecycle cost analysis tool to calculate user costs during treatment. This memo discusses four analysis steps.

- Step 1: Estimate material costs per square yard.
- Step 2: Compare annualized costs across treatments.
- Step 3: Predict local maintenance savings from treatment.
- Step 4: Use RealCost to estimate construction costs to users.

Step 1: Estimate Material Costs Per Square Yard

MnDOT requested that seven surface treatments be considered as appropriate stopgap measures for use on asphalt surfaces (see Table 13). The researchers received four years of materials cost data for these treatments. The final tool will also consider two localized treatments, however materials cost analysis was not possible for those treatments based on information provided by MnDOT.

Table 13. Treatments Considered

Chip Seal
Double Chip Seal
2" Overlay
Mill and 2" Overlay
Micro-Surfacing
CapeSeal
Ultrathin Bonded Wearing Course
Crack Sealing (Localized)*
Mastic Patching (Localized)*

*Detailed cost data unavailable–agency cost estimate based on average costs provided by MnDOT.

Cost data for Minnesota material purchases was available to the researchers in three forms. The first two years of data, 2010 and 2011, described the successful bids on a project-by-project basis with details regarding location, project type, and project dates. Data for 2012 was in an aggregated form with average costs of material purchases for that year. This data did not provide information as to when or where a project was carried out or if the purchase of seal coat aggregate was used for a single chip seal or for a CapeSeal, etc. In 2013, several bids were available for each of a number of unspecified projects. Table 14 shows the general breakdown of the distribution of sample data from each source that was analyzed. More specific cost estimates can be extracted from the asphalt and chip seal data because of the larger sample size. Data from 2012 and 2013 was essential to a more robust analysis of costs.

Table 14. Sample Spaces

Treatment	Total Data Points	Projects greater than 1 mi	2010–2011	2012–2013
Overlay (Asphalt Purchases)	515	449	260	189 (All in 2012)
Chip Seal Materials	56 (Seal Coat) 60 (Aggregate) 81 (Fog Seal)	51 53 (47+6 outliers) 70	8 7 17	43 46(40) 53
Micro-Surfacing & CapeSeal	14	14	6	8
UTBWC	16	16	5	11

For each material, the researchers excluded samples in which the quantity purchased appeared to be for a project smaller than a single lane-mile. Many of these projects had much higher prices than the larger projects and were not considered to fall under the type of stopgap treatments considered in this study. When considering cost drivers for different materials, additional samples were dropped if their quantities were significantly larger than the other data or the price was extremely far from the average. Including these outliers had caused significant distortion of some price trends.

For asphalt purchases, the researchers were able to analyze driving factors of price. Analysis was carried out on other materials, but small sample sizes for those materials make accurate prediction impossible. Major findings for asphalt were that price varies with quantity but location by region does not have significant effect. Analysis of other variables was limited because 2012 data needed to be included due to the large number of data points but its lack of detail limited options for analysis. Numerous incomplete or non-specific entries for 2010 and 2011 also limited the available parameters for analysis. In order to account for a non-linearity in the relationship between asphalt quantity and price, data was divided into two groups based on quantity. These estimates were much more consistent and help to capture a difference in variability as well as slope. The relationships in Table 15 will be used in the final tool to provide more accurate estimated costs of overlay treatments.

Table 15. Asphalt Price-Quantity Relationship

Asphalt Quantity Group	Quantity-Sensitive Estimation
Less than 15,000 tons	\$66.26 base – \$0.00109 per ton (R^2=.23)
More than 15,000 tons	\$56.71 base – \$0.000159 per ton (R^2=.23)

Table 16 provides the best-cost averages for each material using the four years of data provided. All materials have been standardized from their purchase quantity units to square yards. This makes it easier to compare material costs and to construct treatments from their component materials in Step 2 of the analysis. Standard deviations for the data provide by MnDOT are also calculated and displayed in Table 16. These will be used in the final tool to include cost uncertainty by estimating potential high and low costs for each treatment type. Given that crack sealing and mastic patching are localized treatments, agency cost was scaled based on existing pavement condition. These assumptions are provided in Table 16. For calculation of crack lengths the length of one road station was assumed to be 100 feet and the length of each crack 6 feet.

Table 16. Summary of Localized Treatment Required based on Existing Pavement Condition

Existing Pavement Condition	Average Cracks/Road Station	Max. %Pavement Total Areas Requiring Mastic Patching
Moderate	3	5
Poor	6	10
Very Poor	10	15

Table 17. Price Estimates and Variability

Material	Average Price (per sq yd)	Standard Deviation
2” Overlay (Small)	\$6.64	\$1.21
2” Overlay (Large)	\$5.84	\$0.97
Fog Seal	\$0.35	\$0.16
Seal Coat Liquid	\$0.90	\$0.34
Seal Coat Aggregate	\$0.60	\$0.23
MicroSurface – Bituminous Material	\$1.57	\$0.14
MicroSurface – Scratch Course	\$0.72	\$0.22
Microsurface – Surface Course	\$0.72	\$0.22
UTBWC	\$4.95	\$0.71

Step 2. Compare Annualized Costs Across Treatments

The values in Table 17 represent the costs of each of the treatments for which MnDOT has requested analysis. The materials in Table 18 are summed together in Table 17 to provide treatment level analysis rather than material level. Treatment costs do not include non-material expenses such as traffic control, striping, etc. Analysis results show a variety of average costs across treatments, from an average price of $7.51 per square yard for a project involving a 2-inch mill and overlay to $1.85 per square yard for a single chip seal.

Table 18: Treatment Costs Per Square Yard

Treatment	Average Cost	Standard Deviation
2” Overlay (Small)	$6.64	$1.21
2” Overlay (Large)	$5.84	$0.97
2” Mill and Overlay (Small)	$7.51	$1.21
2” Mill and Overlay (Large)	$6.71	$0.97
Chip Seal	$1.85	$0.44
Double Chip Seal	$2.90	$0.55
MicroSurface	$3.01	$0.34
CapeSeal	$4.50	$0.53
UTBWC	$4.95	$0.71
Crack Seal (LF)	$1.36	N/A
Mastic Patching	$4.00	N/A

In addition to significant variation in the costs of treatments, there are differences in service life depending on treatment choice and initial road condition. These range from a one-year service life for chip sealing a surface in poor condition to a seven-year service life for both 2-inch mill and overlay and UTBWC treatments on a moderate condition roadway. To account for this variable service life, project costs will be annualized and reported in equivalent annual costs once they are determined in the selection tool.

Equation 1 describes the formula for calculating the equivalent annual agency cost of a treatment. The final tool will utilize the discount rate suggested by MnDOT but provide the ability to modify this factor. Using the average service life and average treatment cost an equivalent annual benefit will be reported. The tool will also report possible high and low costs, which could occur in the case of higher, lower prices. This memo does not provide annualize costs of treatment because of the numerous factors that will affect the tool’s final calculation.

Equation 1: Equivalent Annual Cost

$$Equivalent\ Annual\ Cost\ (\$) = Initial\ Cost * \frac{d * (1+d)^n}{(1+d)^n - 1}$$

Where
d = the discount rate
n = the expected service life of the treatment in years

Step 3. Predict Local Maintenance Savings from Treatments

Local maintenance savings was identified as the major monetized benefit from treatment. Facilities proposed for treatment projects supported by this tool are assumed to be in a condition such that regular localized maintenance is necessary. Stopgap treatment will partially reduce those current maintenance expenditures over the life of the project. For a given facility, savings should be equal to the percentage reduction in maintenance times the cost of maintenance per square yard times the surface area of the project adjusted for the portion of that area that needs annual treatment.

$$\%Reduction \; X \; PatchingCost \; X \; \%RequiringPatching \; X \; ProjectArea$$

This model represents the researcher's best representation of the conceptualization for agency benefits that they discussed with MnDOT. Accurate values for several of these factors will need to be updated by MnDOT when the information is available. The current values used by each treatment for this analysis are summarized in Table 19.

Table 19: Assumed Reduction in Patching for Each Treatment Based on Existing Pavement Condition

Percent Reduction in Patching Post-Treatment			
Treatment	**Moderate**	**Poor**	**Very Poor**
Chip Seal	25%	50%	N/A
Double Chip Seal	20%	30%	50%
2" Overlay	20%	30%	30%
2" Mill and Overlay	20%	25%	30%
MicroSurface	25%	40%	50%
CapeSeal	20%	30%	40%
UTBWC	20%	25%	30%
Crack Seal	20%	30%	50%
Mastic	20%	25%	30%

Step 4. Use RealCost to Estimate Construction Costs to Users

In addition to agency costs and benefits, this project asks us to account for user costs and benefits of proposed projects. After discussion with MnDOT, it was determined that marginal user benefits between different treatments would be difficult to quantify, because most treatments would provide comparable benefits in both psychological and ride quality aspects. The most important quantifiable user impact identified by MnDOT and the researchers therefore is the cost to users of construction.

The researchers utilize FHWA's life cycle cost analysis tool, RealCost, to estimate user costs. RealCost is designed for exploring the long-term costs of different alternatives for maintenance and rehabilitation efforts of the life of major construction or reconstruction projects. It also provides a well-developed methodology for estimating user costs due to increases in travel time through construction zones and potential delays from increased congestion. For the purpose of creating a final tool, utilizing RealCost has significant benefits over recreating a methodology for the calculation of user costs of construction.

The final tool incorporates RealCost as seamlessly as possible, without major changes to the originally developed tool. As a result the spreadsheet tool has the capability of evaluating, treatment selection, agency costs/benefits, user costs, and other qualitative evaluation parameters using one Excel workbook. A significant factor related to user cost is the time required for construction, this is a function of project geometry and production rate of the various treatments. A literature review was conducted to obtain an initial estimate of the production rates associate with each treatment. Results of this review and the source of information are summarized in Table 20. For integration of production rates into the RealCost framework all rates for surface treatments were converted to units of SY/hr.

Table 20: Summary of Assumed Treatment Production Rates for User Cost Calculations

Treatment	Unit	Production Rate	Reference/Justification
Chip Seal	SY/hr	1760	MnDOT (2005)
Double Chip Seal	SY/hr	880	MnDOT (2005) – Rate was defined as 50% of single chip seal.
Thin (2") OL	SY/hr	3333	MnDOT (2005)
Thin (2") Mill and OL	SY/hr	1875	MnDOT (2005) – Assumed production rate of milling was limiting factor
Micro-Surfacing	SY/hr	2580	MnDOT (2005) – Assumed thickness of 3/8" for unit conversion
Cape Seal	SY/hr	1760	Assumed that chip seal production rate would be limiting factor.
UTBWC	SY/hr	2450	CALTRANS (2008)
Crack Seal	LF/hr	2125	MnDOT (2005)
Mastic	SY/hr	130	MnDOT (2011) – Assumed 10% of pavement area required patching.

Annual Safety Benefits

Safety benefits were evaluated qualitatively based on an assumed value of Friction Number for in-service pavements and published values of Friction Number after placement of the treatments considered by the selection tool. Friction Number minimum threshold values for existing pavements range from 30 to 35 for low and high traffic volume roads respectively (Jayawickrama et al., 2000). Given that the analysis tool was developed for pavements in need of rehabilitation a constant Friction Number threshold of 30 was assigned as a default value. A manual over-ride option was included in the spreadsheet tool to allow administrators to add Friction Number Thresholds related to existing pavement condition.

A literature review was conducted to define the maximum and minimum friction numbers associated with each treatment. This analysis was only applied to full surface treatments, localized treatments (i.e. crack sealing and mastic patching) were not considered. Values and associated references are provided in Table 21.

Table 21: Friction Numbers for Full Surface Treatment Alternatives

Treatment	Minimum	Maximum	Average	Safety Benefit	Reference/Justification
Chip Seal	50	70	60	100%	Li *et al.* (2012)
Double Chip Seal	57	68	62.5	108%	Russell *et al.* (2011)
Thin (2") OL	40	60	50	67%	Clyne. (2012)
Thin (2") Mill and OL	40	60	50	67%	Assumed same values as Thin 2" OL
Micro-Surfacing	28	57	42.5	42%	Li *et al.* (2012)
Cape Seal	28	57	42.5	42%	Assumed same values as micro-surfacing
UTBWC	50	60	55	83%	Clyne. (2012)
Crack Seal	0	0	0	Not Considered	
Mastic	0	0	0		

The safety benefit was calculated based on the average increase in Friction Number of new treatments applied relative to an existing pavement Friction Number of 30. The calculation is provided in Equation 2, where $FN_{Treatment}$ and $FN_{Existing}$ correspond to the Friction Number of the treatment and existing pavement respectively.

Equation 2: Safety Benefit

$$\text{Safety Benefit} = \frac{FN_{Treatment} - FN_{Existing}}{FN_{Existing}}$$

Summary and Conclusion

Cost-effectiveness analysis carried out by this study encompasses three main monetized factors: agency costs, agency benefits and user costs. Costs and benefits will be reported in equivalent annual values to accommodate variable service lives across projects. High and low estimates will also be included to provide consideration of the uncertainty of costs across projects. Qualitative safety benefits were assessed based on an assumed Friction Number of the existing pavement and published values for the various treatments considered in this study. The three-parameter cost analysis methodology and qualitative assessment of safety impacts will be applied to the final tool delivered at Task 6 of this project in order to help decision-makers select cost-effective treatments to best utilize the maintenance budget of MnDOT.

Appendix 3: Environmental Impacts Parameters

In 2011, MnDOT began an investigation of developing a comprehensive method for evaluating treatment options for to serve as a stopgap treatment in extending the service life of pavements in poor condition until they can be rehabilitated. To promote use amongst pavement engineers the project was tasked with integrating this methodology into a spreadsheet-based decision tool with two components 1) Identification of available treatments and definition of expected service life based on existing pavement distress levels and operational characteristics, 2) Summarize selection factors. Factors considered in the analysis include: agency cost, agency benefit, user costs during construction, safety benefits, and environmental impacts. To normalize results based on varying service life all factors were annualized. The Recycled Materials Resource Center (RMRC) was tasked with analyzing the environmental impacts of the treatments.

Treatment Options

The considered treatments address initial roadway condition and incorporate both new and recycled materials. All volumes of treatment materials were calculated per lane-mile and corresponding thicknesses. In practice many of the treatments are specified on an area basis (i.e. SY), however the PaLATE requires volumes to perform environmental impacts analysis. The treatments used, their component materials, and the assumed thicknesses are provided in Table 22.The quantities of material were provided my MnDOT, and the research team assumed thicknesses. Details related to each treatment and thecalculations used to convert the materials quantities into CY of treatment are provided in subsequent sections. In the conversion from SY to CY all component materials provided by MnDOT were maintained. Assumed thicknesses can be adjusted in the Supplemental Data worksheet of the spreadsheet tool, the environmental impacts will be automatically scaled accordingly.

Table 22. List of Treatments with their Corresponding Type and Thickness

Treatment	Type	Thickness (in)	Components
Chip Seal	Surface	0.5”	• 0.30 gal of chip seal emulsion (CRS-2P) • 0.14 gal. of fog seal emulsion (CSS-1h) • 1 SY of aggregate seal coat material
Double Chip Seal	Surface	1”	• 0.45 gal of chip seal emulsion (CRS-2P) • 0.14 gal. of fog seal emulsion (CSS-1h) • 2 SY of aggregate seal coat material
Micro-surfacing	Surface	1”	• 0.50 gal of micro-surfacing emulsion (CSS-1h) • 0.0075 tons of scratch coarse (aggregate) • 0.0075 tons of micro-surfacing wearing course (aggregate)

Treatment	Type	Thickness (in)	Components
CapeSeal	Surface	1.5”	• 0.30 gal of chip seal emulsion (CRS-2P) • 1 SY of aggregate seal coat material • 0.50 gal of micro-surfacing emulsion (CSS-1h) • 0.0075 tons of scratch coarse (aggregate) • 0.0075 tons of micro-surfacing wearing course (aggregate)
UltraThin Bonded Wear Course	Surface	1”	• 0.23 gal. of polymer modified tack coat (CSS-1HP) • 0.038 tons of HMA, 5.5% PMA and 94.5% crushed aggregate
2” HMA Overlay	Surface	2”	• 0.114 tons of HMA, 5.5% asphalt binder, 94.5% aggregate (90% crushed, 10% nat. sand)
Mill & 2” HMA Overlay	Surface	2”	• 1 SY of milling 2” depth • 0.114 tons of HMA, 5.5% asphalt binder, 94.5% aggregate (90% crushed, 10% nat. sand)
Mastic for Patching	Localized	3” (moderate), 6” (severe)	• 93.6 lbs of mastic, 7% asphalt binder, 93% fine aggregate • 0.30 gal of chip seal emulsion (CRS-2P) • 1 SY of seal coat aggregate
Crack Sealing	Localized	1”	• 1 SY of aggregate (filler) • 10% asphalt by volume

Environmental Impacts Analysis Using PaLATE

The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a spreadsheet LCA program designed by the Consortium on Green Design and Manufacturing from the University of California, Berkeley. PaLATE assesses the environmental and economic effects of pavement and road construction. Users input the initial design, initial construction, maintenance, equipment use, and cost for a roadway. Environmental outputs include (Consortium on Green Design and Manufacturing, 2007):

- Energy consumption (GJ)
- Water consumption (kg)
- CO_2 emissions (kg)
- NO_x emissions (kg)
- PM_{10} emissions (kg)

- SO_2 emissions (kg)
- CO emissions (kg)
- Leachate information (including mercury, lead, Resource Conservation and Recovery Act (RCRA) hazardous waste generated, and both cancerous and non-cancerous human toxicity potential, or HTP)[1]

Four environmental factors for impacts analysis: energy, water consumption, CO_2 emissions, and RCRA hazardous waste were deemed sufficient for evaluation of MnDOT maintenance strategies. Neither mercury nor lead results were included in this analysis as their outputs for treatments considered were negligible.

RCRA Hazardous Waste

The Resource Conservation and Recovery Act (RCRA) is a US law that provides general guidelines for a federal waste management program. Enacted by Congress in 1976 and carried out by the US Environmental Protection Agency's (EPA) Office of Solid Waste (OSW), RCRA aims to protect human health and the environment from a diversity of hazardous and nonhazardous wastes. It includes a Congressional mandate direction the EPA to develop a comprehensive set of regulations to implement the law. Hazardous waste, as defined by the EPA, is "a waste with properties that make it dangerous or potentially harmful to human health or the environment" (U.S. EPA, 2012). RCRA hazardous waste falls into two categories: listed wastes and characteristic wastes. Listed wastes include non-specific source wastes, source-specific wastes, and discarded commercial chemical products. Characteristics wastes exhibit one ignitability, corrosively, reactivity, and/or toxicity. The consideration of RCRA in PaLATE demonstrates the advantages of including regulated substances in assessments (Consortium on Green Design and Manufacturing, 2007).

Assumptions

The assumptions made to make the provided treatment information compatible with the PaLATE database are provided below.

1) PaLATE requires volumes of materials in cubic yards as the input, while the treatment materials were provided for one square yard roadway. Therefore, volumes were converted from their initial units (i.e. gallons or square yards) to square yards (SY), and then multiplied by the thicknesses in Table 22.
2) For uniformity, the environmental results were calculated per lane-mile. The provided SY-amount of material was multiplied to represent that quantity of material required for an area of one mile by one lane by the treatment's appropriate thickness (Table 22). One lane was assumed to be 12 feet.
3) For localized treatments (mastic patching and crack sealing), the extent of patching or crack sealing required was scaled based on existing pavement condition. For mastic patching percent total pavement are values were assumed, the quantity of mastic patching in CY was then calculated based on a patch depth of 3 inches. The quantity of crack sealing was based on the presence of both longitudinal and transverse cracks. The number of six-foot cracks per roadway station was adjusted based on existing pavement condition as shown. Each crack was considered to be 0.5" wide and 1.0"

deep. These dimensions were used to calculate the volume of crack sealant required for PaLATE analysis.

Table 23. Dimensions and Frequencies Used to Calculate the Volume of Localized Treatments in One mile of Roadway

Mastic Patching	
Existing Pavement Condition	**Percent Total Area**
Moderate	5%
Poor	10%
Very Poor	15%

Crack Sealing		
Existing Pavement Condition	**Cracks Per Road Station (100')**	**Length of Cracks Per Road Station (ft)**
Moderate	3	18
Poor	6	36
Very Poor	10	60

4) Environmental impacts from water as a material are not considered in the PaLATE analysis. Only the percent asphalt of the bituminous material in each layer was analyzed. The remainder of the bituminous volume (i.e., the water) was ignored. This allowed for differentiation of the bituminous material used in the treatments. Bituminous material with a higher percentage of asphalt has a greater environmental effect then those with a smaller percentage.

5) Some of the materials were provided as weight as opposed to volume quantities. These materials include asphalt binder (bitumen), virgin aggregate, cement, and sand. PaLATE provides average tons-to-CY unit weights for bitumen, aggregate, and cement. These were used to convert tons of bitumen, aggregate, and cement to cubic yards. The HMA Overlay treatment options used natural sand. For this analysis, a unit weight of 1.35 tons/CY for damp, unconsolidated sand was used [2].

6) The polymer coat solids in the UltraThin Bonded Wearing Course were ignored. PaLATE does not have a parameter for this type of material. Since such small amounts were used, it was determined that the solids could be ignored without affecting the analysis.

Approach

PaLATE inputs materials quantities and outputs environmental impacts. In this analysis, only environmental impacts from the material initial processing are considered. Construction methods, maintenance, and transportation effects are not analyzed. The environmental outputs of each individual material in each layer are calculated. Asphalts from different portions of one treatment are kept analyzed separately. Results of each step in the calculation are shown in Table 26. The analysis procedure is as follows:

1. Calculate the percent volume of asphalt in each bituminous layer (in gal).
2. Convert all surface material SY areas to CY volumes based on the thicknesses in Table 22.
3. Multiply the surface material CY volume to the appropriate volume for one lane-mile.
4. Calculate the volume of localized treatment materials per one-lane mile from quantities in Table 23.
5. Enter each material into PaLATE spreadsheet's Initial Cost page.
6. Gather each material's environmental output from Environmental Results page.
7. Sum the total environmental outputs from each material in each treatment layer.
8. Divide the total environmental outputs by the service life of each treatment as stipulated in Table 25.

Results and Recommendations

The results were analyzed by a few different methods. The environmental treatments for each treatment were analyzed separately, then comparatively. To compare environmental outputs of different units, the results were expressed as a percentage of a base treatment, in this instance chip seal. Finally, the results were annualized to account for differences in service life between treatments. Based on the selection criteria provided, treatment service lives were dependent on the type of treatment and the overall condition of the existing pavement. These annualized outputs will be used to quantify environmental impacts in the MnDOT spreadsheet tool.

Overall Results

The results of the analysis are summarized in Table 24 and the normalized results relative to the environmental impacts of chip seal are given in Figure 1. In general, the extent of environmental impact is proportional to the amount of material required for a given treatment.

The localized treatments required far less material, thus had far less environmental impacts. The mill and HMA layers required the most material, thus had the greatest environmental impacts.

Table 24. Total Environmental Results for Each Treatment—Non-annualized

Total Environmental Results					
Type	Treatment	Energy (GJ)	Water consumption (kg)	CO2 (kg)	RCRA Hazardous Waste Generated (kg)
Surface	Chip Seal	169.2	61.6	10,077.0	2,446.6
Surface	Double Chip Seal	326.3	99.3	20,416.8	3,564.3
Surface	Microsurfacing	183.9	73.5	10,733.4	2,917.6
Surface	Cape Seal	397.5	134.9	24,278.4	5,037.9
Surface	UltraThin	414.9	163.2	24,105.7	6,722.3
Surface	2 in HMA Overlay	1,036.7	405.7	60,343.4	16,674.3
Surface	Mill & 2 in HMA Overlay	1,044.3	405.7	62,422.8	16,728.8
Local	Crack Sealing	0.2	0.1	9.4	2.4

Total Environmental Results					
Type	Treatment	Energy (GJ)	Water consumption (kg)	CO2 (kg)	RCRA Hazardous Waste Generated (kg)
Local	Mastic - Moderate	1.2	0.4	70.8	14.7
Local	Mastic - Severe	2.3	0.8	141.7	29.5

Because the results are a variety of units, the treatments were compared to a base treatment, which was defined as chip seal for this analysis. The results of the comparison are shows in Figure 1. Most of the surface treatments have greater environmental output then chip seal, with micro-surfacing providing the most similar environmental impact. The environmental outputs for the HMA and mill & HMA are far greater then any other treatment. Crack sealing and both levels of mastic have a significantly lower environmental output then the base case. Both localized treatments also have very similar results.

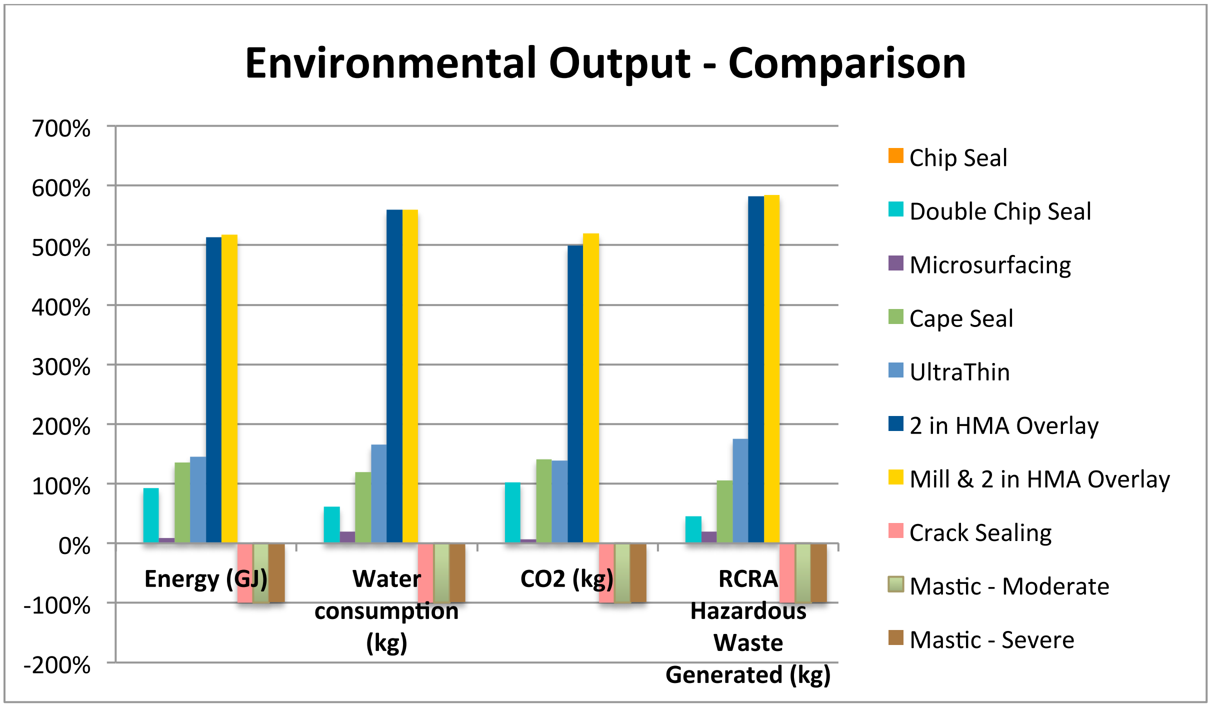


Figure 1. Environmental outputs compared to a base case, chip seal. Each treatment's results were calculated as a percentage of the base case

Individual Environmental Results

The individual environmental results are shown in Figure 2 as radar plots. These plots allow for evaluation of the relative severity of the various environmental impacts considered for each treatment. The individual results are compared in each treatment. The following section discusses comparisons of each individual environmental output.

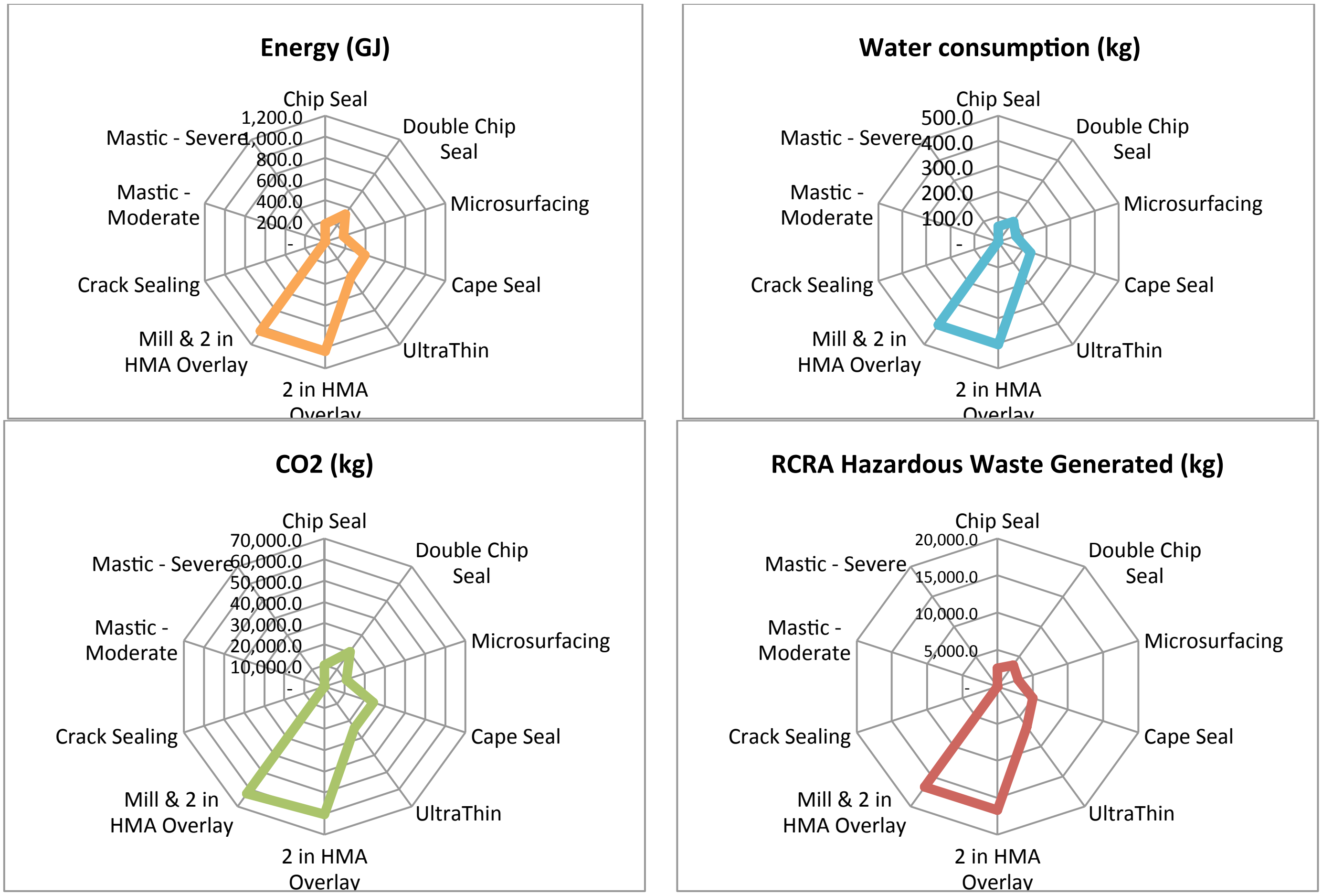


Figure 2. Radar Plot of each treatment results per environmental output

Energy – The least amount of energy is consumed by the localized treatments, and compared to the other treatments, approaches zero. Of the surface treatments, the chip seal and micro-surfacing have the lowest energy consumption. The mill and HMA and HMA layers have significantly larger overall energy consumption.

Water consumption – Water requirements follow a similar trend as energy requirements. The localized treatments' water consumption is next to nothing compared to the other treatments. There is less of a gap between the lowest water consumption surface treatments (again chip seal and micro-surfacing), and the highest water consumption surface treatments (again mill and HMA and HMA).

CO_2 – Carbon dioxide emissions follow a similar trend as energy and water consumptions, with localized treatments emitting comparatively insignificant, chip seal and micro-surfacing the lowest emitting surface treatment, and mill and HMA and HMA the highest emitting surface treatment. In these results, there is a greater difference in the double chip seal versus and the cape seal versus the other low-emitting surface treatments.

RCRA Hazardous Waste – The hazardous waste generation trend is also similar to the above three environmental results. However, unlike CO_2 emissions, there is less of a difference between the double chip and cape seal as compared to the low-generating chip and micro-surfacing treatments.

Additional insights are provided in terms of annualized environmental impacts based on service life in Table 25.

Table 25. Annualized Environmental Results per Treatment per Pavement Initial Condition

Annualized Environmental Results - Energy (GJ)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	42.3	169.2	n/a	33.8	84.6	n/a
Surface	Double Chip Seal	65.3	108.8	326.3	54.4	81.6	163.2
Surface	Microsurfacing	46.0	92.0	183.9	36.8	61.3	92.0
Surface	Cape Seal	79.5	132.5	198.8	66.3	99.4	132.5
Surface	UltraThin	69.1	103.7	138.3	59.3	83.0	103.7
Surface	2 in HMA Overlay	207.3	345.6	345.6	172.8	259.2	259.2
Surface	Mill & 2 in HMA Overlay	174.0	261.1	348.1	149.2	208.9	261.1
Local	Crack Sealing	0.03	0.05	0.16	0.03	0.04	0.08
Local	Mastic	0.19	0.29	0.77	0.17	0.23	0.58

Annualized Environmental Results - Water Consumption (kg)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	15.4	61.6	n/a	12.3	30.8	n/a
Surface	Double Chip Seal	19.9	33.1	99.3	16.5	24.8	49.6
Surface	Microsurfacing	18.4	36.7	73.5	14.7	24.5	36.7
Surface	Cape Seal	27.0	45.0	67.4	22.5	33.7	45.0
Surface	UltraThin	27.2	40.8	54.4	23.3	32.6	40.8
Surface	2 in HMA Overlay	81.1	135.2	135.2	67.6	101.4	101.4
Surface	Mill & 2 in HMA Overlay	67.6	101.4	135.2	58.0	81.1	101.4
Local	Crack Sealing	0.01	0.02	0.06	0.01	0.01	0.03
Local	Mastic	0.06	0.10	0.26	0.06	0.08	0.19

Annualized Environmental Results - CO_2 (kg)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	2519.3	10077.0	n/a	2015.4	5038.5	n/a
Surface	Double Chip Seal	4083.4	6805.6	20416.8	3402.8	5104.2	10208.4
Surface	Microsurfacing	2683.3	5366.7	10733.4	2146.7	3577.8	5366.7
Surface	Cape Seal	4855.7	8092.8	12139.2	4046.4	6069.6	8092.8
Surface	UltraThin	4017.6	6026.4	8035.2	3443.7	4821.1	6026.4
Surface	2 in HMA Overlay	12068.7	20114.5	20114.5	10057.2	15085.8	15085.8
Surface	Mill & 2 in HMA Overlay	10403.8	15605.7	20807.6	8917.5	12484.6	15605.7
Local	Crack Sealing	1.88	3.13	9.40	1.57	2.35	4.70
Local	Mastic	11.80	17.70	47.23	10.11	14.16	35.42

Annualized Environmental Results - RCRA Hazardous Waste (kg)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	611.7	2,446.6	n/a	489.3	1,223.3	n/a
Surface	Double Chip Seal	712.9	1,188.1	3,564.3	594.1	891.1	1,782.2
Surface	Microsurfacing	729.4	1,458.8	2,917.6	583.5	972.5	1,458.8
Surface	Cape Seal	1,007.6	1,679.3	2,518.9	839.6	1,259.5	1,679.3
Surface	UltraThin	1,120.4	1,680.6	2,240.8	960.3	1,344.5	1,680.6
Surface	2 in HMA Overlay	3,334.9	5,558.1	5,558.1	2,779.1	4,168.6	4,168.6
Surface	Mill & 2 in HMA Overlay	2,788.1	4,182.2	5,576.3	2,389.8	3,345.8	4,182.2
Local	Crack Sealing	0.47	0.79	2.37	0.39	0.59	1.18
Local	Mastic	2.45	3.68	9.83	2.10	2.94	7.37

Initial Treatment Quantities and Service Life Range

Table 26. Service life per treatment per initial roadway condition

Service Life							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	4	1	n/a	5	2	n/a
Surface	Double Chip Seal	5	3	1	6	4	2
Surface	Microsurfacing	4	2	1	5	3	2
Surface	Cape Seal	5	3	2	6	4	3
Surface	UltraThin	6	4	3	7	5	4
Surface	2 in HMA Overlay	5	3	3	6	4	4
Surface	Mill & 2 in HMA Overlay	6	4	3	7	5	4
Local	Crack Sealing	5	3	1	6	4	2
Local	Mastic	6	4	3	7	5	4

Chip Seal

0.3 gallons of bituminous material for seal coat (emulsion CRS-2P[2])
0.14 gallons of bituminous material for a fog seal (emulsion CSS-1h[3])
*Fog seal is diluted with water at 1:1 ratio with water, minimum asphalt residue content of 28%
1 square yard of aggregate seal coat material

Double Chip Seal

0.45 gallons of bituminous material for seal coat (emulsion CRS-2P)
0.14 gallons of bituminous material for a fog seal (emulsion CSS-1h)
2 square yard of aggregate seal coat material

[2] Emulsion CRS-2P has asphalt residue content of 65% asphalt (35% water)

[3] Emulsion CSS-1h has asphalt residue content of 57% asphalt (43% water)

Micro-surfacing

0.4947 gallons of bituminous material for micro-surfacing treatment (emulsion CSS-1h)
0.0075 tons of micro-surfacing scratch course.
0.0075 tons of micro-surfacing wearing course.
*Micro-surfacing scratch and wearing course are the same materials:

- 91% virgin aggregate.
- 7.5% emulsion CSS-1HP (3% solids)
- 1.5% cement

CapeSeal:

0.3 gallons of bituminous material for seal coats (emulsion CRS-2P)
1 square yard of aggregate seal coat material (100% virgin aggregate)
0.4947 gallons of bituminous material for MicroSurface treatments (emulsion CSS-1h)
0.0075 tons of micro-surfacing scratch course.
0.0075 tons of micro-surfacing wearing course.

UltraThin Bonded Wear Course

(estimated composition need to verify with MnDOT)

0.23 gallons of Polymer Modified Tack Coat (CSS-1HP[4])
0.038 tons of HMA consisting of:

- 0.0021 tons of polymer modified asphalt binder (5.5%)
- 0.0359 tons of aggregate all crushed (94.5%)

2 inch HMA Overlay

0.114 tons of HMA consisting of:

- 0.0067 tons of asphalt binder (5.5%)
- 0.1073 tons of aggregate (94.5%) consisting of:
  - 0.0966 tons of crushed aggregate
  - 0.0107 tons of natural sand.

Mill & 2 inch HMA Overlay

1 SY of milling 2 inches of pavement
0.114 tons of HMA consisting of:

- 0.0067 tons of asphalt binder (5.5%)
- 0.1073 tons of aggregate (94.5%) consisting of:
  - 0.0966 tons of crushed aggregate
  - 0.0107 tons of natural sand

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[4] Emulsion CSS-1HP has asphalt residue content of 63% asphalt (34% water, 3% solids)

Mastic for patching

93.6 lbs of mastic consisting of:

- Asphalt Binder (7%)
- Fine Aggregates (93%)

1 SY of seal coat material consisting of:

- 1 SY of seal coal aggregate
- 0.3 gallons of bituminous material (emulsion CRS-2P)

Crack Sealing

1 SY of aggregate
Asphalt 10% by volume

Calculations

Step 1. Calculate the percent volume of asphalt in each bituminous layer (in gal)
- Used in following materials: bituminous material for seal coal, bituminous material for fog seal, and bituminous material for microsurfacing

$$Initial\ Quantity\ (gal) * Emulsion\ Percent = Percent\ Asphalt\ (gal)$$

Step 2. Convert all surface material SY areas to CY volumes based on thicknesses in Table 1
- Conversion factors:

  - Bitumen: 0.84 tons/CY
  - Aggregate: 2.23 tons/CY
  - Cement: 1.27 tons/CY
  - Sand: 1.35 tons/CY[5]

$$Material\ (Non\ SY) * Conversion\ factor\ = Material\ (SY)$$

Step 3. Multiply the surface material CY volume to the appropriate volume for one lane-mile

$$Material\ (1\ SY) * 1\ mile * 12'lane * thickness$$

Step 4. Calculate the volume of localized treatment materials per one-lane mile from quantities in Table 2.

$$Lenth\ x\ width\ x\ thickness\ x\ frequency = volume\ per\ mile$$

Step 5. Enter each material into PaLATE spreadsheet's "Initial Cost" page

Step 6. Gather each material's environmental output from "Environmental Results" page

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[5] This conversion was not provided by PaLATE. The sand was assumed loose and dry to find this unit weight (Densities of Some Common Materials , 2014)

Step 7. Sum the total environmental outputs from each material in each layer

$$Total\ environmental\ result\ (per\ treatment) = \Sigma\ Environmental\ results\ for\ each\ material$$

Step 8. Divide the total environmental outputs by the service life of each treatment as stipulated in Table 4.

$$\frac{Total\ environmental\ output}{Service\ Life} = Annualized\ environmental\ output$$

Table 27. Complete calculations for surface and localized treatments

Treatment	Thickness (in)	Materials	Amount	Volume (gal)	Unit Volume (CY) - 1 mi x 12 ft x Thickness
Chip Seal	**0.5**				**97.78**
		Seal coat asphalt	.3 gal, 65%	0.195	6.80
		Fog seal asphalt	.14 gal, 28%	0.0392	1.37
		Asphalt Total		0.2342	8.16
		aggregate	1 SY		97.78
Total					
Double Chip Seal	**1**				**195.56**
		Seal coat asphalt	.45 gal, 65%	0.2925	10.20
		Fog seal asphalt	.14 gal, 28%	0.0392	1.37
		Asphalt total		0.3317	11.56
		aggregate	2 SY		391.11
Total					
Microsurfacing	**1**				**195.56**
		Micro-surf asphalt	.4947 gal, 57%	0.281979	9.83
		MS scratch course-aggregate	0.0075 tons, 91%	x	21.55
		MS scratch course - cement	.0075 tons, 1.5%	x	0.62
		MS wearing course - agg	0.0075 tons, 91%	x	21.55
		MS wearing course - cement	.0075 tons, 1.5%	x	0.62
		Asphalt total			9.83
		Aggregate Total			43.09
		Cement Total			1.25
Total					
Cape Seal	**1.5**				**293.33**
		Seal coal asphalt	.3 gal, 65%	0.195	6.80
		aggregate seal coat	1 SY		293.33
		Microsurf asphalt	.4947 gal, 57%	0.281979	9.83

Treatment	Thickness (in)	Materials	Amount	Volume (gal)	Unit Volume (CY) - 1 mi x 12 ft x Thickness
		MS scratch course-aggregate	0.0075 tons, 91%	x	21.55
		MS scratch course - cement	.0075 tons, 1.5%	x	0.62
		MS wearing course - agg	0.0075 tons, 91%	x	21.55
		MS wearing course - cement	.0075 tons, 1.5%	x	0.62
		Asphalt total			16.63
		Aggregate total			336.43
		Cement total			1.25
Total					
Ultra Thin Bonded Wearing Course	**1**				
		Polymer Coat asphalt	.23 gal, 63%	0.1449	5.05
		Polymer coat solids	.23 gal, 3%	0.0069	0.24
		HMA - Polymer asphalt binder	.0021 tons		17.60
		HMA - Aggregate	0.0359 tons		113.33
		Asphalt total			22.65
Total					
2 in HMA Overlay	**2**				**391.11**
		Asphalt binder	.0067 tons		56.15
		Crushed aggregate	.0966 tons		304.96
		Natural sand*	.0107 tons		55.80
Total					
Mill & 2 in HMA Overlay	**2**				**391.11**
		Milling of 2 inches pavement	1 SY		391.11
		HMA asphalt binder	0.0067 tons		56.15
		Crushed aggregate	.0966 tons		304.96
		Natural sand	.0107 tons		55.80
Total					

Patch Treatments

Treatment	Thickness (in)	Thickness (yd)	Materials	Amount	Density	Volume (gal)	Volume (1 SY)	Unit Volume (CY) - 1 mi x 12 ft x Thickness
Crack Sealing	1	0.027777778						0.079320988
			Asphalt	10% volume			0.0028	0.0079

Patch Treatments								
Treatment	**Thickness (in)**	**Thickness (yd)**	**Materials**	**Amount**	**Density**	**Volume (gal)**	**Volume (1 SY)**	**Unit Volume (CY) - 1 mi x 12 ft x Thickness**
			Aggregate	1 SY			0.0278	0.0793
Total								
Mastic - Moderate	**3**	0.083333333						0.8333
			Mastic asphalt binder	93.6 lbs, 7%	0 .84 tons/CY		0.0039	0.0390
			Aggregates	93.6 lbs, 93%	2.23 tons/CY		0.0195	0.1952
			Seal Coat asphalt	.3 gal, 65%		0.195	0.0010	0.0097
			Seal Coat aggregate	1 SY			0.0833	0.8333
			Asphalt total				0.0049	0.0486
			Aggregate total				0.1029	1.0285
Total								
Mastic - Severe	**3**	0.083333333						1.6667
			Mastic asphalt binder	93.6 lbs, 7%	0 .84 tons/CY		0.0039	0.0779
			Aggregates	93.6 lbs, 93%	2.23 tons/CY		0.0195	0.3903
			Seal Coat asphalt	.3 gal, 65%		0.195	0.0010	0.0193
			Seal Coat aggregate	1 SY			0.0833	1.6667
			Asphalt total				0.0049	0.0972
			Aggregate total				0.1029	2.0570
Total								

Results

Table 28. Total environmental results from PaLATE

Treatment	Energy (MJ)	Water consumption (g)	CO2 (kg)	Nox (g)	PM-10 (g)	SO2 (g)	CO (g)	RCRA Hazardous Waste Generated (g)	HTP Cancer	HTP non cancer
Chip Seal										
Seal coat asphalt	112,804	47,344	6,406	35,622	6,038	32,276	27,042	2,003,694	31,029	12,846
Fog seal asphalt	22,737	9,543	1,291	7,180	1,217	6,506	5,451	403,864	6,254	2,589
Asphalt Total	135,541	56,887	7,697	42,802	7,255	38,782	32,493	2,407,558	37,283	15,435
aggregate	33,612	4,682	2,380	4,797	34,110	2,337	3,134	39,061	3,188	40,252,046
Total	**169,153**	**61,569**	**10,077**	**47,599**	**41,365**	**41,119**	**35,627**	**2,446,619**	**40,471**	**40,267,481**
Double Chip Seal										
Seal coat asphalt	169,198	71,013	9,608	53,430	9,056	48,412	40,561	3,005,394	46,542	19,268
Fog seal asphalt	22,670	9,515	1,287	7,159	1,213	6,487	5,435	402,684	6,236	2,582
Asphalt total	191,869	80,528	10,896	60,589	10,269	54,899	45,996	3,408,079	52,778	21,850
aggregate	134,444	18,726	9,521	19,186	136,437	9,347	12,536	156,241	12,754	161,004,067
Total	**326,313**	**99,254**	**20,417**	**79,775**	**146,706**	**64,246**	**58,532**	**3,564,320**	**65,532**	**161,025,917**
Microsurfacing										
Micro-surf asphalt	163,141	68,470	9,264	51,517	8,732	46,679	39,109	2,897,795	44,876	18,578
MS scratch course-aggregate	7,406	1,032	525	1,057	7,516	515	691	8,607	703	8,869,611
MS scratch course - cement	2,991	1,482	210	2,525	473	2,503	897	1,297	12	20,839
MS wearing course - agg	7,406	1,032	525	1,057	7,516	515	691	8,607	703	8,869,611
MS wearing course - cement	2,991	1,482	210	2,525	473	2,503	897	1,297	12	20,839
Asphalt total	163,141	68,470	9,264	51,517	8,732	46,679	39,109	2,897,795	44,876	18,578
Aggregate Total	14,813	2,063	1,049	2,114	15,033	1,030	1,381	17,214	1,405	17,739,222
Cement Total	5,983	2,965	420	5,050	946	5,006	1,794	2,594	23	41,678
Total	**183,936**	**73,498**	**10,733**	**58,680**	**24,710**	**52,714**	**42,284**	**2,917,604**	**46,304**	**17,799,479**
Cape Seal										
Seal coal asphalt	112,804	47,344	6,406	35,622	6,038	32,276	27,042	2,003,694	31,029	12,846
aggregate seal coat	100,832	14,044	7,141	14,389	102,327	7,010	9,402	117,180	9,565	120,752,021
Microsurf asphalt	163,107	68,456	9,263	51,507	8,730	46,669	39,101	2,897,206	44,867	18,574
MS scratch course-aggregate	7,406	1,032	525	1,057	7,516	515	691	8,607	703	8,869,611
MS scratch course - cement	2,991	1,482	210	2,525	473	2,503	897	1,297	12	20,839
MS wearing course - agg	7,406	1,032	525	1,057	7,516	515	691	8,607	703	8,869,611

Treatment	Energy (MJ)	Water consumption (g)	CO2 (kg)	Nox (g)	PM-10 (g)	SO2 (g)	CO (g)	RCRA Hazardous Waste Generated (g)	HTP Cancer	HTP non cancer
MS wearing course - cement	2,991	1,482	210	2,525	473	2,503	897	1,297	12	20,839
Asphalt total	275,912	115,801	15,668	87,128	14,768	78,946	66,143	4,900,900	75,896	31,420
Aggregate total	115,645	16,107	8,190	16,503	117,360	8,040	10,783	134,394	10,970	138,491,243
Cement total	5,983	2,965	420	5,050	946	5,006	1,794	2,594	23	41,678
Total	**397,540**	**134,873**	**24,278**	**108,681**	**133,073**	**91,991**	**78,721**	**5,037,888**	**86,890**	**138,564,342**
Ultra Thin Bonded Wearing Course										
Polymer Coat asphalt	83,811	35,175	4,759	26,466	4,486	23,980	20,092	1,488,694	23,054	9,544
Polymer coat solids	<-- Ignored									
HMA - Polymer asphalt binder	292,093	122,592	16,587	92,238	15,634	83,575	70,022	5,188,321	80,347	33,263
HMA - Aggregate	38,957	5,426	2,759	5,559	39,535	2,708	3,633	45,273	3,696	46,653,348
Asphalt total	375,904	157,767	21,347	118,704	20,119	107,556	90,114	6,677,016	103,401	42,807
Total	**414,861**	**163,193**	**24,106**	**124,263**	**59,654**	**110,264**	**93,747**	**6,722,289**	**107,097**	**46,696,155**
2 in HMA Overlay										
Asphalt binder	931,877	391,110	52,919	294,271	49,877	266,634	223,395	16,552,514	256,335	106,120
Crushed aggregate	104,830	14,601	7,424	14,960	106,384	7,288	9,775	121,826	9,944	125,539,619
Natural sand*	-	-	-	-	-	-	-	-	-	-
Total	**1,036,707**	**405,711**	**60,343**	**309,230**	**156,261**	**273,922**	**233,170**	**16,674,339**	**266,279**	**125,645,739**
Mill & 2 in HMA Overlay										
Milling of 2 inches pavement	7,556	-	2,079	13,578	964	898	2,926	54,446	10,594	18,863,819
HMA asphalt binder	931,877	391,110	52,919	294,271	49,877	266,634	223,395	16,552,514	256,335	106,120
Crushed aggregate	104,830	14,601	7,424	14,960	106,384	7,288	9,775	121,826	9,944	125,539,619
Natural sand	-	-	-	-	-	-	-	-	-	-
Total	**1,044,263**	**405,711**	**62,423**	**322,808**	**157,225**	**274,820**	**236,096**	**16,728,785**	**276,873**	**144,509,558**

Treatment	Energy (MJ)	Water consumption (g)	CO2 (kg)	Nox (g)	PM-10 (g)	SO2 (g)	CO (g)	RCRA Hazardous Waste Generated	HTP Cancer	HTP non cancer
Crack Sealing										
Asphalt	131.6	55.2	7.5	41.6	7.0	37.7	31.5	2,337.7	36.2	15.0
Aggregate	27.3	3.8	1.9	3.9	27.7	1.9	2.5	31.7	2.6	32,644.6
Total	158.9	59.0	9.4	45.4	34.7	39.6	34.1	2,369.4	38.8	32,659.6

Treatment	Energy (MJ)	Water consumption (g)	CO2 (kg)	Nox (g)	PM-10 (g)	SO2 (g)	CO (g)	RCRA Hazardous Waste Generated	HTP Cancer	HTP non cancer
Crack Sealing										
Mastic - Moderate										
Mastic asphalt binder	645.6	271.0	36.7	203.9	34.6	184.7	154.8	11,467.4	177.6	73.5
Aggregates	67.0	9.3	4.7	9.6	68.0	4.7	6.3	77.9	6.4	80,273.6
Seal Coat asphalt	160.2	67.2	9.1	50.6	8.6	45.8	38.4	2,844.7	44.1	18.2
Seal Coat aggregate	286.3	39.9	20.3	40.9	290.6	19.9	26.7	332.8	27.2	342,912.2
Asphalt total	805.7	338.2	45.8	254.4	43.1	230.5	193.2	14,312.1	221.6	91.8
Aggregate total	353.4	49.2	25.0	50.4	358.6	24.6	33.0	410.7	33.5	423,185.8
Total	1,159.1	387.4	70.8	304.9	401.7	255.1	226.1	14,722.8	255.2	423,277.5
Mastic - Severe										
Mastic asphalt binder	1,292.8	542.6	73.4	408.3	69.2	369.9	309.9	22,964.2	355.6	147.2
Aggregates	134.1	18.7	9.5	19.1	136.1	9.3	12.5	155.8	12.7	160,547.1
Seal Coat asphalt	320.3	134.4	18.2	101.1	17.1	91.6	76.8	5,689.5	88.1	36.5
Seal Coat aggregate	573.0	79.8	40.6	81.8	581.5	39.8	53.4	665.9	54.4	686,236.0
Asphalt total	1,613.2	677.0	91.6	509.4	86.3	461.6	386.7	28,653.7	443.7	183.7
Aggregate total	707.1	98.5	50.1	100.9	717.6	49.2	65.9	821.7	67.1	846,783.2
Total	2,320.2	775.5	141.7	610.3	803.9	510.7	452.6	29,475.4	510.8	846,966.9

Table 29. Summary of total environmental results for each treatment

Total Environmental Results					
Type	**Treatment**	**Energy (GJ)**	**Water consumption (kg)**	**CO_2 (kg)**	**RCRA Hazardous Waste Generated (kg)**
Surface	Chip Seal	169.2	61.6	10,077.0	2,446.6
Surface	Double Chip Seal	326.3	99.3	20,416.8	3,564.3
Surface	Microsurfacing	183.9	73.5	10,733.4	2,917.6
Surface	Cape Seal	397.5	134.9	24,278.4	5,037.9
Surface	UltraThin	414.9	163.2	24,105.7	6,722.3
Surface	2 in HMA Overlay	1,036.7	405.7	60,343.4	16,674.3
Surface	Mill & 2 in HMA Overlay	1,044.3	405.7	62,422.8	16,728.8
Local	Crack Sealing	0.16	0.1	9.4	2.4
Local	Mastic - Moderate	1.16	0.4	70.8	14.7
Local	Mastic - Severe	2.32	0.8	141.7	29.5

Table 30. Environmental results per treatment compared to Chip Seal base case. Results are presented as a percentage of base case.

Compared Environmental Results to Base Case					
Type	**Treatment**	**Energy (GJ)**	**Water consumption (kg)**	**CO2 (kg)**	**RCRA Hazardous Waste Generated (kg)**
Surface	**Chip Seal**	0%	0%	0%	0%
Surface	**Double Chip Seal**	93%	61%	103%	46%
Surface	**Microsurfacing**	9%	19%	7%	19%
Surface	**Cape Seal**	135%	119%	141%	106%
Surface	**UltraThin**	145%	165%	139%	175%
Surface	**2 in HMA Overlay**	513%	559%	499%	582%
Surface	**Mill & 2 in HMA Overlay**	517%	559%	519%	584%
Local	**Crack Sealing**	-100%	-100%	-100%	-100%
Local	**Mastic - Moderate**	-99%	-99%	-99%	-99%
Local	**Mastic - Severe**	-99%	-99%	-99%	-99%

Table 31. Annualized environmental results per treatment per pavement initial condition.

Annualized Environmental Results - Energy (GJ)							
		Minimum Service Life			**Maximum Service Life**		
Type	**Treatment**	**Moderate**	**Poor**	**Very Poor**	**Moderate**	**Poor**	**Very Poor**
Surface	Chip Seal	42.3	169.2	n/a	33.8	84.6	n/a
Surface	Double Chip Seal	65.3	108.8	326.3	54.4	81.6	163.2
Surface	Microsurfacing	46.0	92.0	183.9	36.8	61.3	92.0
Surface	Cape Seal	79.5	132.5	198.8	66.3	99.4	132.5
Surface	UltraThin	69.1	103.7	138.3	59.3	83.0	103.7
Surface	2 in HMA Overlay	207.3	345.6	345.6	172.8	259.2	259.2
Surface	Mill & 2 in HMA Overlay	174.0	261.1	348.1	149.2	208.9	261.1
Local	Crack Sealing	0.03	0.05	0.16	0.03	0.04	0.08
Local	Mastic	0.19	0.29	0.77	0.17	0.23	0.58

Annualized Environmental Results - Water Consumption (kg)							
		Minimum Service Life			**Maximum Service Life**		
Type	**Treatment**	**Moderate**	**Poor**	**Very Poor**	**Moderate**	**Poor**	**Very Poor**
Surface	Chip Seal	15.4	61.6	n/a	12.3	30.8	n/a
Surface	Double Chip Seal	19.9	33.1	99.3	16.5	24.8	49.6
Surface	Microsurfacing	18.4	36.7	73.5	14.7	24.5	36.7
Surface	Cape Seal	27.0	45.0	67.4	22.5	33.7	45.0
Surface	UltraThin	27.2	40.8	54.4	23.3	32.6	40.8
Surface	2 in HMA Overlay	81.1	135.2	135.2	67.6	101.4	101.4
Surface	Mill & 2 in HMA Overlay	67.6	101.4	135.2	58.0	81.1	101.4
Local	Crack Sealing	0.01	0.02	0.06	0.01	0.01	0.03
Local	Mastic	0.06	0.10	0.26	0.06	0.08	0.19

Annualized Environmental Results - CO_2 (kg)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	2519.3	10077.0	n/a	2015.4	5038.5	n/a
Surface	Double Chip Seal	4083.4	6805.6	20416.8	3402.8	5104.2	10208.4
Surface	Microsurfacing	2683.3	5366.7	10733.4	2146.7	3577.8	5366.7
Surface	Cape Seal	4855.7	8092.8	12139.2	4046.4	6069.6	8092.8
Surface	UltraThin	4017.6	6026.4	8035.2	3443.7	4821.1	6026.4
Surface	2 in HMA Overlay	12068.7	20114.5	20114.5	10057.2	15085.8	15085.8
Surface	Mill & 2 in HMA Overlay	10403.8	15605.7	20807.6	8917.5	12484.6	15605.7
Local	Crack Sealing	1.88	3.13	9.40	1.57	2.35	4.70
Local	Mastic	11.80	17.70	47.23	10.11	14.16	35.42

Annualized Environmental Results - RCRA Hazardous Waste (kg)							
		Minimum Service Life			Maximum Service Life		
Type	Treatment	Moderate	Poor	Very Poor	Moderate	Poor	Very Poor
Surface	Chip Seal	611.7	2,446.6	n/a	489.3	1,223.3	n/a
Surface	Double Chip Seal	712.9	1,188.1	3,564.3	594.1	891.1	1,782.2
Surface	Microsurfacing	729.4	1,458.8	2,917.6	583.5	972.5	1,458.8
Surface	Cape Seal	1,007.6	1,679.3	2,518.9	839.6	1,259.5	1,679.3
Surface	UltraThin	1,120.4	1,680.6	2,240.8	960.3	1,344.5	1,680.6
Surface	2 in HMA Overlay	3,334.9	5,558.1	5,558.1	2,779.1	4,168.6	4,168.6
Surface	Mill & 2 in HMA Overlay	2,788.1	4,182.2	5,576.3	2,389.8	3,345.8	4,182.2
Local	Crack Sealing	0.47	0.79	2.37	0.39	0.59	1.18
Local	Mastic	2.45	3.68	9.83	2.10	2.94	7.37

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