Environmental Benefits of Cold-in-Place Recycling

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September 2017

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DISCLAIMER

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Acknowledgements

This research was funded by the Wisconsin Department of Transportation under the College of Engineering Construction and Materials and Support Center. The authors gratefully acknowledge their support. The authors would also like to thank Girum Merine, Barry Paye and Peter Kemp from WisDOT, Ervin Dukatz of Mathy Construction, Michael Gonnering and Ric Szalewski of Northeast Asphalt, Dustin Albert of American Asphalt, Gary Whited of the Construction and Materials and Support Center and others who contributed to data collection for this report.

Executive Summary

This report evaluates nine highway maintenance projects in Wisconsin that were constructed using Cold-in-Place Recycling (CIR) as an alternative to the conventional Mill and Overlay method. The goal of this report is to quantify the environmental impacts of CIR and Mill and Overlay, and to compare the results to determine the relative environmental benefits of CIR. The nine project locations were:

- CTH H (Reedsburg to Wisconsin Dells)
- STH 13 (Medford to Westboro)
- STH 27 (Sparta to Black River Falls)
- STH 48 (Grantsburg to Frederic)
- STH 48 (Rice Lake to Birchwood)
- STH 64 (Gilman to Medford)
- STH 72 (Ellsworth to Elmwood)
- STH 95 (Blair to Merrillan)
- STH 187 (Shiocton to North County Line)

To quantify the environmental impacts associated with CIR and Mill and Overlay, a life cycle assessment (LCA) was conducted using the tool PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects). Energy consumption, water usage, and carbon dioxide emissions were chosen as the scope of the LCA for this project. An LCA was performed for both the constructed CIR design and a hypothetical Mill and Overlay design of the same roadway. In each project, variables subject to change included thickness of hot mix asphalt (HMA) in the Mill and Overlay design, thickness of CIR and thickness of HMA overlay in the CIR construction, road width, project length, hauling distance to the nearest asphalt plant, and equipment used for construction. Seven of the nine projects were constructed using a multi-unit recycling train, STH 27 was constructed using a single-unit recycling train, and CTH H was constructed partially with a single-unit and partially with a multi-unit recycling train. Contractors provided material quantities and equipment used for the constructed CIR projects as well as estimated material quantities and equipment information for the same projects if they had been constructed using Mill and Overlay.

Results show an average of 23% savings in energy consumption and carbon dioxide emissions when using CIR in place of Mill and Overlay, and 20% savings in water usage. The nine projects in summation saved 24,341,387 kWh in energy consumption, 5,029 tons of carbon dioxide

emissions, and 30 tons of water consumption. It was determined that the environmental savings achieved by using CIR are directly related to the reduction in volume of HMA used in the thinner HMA overlay, and to the reduction in transportation of materials to and from site. Linear correlations using volume of HMA avoided and hauling distance have been made to estimate the energy consumption, water usage, and carbon dioxide emission savings achieved when using CIR in place of Mill and Overlay for future construction projects in Wisconsin.

Objective

The project objective was to quantify the environmental life cycle benefits associated with using Cold-in-Place Recycling (CIR) for highway resurfacing instead of the conventional Mill and Overlay process. Equipment used and quantity of materials used for both the CIR process and what would have been used in the Mill and Overlay process for the same project was collected for nine highway projects in Wisconsin. With this information, a life cycle assessment (LCA) tool, Pavement Life-cycle Assessment Tool for Environment and Economic Effects (PaLATE), was used to analyze and compare each project's data.

Introduction

The United States uses approximately 1.3 billion tons of aggregate every year, 58% of which is for road construction (Carpenter et al, 2007). Furthermore, 90% of aggregate used in road construction is virgin aggregate (Carpenter et al, 2007). With the increasing cost of virgin materials and the growing pressure to build more sustainably, the use of recycled materials in roads is becoming increasingly widespread. The triple bottom line of sustainability requires that a project is economically, socially, and environmentally beneficial relative to conventional methods. Cold-in-Place Recycling (CIR) is a method for highway resurfacing that has become more widely used in the past decade for its demonstrated benefits to the triple bottom line.

CIR has the potential to yield economic savings and improve the quality of roads. Surface irregularities are remediated without disturbing the base and subgrade, and traffic disruptions are reduced when using CIR in place of Mill and Overlay (Basic Asphalt Recycling Manual, 2001). CIR saves up to 50% in resurfacing costs compared to other methods by eliminating the need of material disposal through reuse of reclaimed asphalt on site, by reducing both the demand for nonrenewable virgin resources, and by reducing the transportation of materials to and from the site (Cold Recycling, 2016). Disadvantages of CIR that should be recognized include relatively weak early-life strength and longer curing times; however, in the long-term, CIR improves the strength and extends the life of the road without need for reconstruction (Tabakovic et al, 2016).

Despite the understanding of the benefits of CIR, there is insufficient literature that quantifies the environmental benefits of CIR with respect to the conventional Mill and Overlay. One study by Tuk et al. compared CIR to traditional methods by examining CIR and conventional construction on one road with a life cycle assessment tool (Tuk et al, 2016). It was determined that CIR reduced global warming potential[a] by 1%, reduced acidification by 18%, reduced fossil fuel consumption by 15%, and reduced primary energy consumption by 16% compared to conventional methods (Tuk et al, 2016). This study, however, used cement in the process and looked at the use of RAP in the subbase layer, as opposed to using it in the surface wearing course layer of the road (Tuk et al, 2016). Another study by Thenoux et al. compared asphalt overlay, total reconstruction, and CIR in rural Chile, and found CIR to have the lowest environmental impacts (Thenoux et al, 2007). However, this study is not directly applicable to Wisconsin due to different construction processes and reveals a major gap in today's research on CIR. It is understood by all the available studies that hauling distance to the nearest asphalt plant plays a significant role in savings associated with CIR (Tabakovic et al, 2016), (Tuk et al, 2016), (Thenoux et al, 2007). Outside of these studies, little was found to quantitatively compare the environmental benefits of CIR to conventional methods, in particular to Mill and Overlay.

The Recycled Materials Resource Center (RMRC) located at the University of Wisconsin - Madison has worked closely with the Wisconsin Department of Transportation (WisDOT) to quantify these environmental benefits. For this report, case studies of nine highway projects across Wisconsin that utilized CIR have been analyzed and compared to conventional Mill and Overlay using life cycle assessments (LCA). The nine project locations are represented in Figure 1.

[a] Global warming potential is the measure of energy absorbed by 1 ton of greenhouse gas emissions relative to 1 ton of carbon dioxide. It is a unit of measure that allows the analysis to include cumulative emissions of several different greenhouse gases. (Understanding Global Warming Potentials, US EPA)

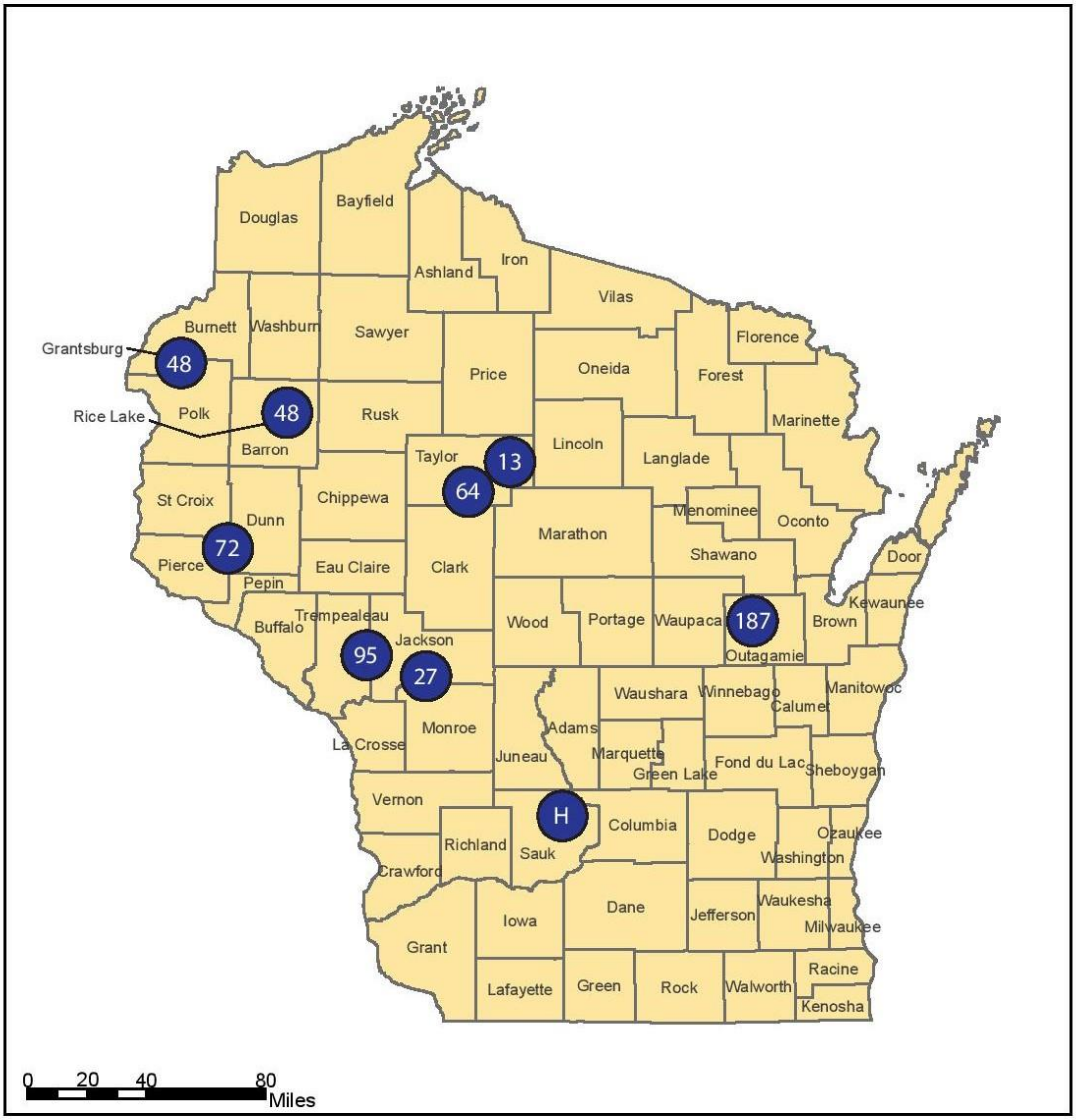

Figure 1. CIR Projects in Wisconsin

CTH H (Reedsburg to Wisconsin Dells)

STH 13 (Medford to Westboro)

STH 27 (Sparta to Black River Falls)

STH 48 (Grantsburg to Frederic)

STH 48 (Rice Lake to Birchwood)

STH 64 (Gilman to Medford)

STH 72 (Ellsworth to Elmwood)

STH 95 (Blair to Merrillan)

STH 187 (Shiocton to North County Line)

CIR and Mill and Overlay Processes

The first step in the CIR process is to mill the existing roadway to a specified depth. In the nine projects studied here, and for most cases, milling depth is 2 to 4 inches when the recycling agent is an asphalt emulsion agent (Basic Asphalt Recycling Manual, 2001). Depending on the distress of the roadway, however, some pre-milling may be necessary for a project. Generally, all the recycled asphalt pavement (RAP) generated during the milling of the existing road is used for reconstruction (Basic Asphalt Recycling Manual, 2001). After milling, the material is crushed and graded to achieve the desired gradation and particle size. A stabilizing agent (e.g. asphalt emulsion) is added and the mixture is once again placed onto the roadway using a traditional asphalt paver. The new stabilized base is compacted and the CIR mixture is left to cure; curing periods for CIR can take a few hours or up to several weeks depending on conditions. The most common curing periods are 2-3 days (Cold Recycling, 2016). After curing, a wearing course layer of hot mix asphalt (HMA) is laid over top.

CIR is a more intensive construction process than the traditional Mill and Overlay process, also called mill and fill. Like CIR, the first step in the Mill and Overlay process is to mill the existing roadway, but instead of being recycled in-situ the milled material is hauled to the nearest asphalt plant to be recycled. Then, 4 to 4.5 inches of new HMA produced from virgin materials is paved on top of the milled original pavement surface (Mathy Construction). The chosen milling depth is dependent on distress of the roadway; for the projects in this study, the milling depth was between 4 and 5 inches. A side-by-side road profile comparison of the Mill and Overlay and CIR processes is detailed in Figure 2 below. Although the CIR has a more involved construction process, it requires less transportation of materials to and from the HMA plant and less new HMA from virgin materials.

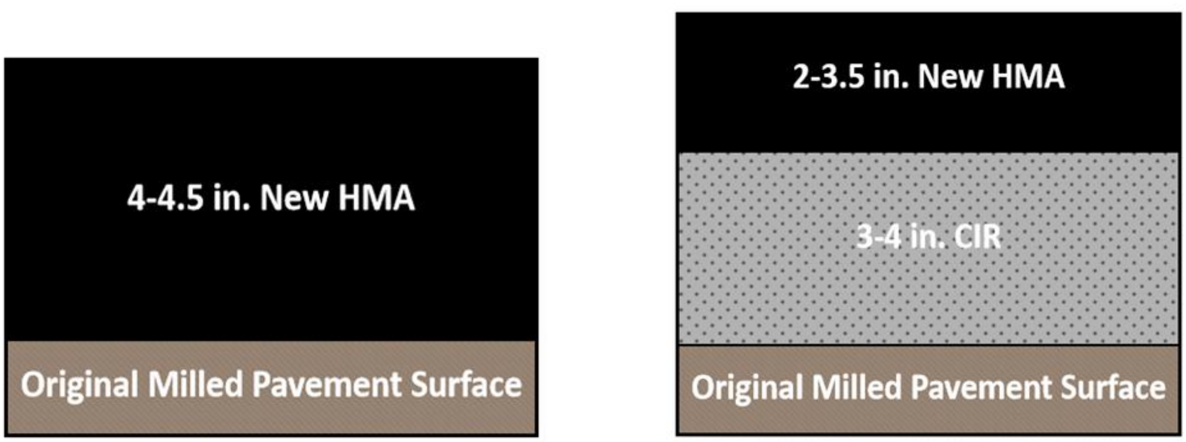

Figure 2. Mill and Overlay and Cold-in-Place Recycling Road Profiles.

There are presently three methods of CIR construction: single-unit recycling train, two-unit recycling train, and multi-unit recycling train. The single-unit recycling train accomplishes the CIR process in one fell swoop. The milling machine, crushing and sizing machine, and pugmill machine are all combined into one unit that mills the roadway using a down cutting rotor, grades the milled material, and adds the stabilizing agents in the cutting chamber (Basic Asphalt Recycling Manual, 2001). A paver then relays the modified RAP, and compaction rollers stabilize the base. After the curing period, the road is ready for the HMA overlay. Figure 3 below illustrates the single-unit recycling train setup. The left-hand image is the single-unit CIR Recycler that mills, grades, and adds the stabilizing agent, and the right-hand image is of the paver (Mathy Construction, 2016). The CIR process proceeds from right to left in this example. Only one project analyzed in this report used a single-unit Recycling train: STH 27. Similarly, a two-unit recycling train consists of a milling machine and a mix paver, where the mix paver acts as both a pugmill machine to add the stabilizing agent and a paver. No projects evaluated in this report utilized a two-unit recycling train.

Figure 3. Example Single-unit Recycling Train. (Mathy Construction, 2016)

Multi-unit recycling trains involve different machines for each of the different processes, see Figure 4. A typical multi-unit recycling train consists of a milling machine to mill the existing roadway, a screening and crushing machine to grade the milled material, a pug mill machine to add the stabilizing agent, and a paver to relay the modified RAP mixture (Basic Asphalt Recycling Manual, 2001). A compaction roller then finishes the job and the stabilized base is left to cure until it is ready for the HMA overlay. A multi-unit recycling train was used in all the case studies presented in this report, with the exception of STH 27.

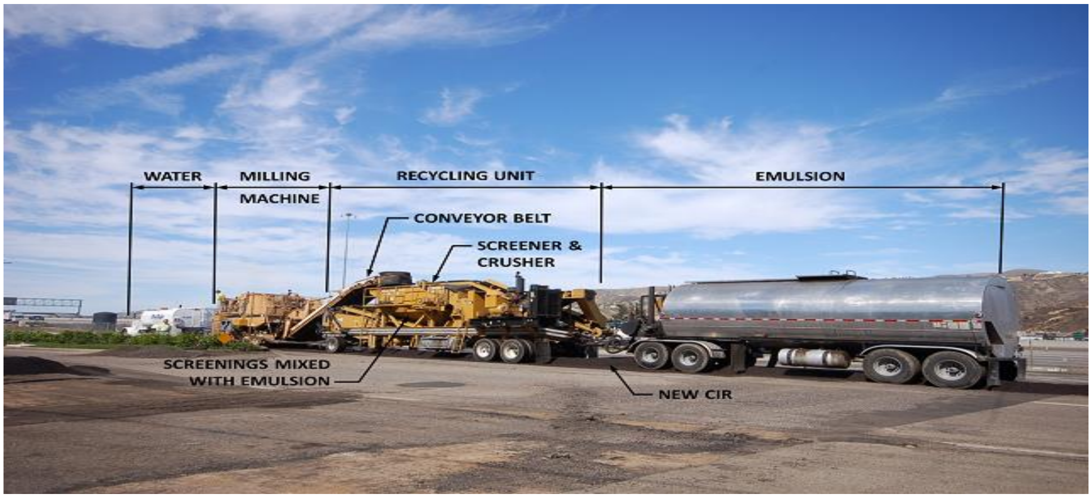

Figure 4. Example Multi-unit Recycling Train. (LA County Department of Public Works)

Environmental Impacts Analysis using PaLATE

To most effectively determine the environmental benefits associated with the implementation of the CIR process, a life cycle assessment (LCA) of each the CIR and Mill and Overlay processes was performed. LCA refers to the systematic evaluation of a process or product in which the environmental impacts associated with all stages of the process are considered. LCAs can assist in gaining a better understanding of the environmental impacts of materials and processes throughout the product life cycle, also known as a cradle-to-grave analysis, and provide relevant data to make informed decisions. To achieve this, the LCA tool PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) was chosen. PaLATE is a spreadsheet LCA program that was developed by the Consortium on Green Design and Manufacturing from the University of California-Berkeley (2007) to assess the environmental and economic effects of pavement and road construction under the sponsorship of RMRC (Consortium on Green Design and Manufacturing, 2007). It follows the production of materials, transportation of materials, construction, maintenance, and end-of-life processes. Many of the PaLATE outputs are based upon the volumes or weights of materials used and the parameters of specific equipment used. The environmental outputs of PaLATE include: energy consumption (MJ), water consumption (kg), CO_2 emissions (kg), NO_x emissions (kg), PM_{10} emissions (kg), SO_2 emissions (kg), CO emissions (kg), leachate information (mercury, lead), and hazardous waste generated (g) (Consortium on Green Design and Manufacturing, 2007). PaLATE outputs have been converted to English units in the writing of this report.

The first step in executing an LCA is to define the functional scope of the project. Energy use, water consumption, and carbon dioxide emissions were the chosen environmental factors for impact analysis as the scope of this assessment. The scope of this project only included the benefits associated with the CIR process in place of Mill and Overlay, thus the benefits of utilizing recycled materials within the HMA in either process was not specifically investigated. Next a complete inventory of each component of the construction process is taken within the defined scope of the project. To determine the equipment and materials used during the CIR process, the RMRC research team worked closely with the Wisconsin Department of Transportation (WisDOT) and contractors Mathy Construction, WK, Mid States Reclamation, American Asphalt, and Northeast Asphalt. The nine chosen projects were all constructed using CIR, for which the contractors tracked and provided the quantity of materials and equipment used in the process. Additionally, contractors were asked to provide hypothetical material quantities and equipment specifications for the nine projects as if the project were to be constructed using Mill and Overlay. For each project, two PaLATE scenarios were run for (1) the actual CIR construction and (2) the hypothetical Mill and Overlay construction and the environmental outputs were compared. Information used to run LCAs was provided either directly from WisDOT or the contractor responsible for the project. Such information included amount of HMA, tack coat, and surface area of milling for the CIR process and the hypothetical Mill and Overlay, and additionally the asphalt stabilizing agent and surface area of the CIR layer for the CIR process. More information regarding project specific quantities and PaLATE inputs is detailed by project in Appendices B-J. CIR thickness and HMA thickness varied by project to meet the design requirements of the road; HMA mix designs for each project were found using a database provided by Attwood Systems.

Contractors also provided the equipment used during the CIR process and the hypothetical equipment for the Mill and Overlay process. Productivity and fuel consumption data for the equipment were obtained from the equipment manufacturers (CMI RoadBuilding, and Cummins Engine Company, Inc.). Frequently, the equipment used in the actual construction process was outdated and not available in PaLATE as an input. In these cases, significant research was conducted to choose an equivalent piece of equipment as the PaLATE input that had the most similar fuel consumption and productivity specifications as the given equipment. Information on PaLATE equipment inputs can be found in Appendix A and the equipment lists provided by the contractors for each project can be found in Appendices B-J. For the eight projects that were evaluated as multi-unit recycling train processes, the number of machines used in the process exceeded the available PaLATE equipment inputs. A second PaLATE spreadsheet was used to accommodate for the additional equipment, meaning for eight of the nine projects there were three PaLATE spreadsheets: (1) Mill and Overlay, (2) CIR Run 1, and (3) CIR Run 2. Total CIR environmental impacts for the multi-unit recycling trains was considered to be the sum of the outputs of spreadsheet (2) and (3). Hauling distances from the asphalt plant to the project site were found using site locations provided by the contractors and were calculated to the midpoint of each project using Google Maps.

With all inputs compiled, each assessment was run in the PaLATE spreadsheet. For this report, the impact assessment results for energy use, water consumption, and carbon dioxide emissions were compared for both CIR and Mill and Overlay. Conclusions were drawn such that the results of this project can help future contractors in Wisconsin to estimate the savings associated with using CIR instead of Mill and Overlay for their highway construction projects.

Assumptions

In order to input the inventory data into PaLATE, some assumptions had to be made:

- Mill and Overlay projects were assumed to have milling depths of 4 - 5 inches and HMA Overlay of 4 - 4.5 inches.
- Mix design was assumed to be the same for the Mill and Overlay process and the CIR process for a given project; however, the HMA mix design varied between each project based upon asphalt binder percentages provided from the job mix formulas.
- Material quantities were assumed to be those found in the State of Wisconsin Department of Transportation Proposed Plan of Improvement specific to each project.
- Hauling distances were assumed to be from the midpoint of each project to the closest HMA plant provided by each contractor.
- Hauling distance was assumed to be the same for material hauled to the project site and material hauled away from the project site.
- Material densities were assumed to be the listed densities in PaLATE, see Appendix A.
- Due to the use of outdated equipment and lack of performance data on this equipment, all projects using a multi-unit recycling train were assumed to use the same equipment within the train. More equipment information can be found in Appendix A.
- Water trucks were not included in the analyses because they were used in both the Mill and Overlay alternative and the CIR process.

- Initial construction was not considered because each of the projects was completed on existing roads. Instead maintenance materials, transportation, and construction were analyzed.

Approach

Quantities and equipment were entered into the PaLATE spreadsheet and the environmental impact outputs were retrieved. For calculation examples, refer to the Appendix A. The assessment procedure for each project site went as follows:

Step 1. Enter the project specifications (length, width, and depth) into the PaLATE spreadsheet's "Design" page.

Step 2. Calculate the volume (CY) of virgin aggregate, asphalt cement (bitumen), recycled asphalt pavement (RAP), CIR, Hot-in-Place Recycling (HIPR)[b], and RAP to landfill quantities[c] using the data provided by the construction plans for Mill and Overlay.

Step 3. Enter each into the PaLATE spreadsheet's "Maintenance" page.

Step 4. Enter the project equipment provided by the construction companies into the PaLATE spreadsheet's "Equipment" page.

Step 5. Gather the environmental outputs from the "Environmental Results" page.

Step 6. Repeat this process using the data provided by the construction plans for CIR.

Step 7. For multi-unit recycling trains, perform a second PaLATE run to account for additional equipment.

[b] There was no HIPR in any of the projects; however, the HIPR PaLATE input cell was used in the assessment to account for the volume of milled material in the processes. For a more detailed breakdown of PaLATE inputs, refer to Appendix A. Calculations.

[c] RAP to landfill is the name of the PaLATE cell, but for this assessment we assumed there was no RAP taken to landfill but rather this cell was used to track Excess RAP to HMA plant.

Results

The results of the nine projects were analyzed using a few different methods. Table 1 below illustrates the variables that were subject to change with every project. Thickness of HMA for Mill and Overlay and CIR, road width, and project length all affect the quantities of materials needed for construction, as well as determine the amount of hauling trips needed to transport the materials to and from the site. Distance from the midpoint of the project to the HMA plant, the type of recycling train used, and equipment for Mill and Overlay all control the transportation and construction related environmental impacts. For a breakdown of the specific savings of a given project, refer to the *Individual Project Details* (Page 27). For additional information regarding project details such as equipment and quantities of materials, refer to the project specific appendices, B through J.

Table 1. Summary of Project Information.

Project	Mill and Overlay HMA Thickness (inches)	CIR Base Thickness (inches)	CIR HMA Thickness (inches)	Road Width (ft)	Project Length (miles)	Hauling Distance (miles)[d]	Excess RAP Hauled Away (tons)[e]	Single- or Multi-Unit Recycling Train
CTH H	4.5	4	3.5	30	9.5[f]	5.3	0	Multi[c]
STH 13	4	4	2.25	30	5.64	11.6	5811	Multi
STH 27	4	4	2.25	30	8.99	8.7	9206	Single
STH 48 (Rice Lake)	4	3	2	30	8.10	10.3	8898	Multi
STH 48 (Grantsburg)	4	4	2.25	24	12.5	4.3	10382	Multi
STH 64	4	4	3	30	4.46[g]	3.7	5426	Multi
STH 72	4	4	2.25	30	4.63	18.3	0	Multi
STH 95	4	4	2.5	30	4.42	24.4	0	Multi
STH 187	4	3	2.5	30	9.84	21.3	5575	Multi

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[d] Hauling distance to the nearest asphalt plant taken from the midpoint of the project, see Project Appendices for maps.
[e] The asphaltic surface was too distressed to use for CIR, so it was hauled to the HMA plant.
[f] Originally a 12.3-mile project. 2.8 miles were constructed using single-unit recycling train and the remaining 9.5 were constructed using a multi-unit recycling train. This project was looked at as a 9.5-mile multi-unit project. The project quantities were adjusted. See Appendix B. CTH H Project Information.
[g] This is a 13.3-mile project for which 4.5 were constructed using a multi-unit recycling train and the remaining 8.8 miles were constructed using MOL due to inclement weather.

Environmental parameters were assessed at the material production, transportation, and construction levels and combined as total percent reductions. Percent reductions in environmental outputs behave relatively consistently throughout the nine projects. The average reduction in energy consumption and carbon dioxide emissions is 23% and for water usage 20%. The percent reductions within each of the environmental output categories for each project are illustrated in Figure 5 below. For calculation of percent reduction, refer to Appendix A, Calculations.

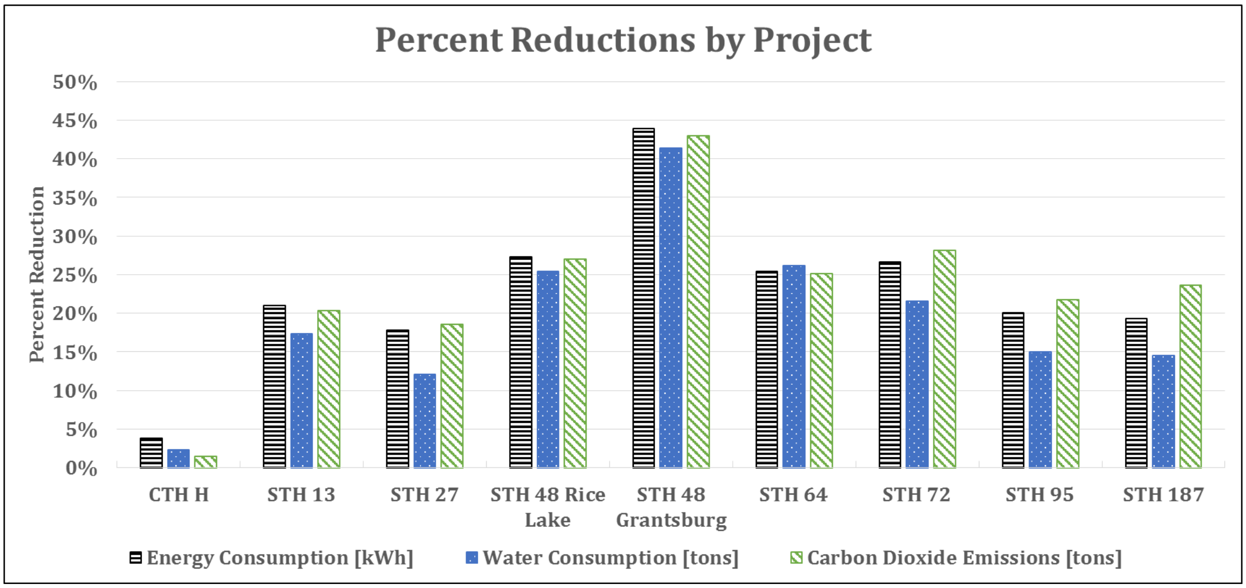

Figure 5. Percent reductions achieved using CIR in place of Mill and Overlay for each project.

The nine projects saved 24,341,387 kWh of energy, 30 tons of water, and 5,029 tons of carbon dioxide emissions in total. A summary of savings by project can be found below in Table 2. The cumulative savings translate to a savings in energy equivalent to the energy consumption of 2,226 U.S. households for a year, a savings in carbon dioxide emissions equivalent to pulling 971 cars off the road for a year, and a savings in water equivalent to 158 bathtubs (Transportation, Air Pollution, and Climate Change, U.S. EPA), (Portland Water Bureau), (U.S. Energy Information Administration).

Table 2. Environmental Savings by Project.

Project	Energy Consumption [kWh]	Water Consumption [tons]	Carbon Dioxide Emissions [tons]	Virgin Aggregate Savings [tons]
CTH H	1,102,742	1.0	209	6,880
STH 13	2,008,621	2.3	411	7,620
STH 27	2,030,254	1.8	395	12,436
STH 48 Rice Lake	3,930,466	5.1	820	11,142
STH 48 Grantsburg	8,394,554	11.0	1,738	23,802
STH 64	3,490,967	5.3	752	4,068
STH 72	1,042,298	1.1	214	4,762
STH 95	1,200,413	1.2	250	5,159
STH 187	1,141,070	1.0	239	5,826
Total	**24,341,387**	**29.7**	**5,029**	**81,694**

Due to the thinner HMA overlay needed for CIR projects, virgin aggregate consumption was reduced by 37%. The environmental savings achieved in each of the nine projects are predominantly the result of the reduction of virgin materials, as further demonstrated in the *Individual Project Details* section of this report where environmental savings are subdivided into material production-related, transportation-related, and construction-related savings. In fact, the CIR process requires some additional construction activity because two layers are placed: compacted CIR and the thinner HMA overlay. Other studies that have looked at the environmental impacts of CIR have concluded that hauling distance is the key factor in savings (Tabakovic et al, 2016), (Tuk et al, 2016), (Thenoux et al, 2007). Figures 6-8 below show the savings of each project overlain with a line representing the hauling distance of each project. These figures indicate that there is another key driving factor in environmental savings when using CIR. This report has determined that HMA saved using CIR is the largest influential factor.

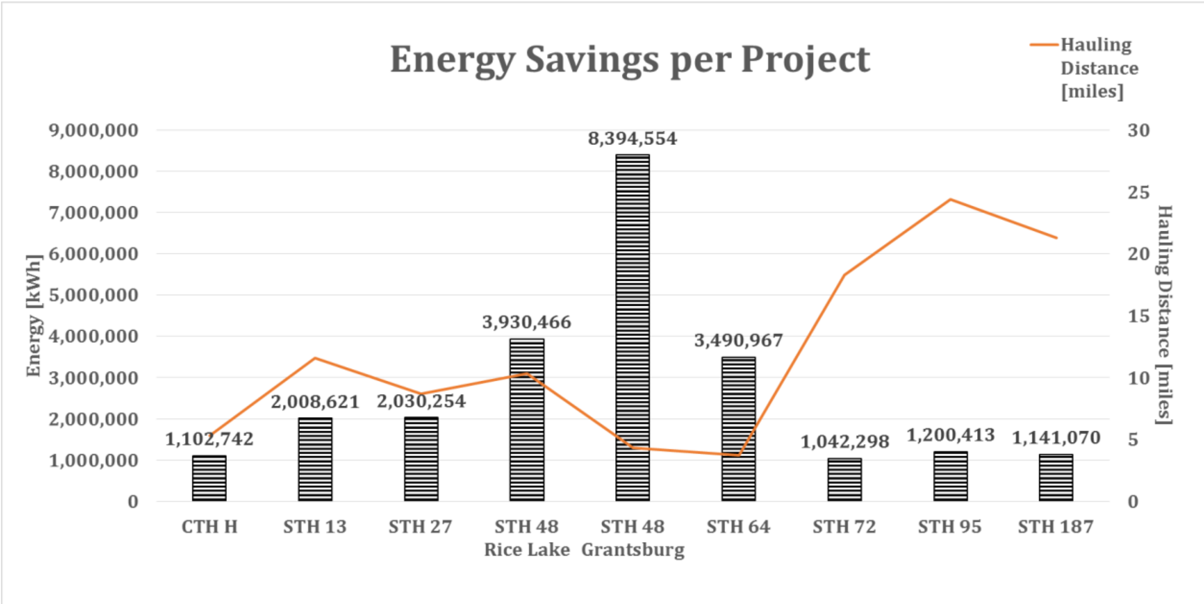

Figure 6. Energy savings achieved per project. Plotted with hauling distance.

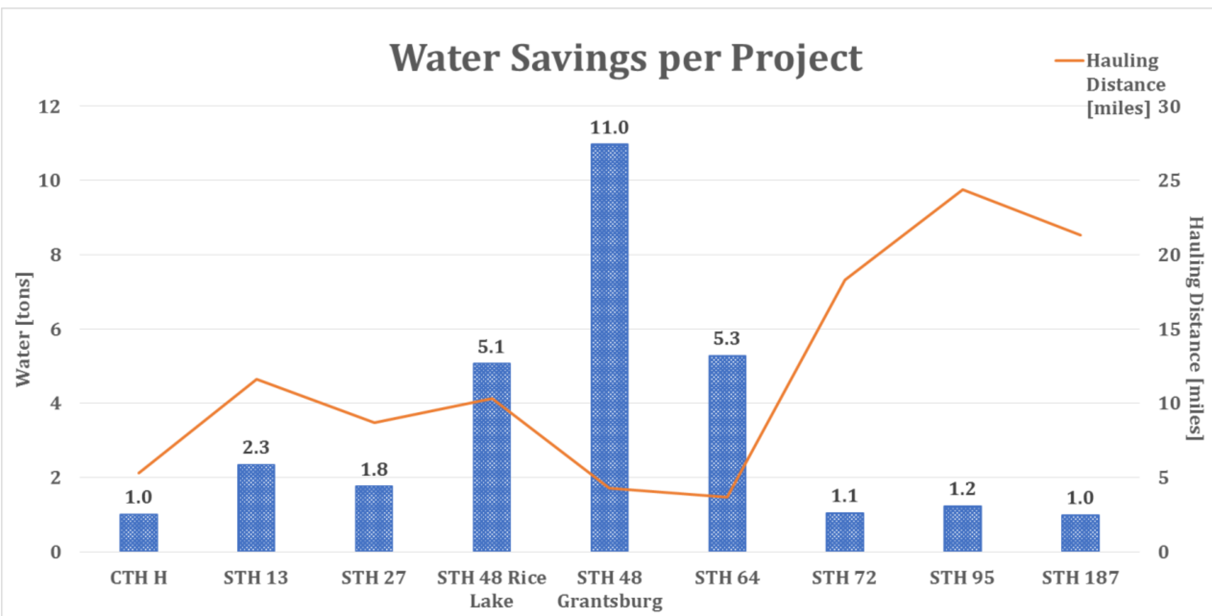

Figure 7. Water savings achieved per project. Plotted with hauling distance.

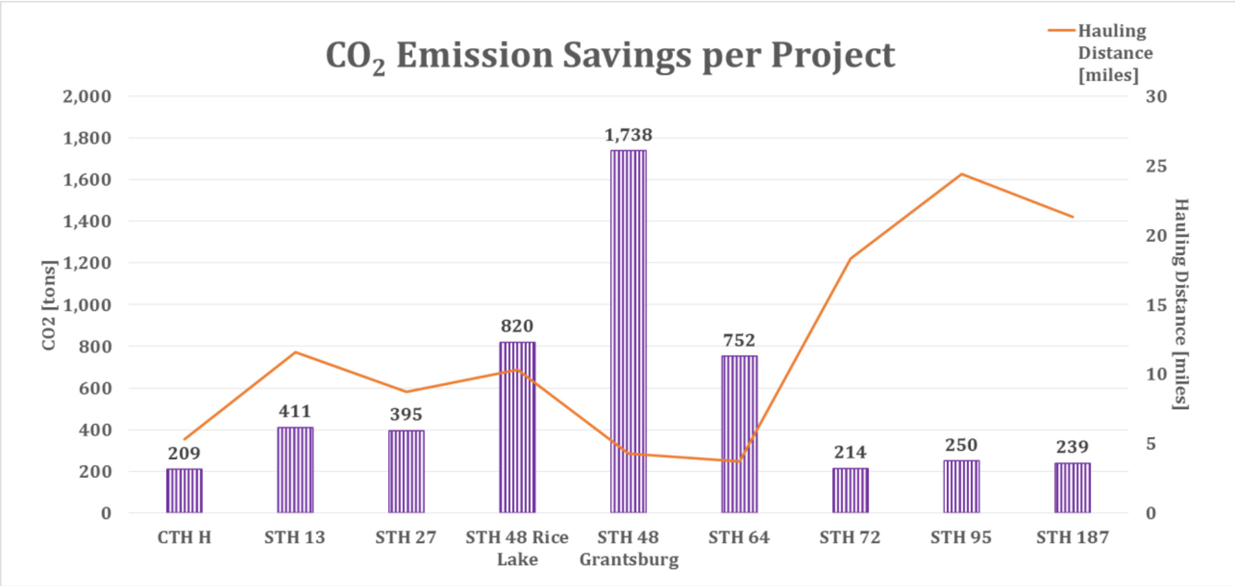

Figure 8. Carbon dioxide emission savings achieved per project. Plotted with hauling distance.

Analysis of Data and Observed Trends

To normalize the data and demonstrate the parameters in a project that will determine the savings, Figures 9-11 below were generated. These graphs represent a framework for the quantity of savings achieved by using CIR in place of Mill and Overlay by reducing the project specifications to one number: volume of HMA avoided divided by hauling distance. In the figures, this number is labeled as Normalized HMA Reduction on the horizontal axis. This normalization produces a linear trend, which demonstrates that the two key factors in CIR savings with respect to Mill and Overlay are reduction in HMA production and hauling distance. It should be noted that when CTH H and the single train project, STH 27, are removed from the data set, the linear correlation improves and the R^2 values increases to around 0.95. For CTH H, the layer of HMA placed over the CIR base is particularly thick. This resulted in only a one inch reduction in HMA use when CIR was implemented, relative to traditional Mill and Overlay, whereas all other projects had a larger reduction in HMA thickness proportionally. The resource intensive nature of asphalt makes reduction of HMA a key factor in the environmental savings achieved by using CIR instead of Mill and Overlay. For that reason, the environmental savings achieved in CTH H are less significant than in other projects because there is a smaller reduction in the HMA profile. An example of how a construction company would use these figures in future projects to estimate their energy, water, and carbon dioxide savings achieved by using CIR is offered in Appendix A, Example Project Savings Projection.

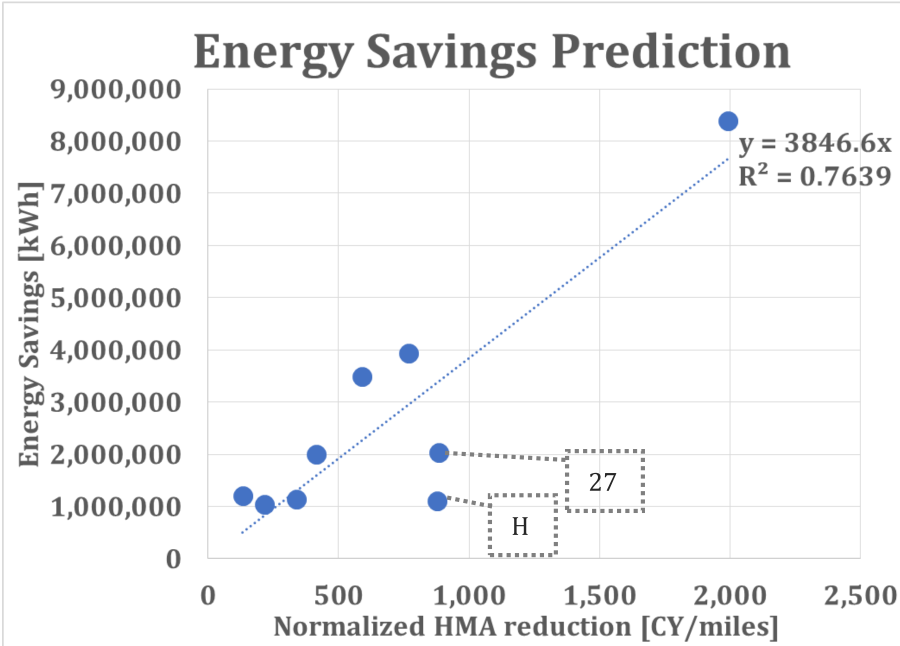

Figure 9. Energy Savings Predictions.

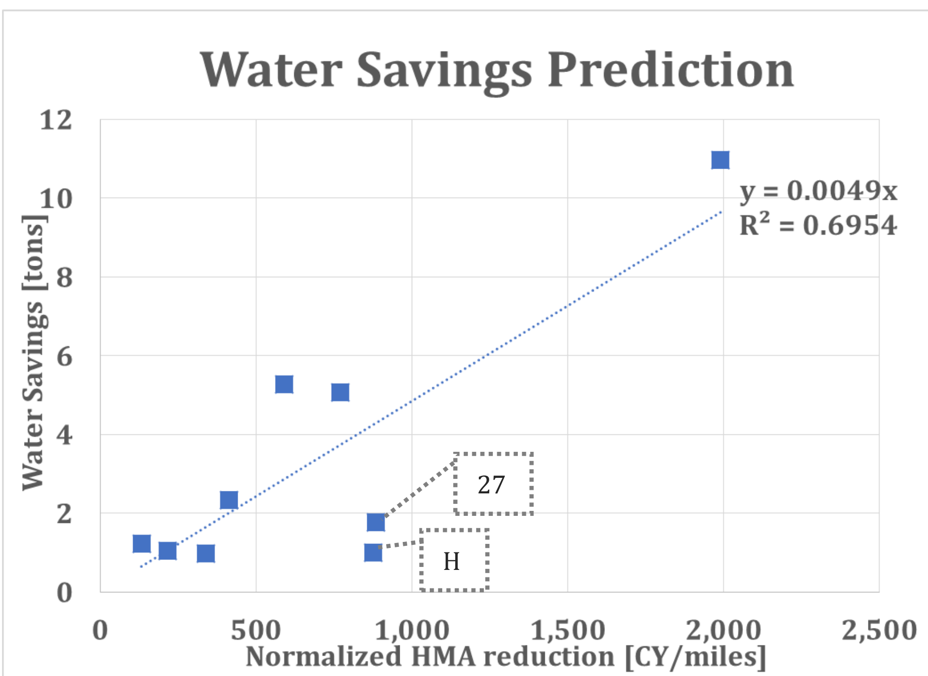

Figure 10. Water Savings Projections.

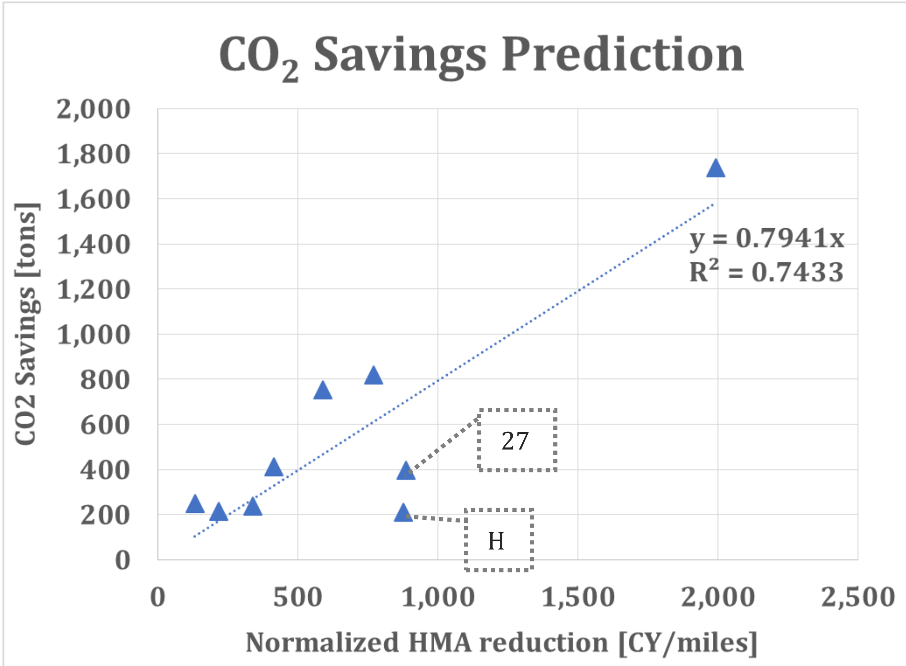

Figure 11. Carbon Dioxide Savings Predictions.

Individual Project Details

Project 1: CTH H

This project was located on CTH H in Sauk County, covering 9.5 miles from Reedsburg to Wisconsin Dells. Completed in 2015 by Mathy, the treatment comprised of 4 inches of CIR below 3.5 inches of new HMA overlay with 5.2% asphalt binder. The hauling distance for this project was 5.3 miles.

The length of this project was 12.3 miles, 2.8 miles of which was constructed using a single-unit recycling train and the remaining 9.5 miles of which were constructed using a multi-unit recycling train. For simplicity, this report neglected the 2.8 miles of single-unit and adjusted quantities such that the project was analyzed as a 9.5-mile multi-unit recycling train project. Additional project information can be found in Appendix B.

The implementation of the CIR process for this project yielded a total energy savings of 1,102,742 kWh, reduced water usage by 1.01 tons, and reduced carbon dioxide emission by 209 tons. The breakdown of each savings can be found in Figure 12 below.

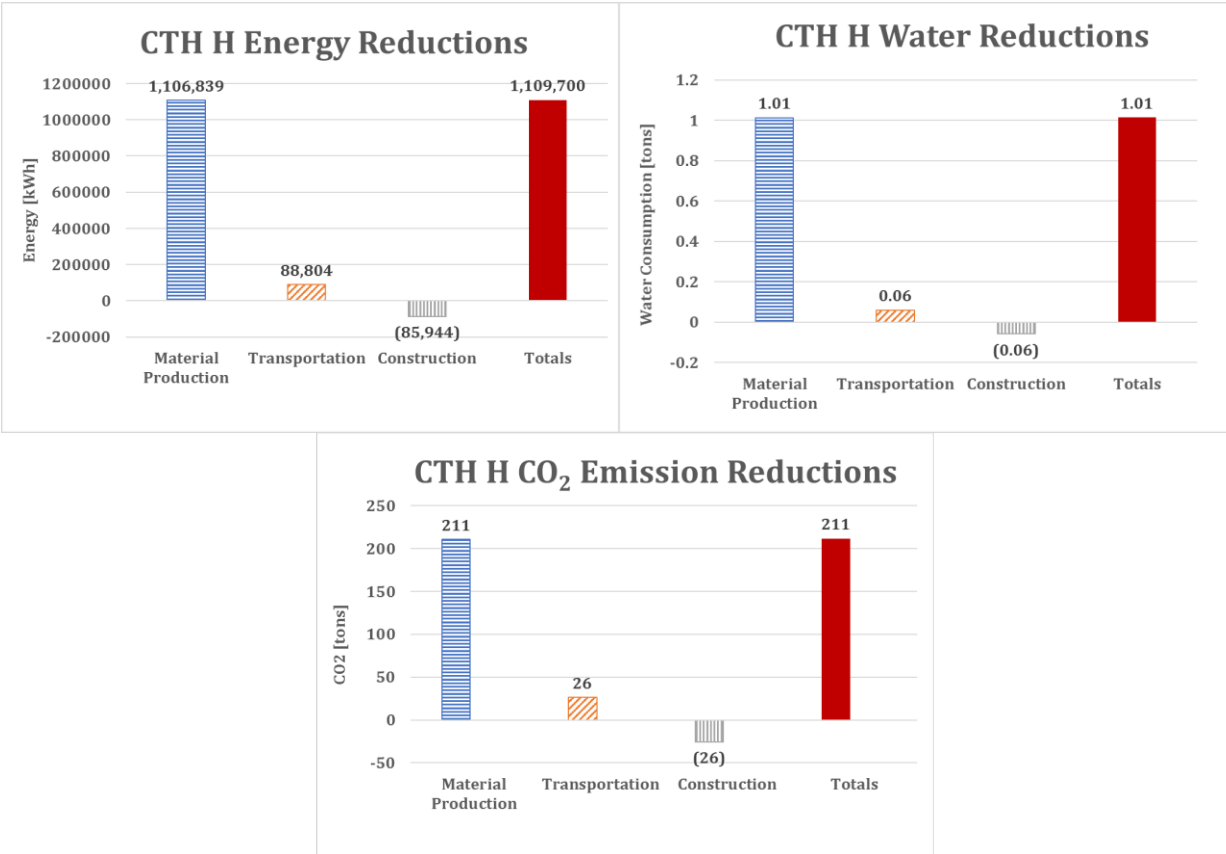

Figure 12. Environmental savings achieved at each phase of CTH H.

When compared to Mill and Overlay these gross savings translate to a 3.9% reduction in energy used, 2.3% reduction in water consumption, and a 1.5% reduction in carbon dioxide emitted. Total percent reductions achieved were the lowest in CTH H out of all nine projects evaluated. This is likely because the difference in HMA overlay required for CIR was only one inch less than what it would have been for Mill and Overlay, so there was not as significant of a reduction in virgin materials and material-production-related emissions. The percent reductions achieved by each element of the process are illustrated in Figure 13 below.

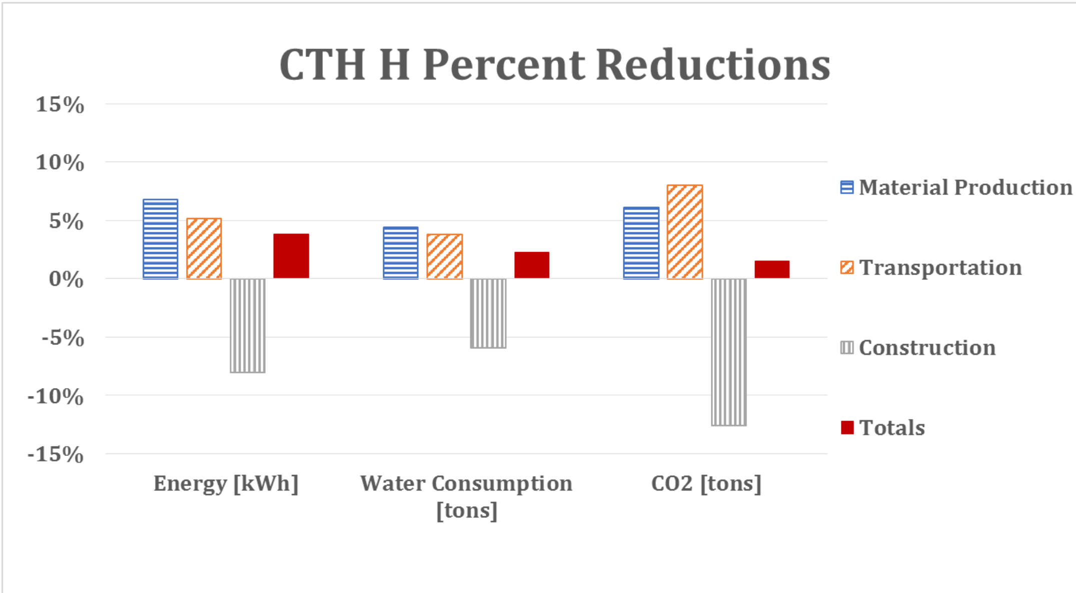

Figure 13. Percent reductions achieved in each phase of CTH H.

Project 2: STH 13

This project was located on STH 13 in Taylor County, covering 5.6 miles from Medford to Westboro. Under construction in 2016 by WK and Mathy using a multi-unit recycling train, the treatment was 4 inches of CIR under 2.25 inches of new HMA overlay with 6.3% asphalt binder. The hauling distance for this project was 11.6 miles.

The implementation of the CIR process for this project yielded a total energy savings of 2,008,621 kWh, reduced water usage by 2.35 tons, and reduced carbon dioxide emission by 411 tons. The breakdown of each savings can be found in Figure 14 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

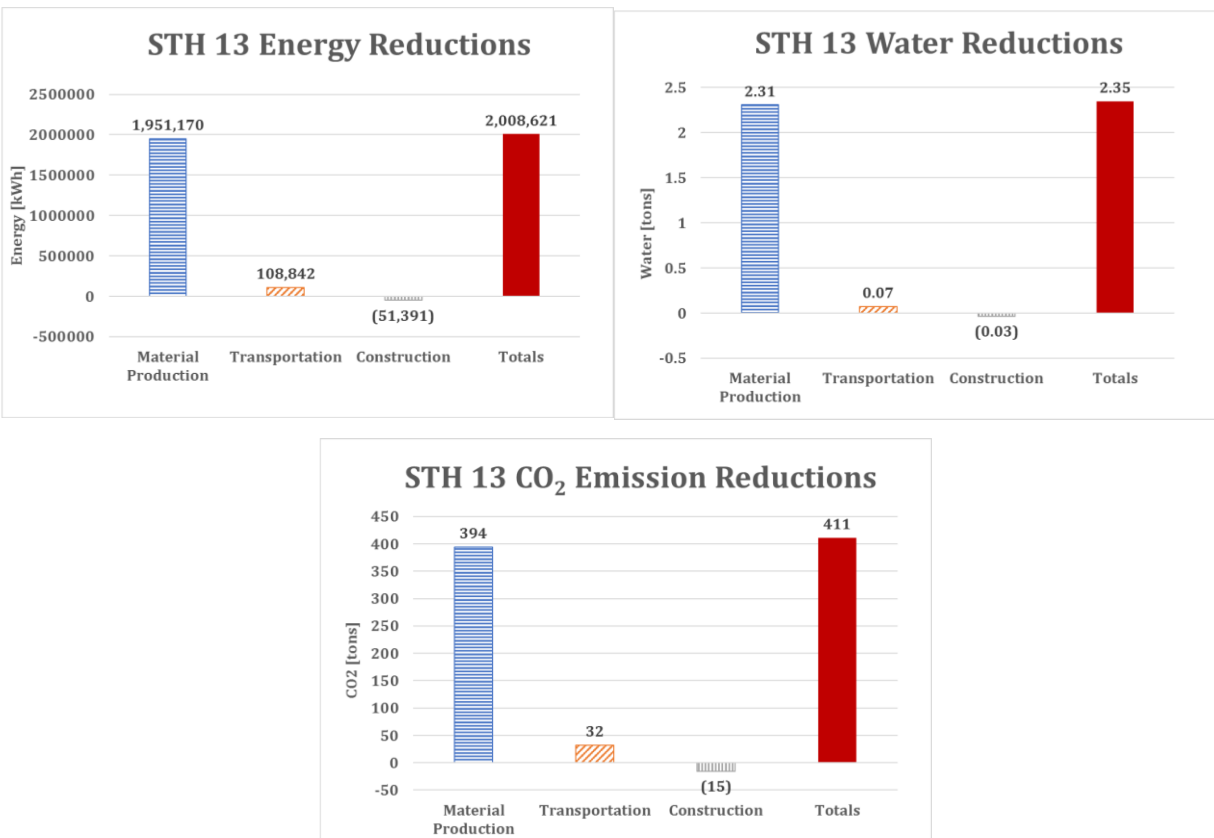

Figure 14. Environmental savings achieved at each phase of STH 13.

When compared to Mill and Overlay these gross savings translate to a 21% reduction in energy used, 17% reduction in water consumption, 20% reduction in and carbon dioxide emitted.

The percent reductions achieved by each element of the process are illustrated in Figure 15 below. Additional project information can be found in Appendix C.

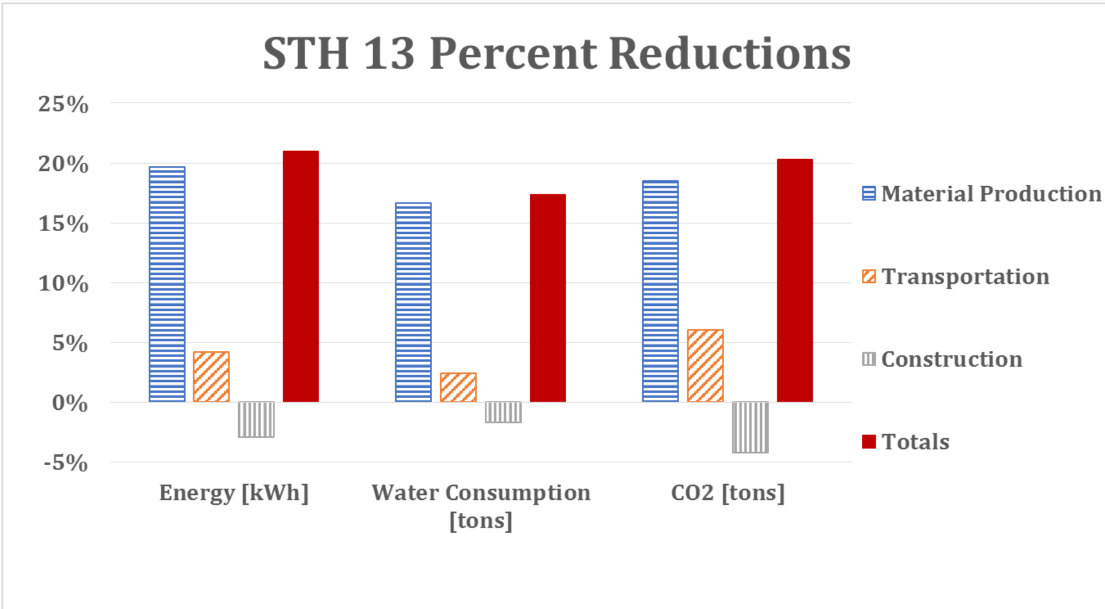

Figure 15. Percent reductions achieved in each phase of STH 13.

Project 3: STH 27

This project was located on STH 27 in Jackson County, covering 9.0 miles from Sparta to Black River Falls. Completed in 2016 by Mathy using a single-unit recycling train, the treatment was 4 inches of CIR beneath 2.25 inches of new HMA overlay with 5.4% asphalt binder. This was the only project in the report that used a single-unit recycling train. The hauling distance for this project was 8.7 miles.

The implementation of the CIR process for this project yielded a total energy savings of 2,030,254 kWh, reduced water usage by 1.8 tons, and reduced carbon dioxide emission by 395 tons. The breakdown of each savings can be found in Figure 16 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

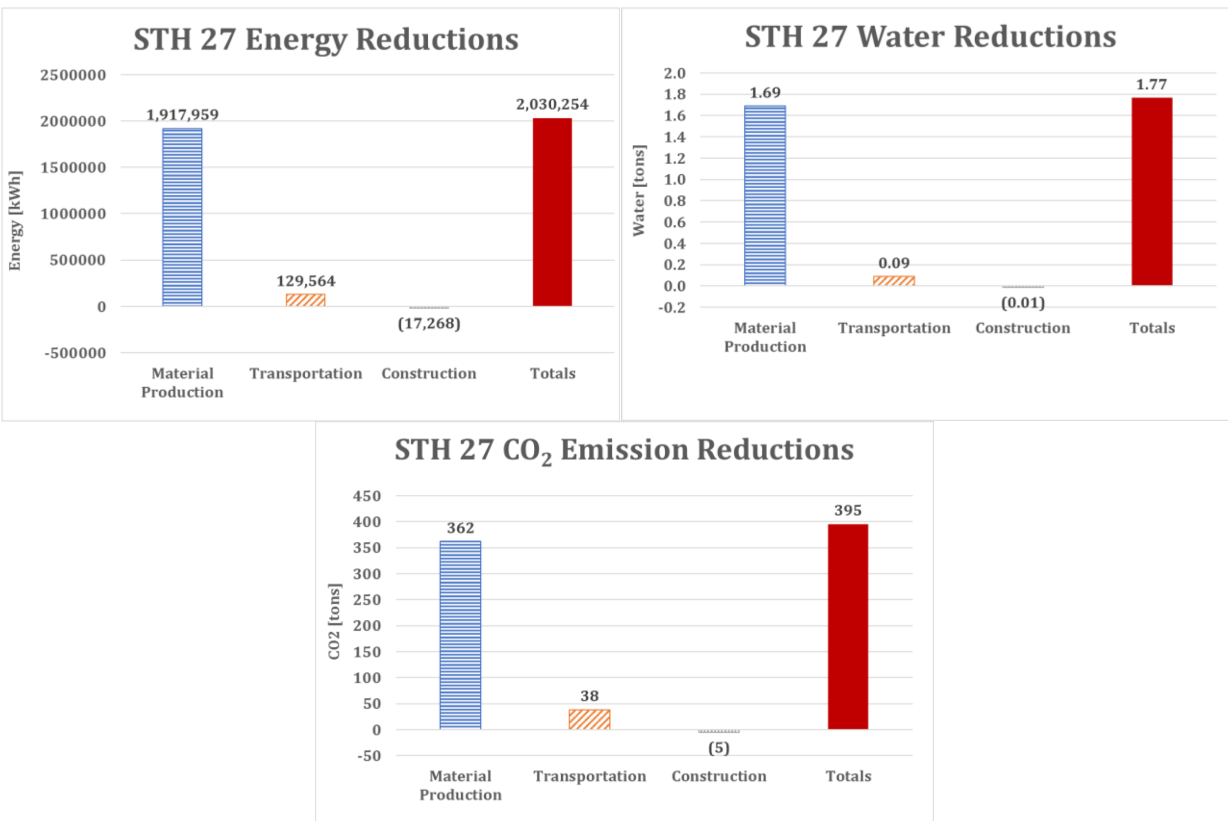

Figure 16. Environmental savings achieved at each phase of STH 27.

When compared to Mill and Overlay these gross savings translate to a 18% reduction in energy used, 12% reduction in water consumption, and a 19% reduction in carbon dioxide emitted. The percent reductions achieved by each element of the process are illustrated in Figure 17 below. Additional project information can be found in Appendix D.

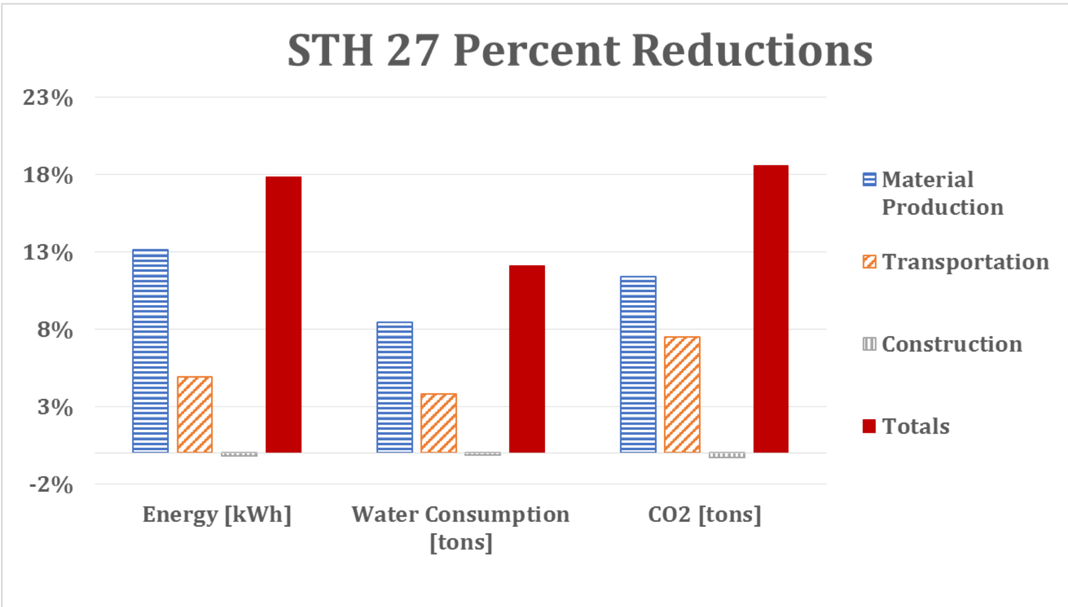

Figure 17. Percent reductions achieved in each phase of STH 27.

Project 4: STH 48 Rice Lake

This project was located on STH 48 in Barron County, covering 8.1 miles from Rice Lake to Birchwood. Completed in 2015 by WK and Mathy using a multi-unit recycling train, the treatment was 3 inches of CIR under 2 inches of new HMA overlay with 5.6% asphalt binder. The hauling distance for this project 10.3 miles.

The implementation of the CIR process for this project yielded a total energy savings of 3,930,466 kWh, reduced water usage by 5.1 tons, and reduced carbon dioxide emission by 820 tons. The breakdown of each savings can be found in Figure 18 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

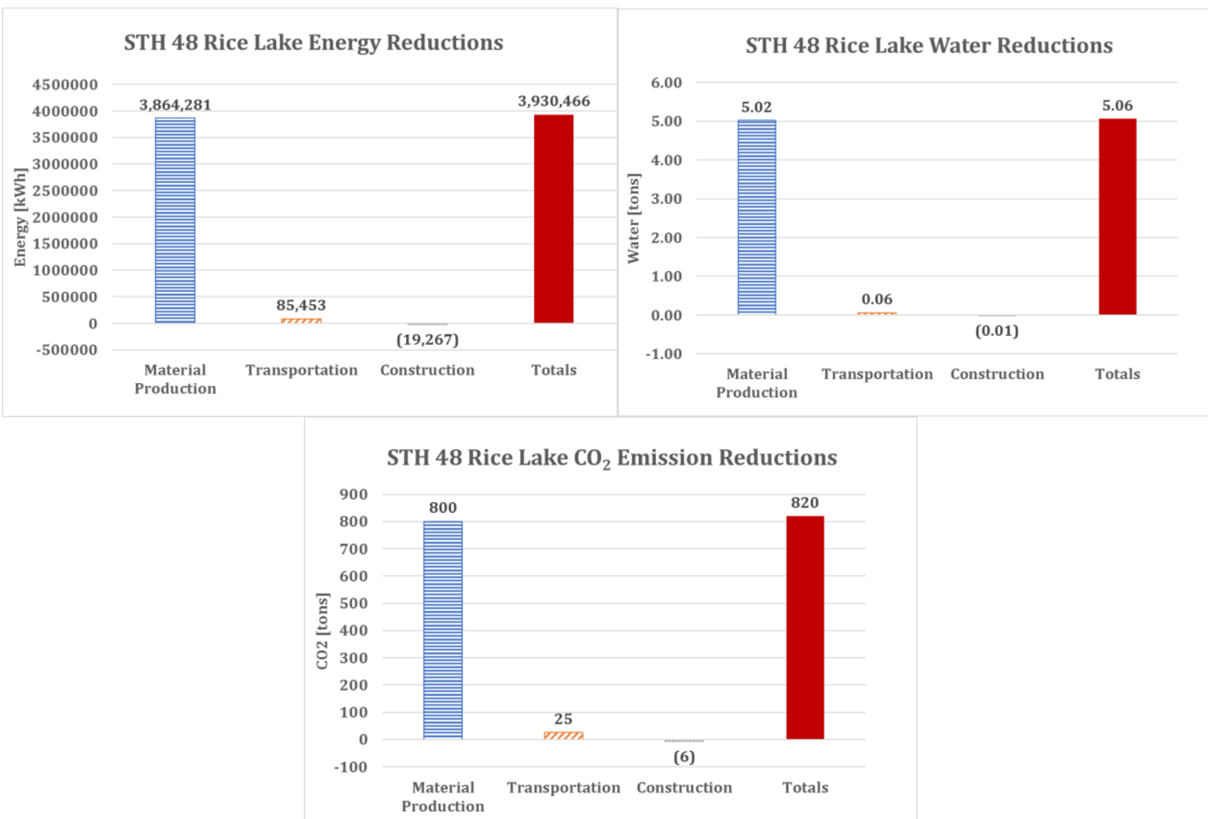

Figure 18. Environmental savings achieved at each phase of STH 48 Rice Lake.

When compared to Mill and Overlay these gross savings translate to a 27% reduction in energy used, 25% reduction in water consumption, and a 27% reduction in carbon dioxide emitted. The percent reductions achieved by each element of the process are illustrated in Figure 19 below. Additional project information can be found in Appendix E.

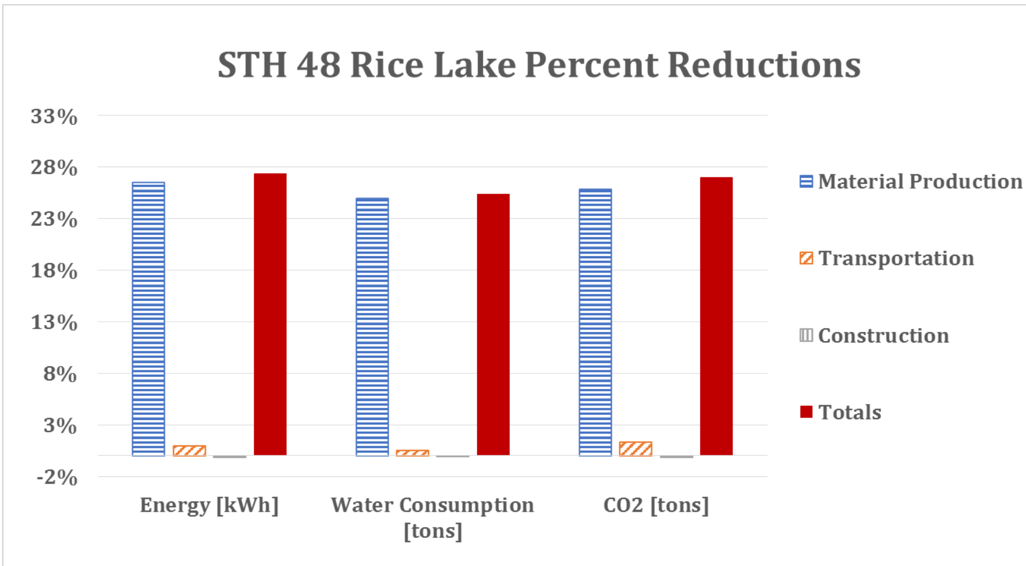

Figure 19. Percent reductions achieved in each phase of STH 48 Rice Lake.

Project 5: STH 48 Grantsburg

This project was also located on STH 48 in Burnett and Polk Counties, covering 12.5 miles from Grantsburg to Frederic. Completed in 2012 by WK and Mathy using a multi-unit recycling train, the treatment was 4 inches of CIR under 2.25 inches of new HMA overlay with 5.5% asphalt binder. The hauling distance for this project was 4.3 miles.

The implementation of the CIR process for this project yielded a total energy savings of 8,394,554 kWh, reduced water usage by 11 tons, and reduced carbon dioxide emission by 1,738 tons. The breakdown of each savings can be found in Figure 20 below. Most of the savings for each measure are realized in material production, some in transportation, and negative savings come from the construction phase as CIR is more of an intensive construction process than Mill and Overlay.

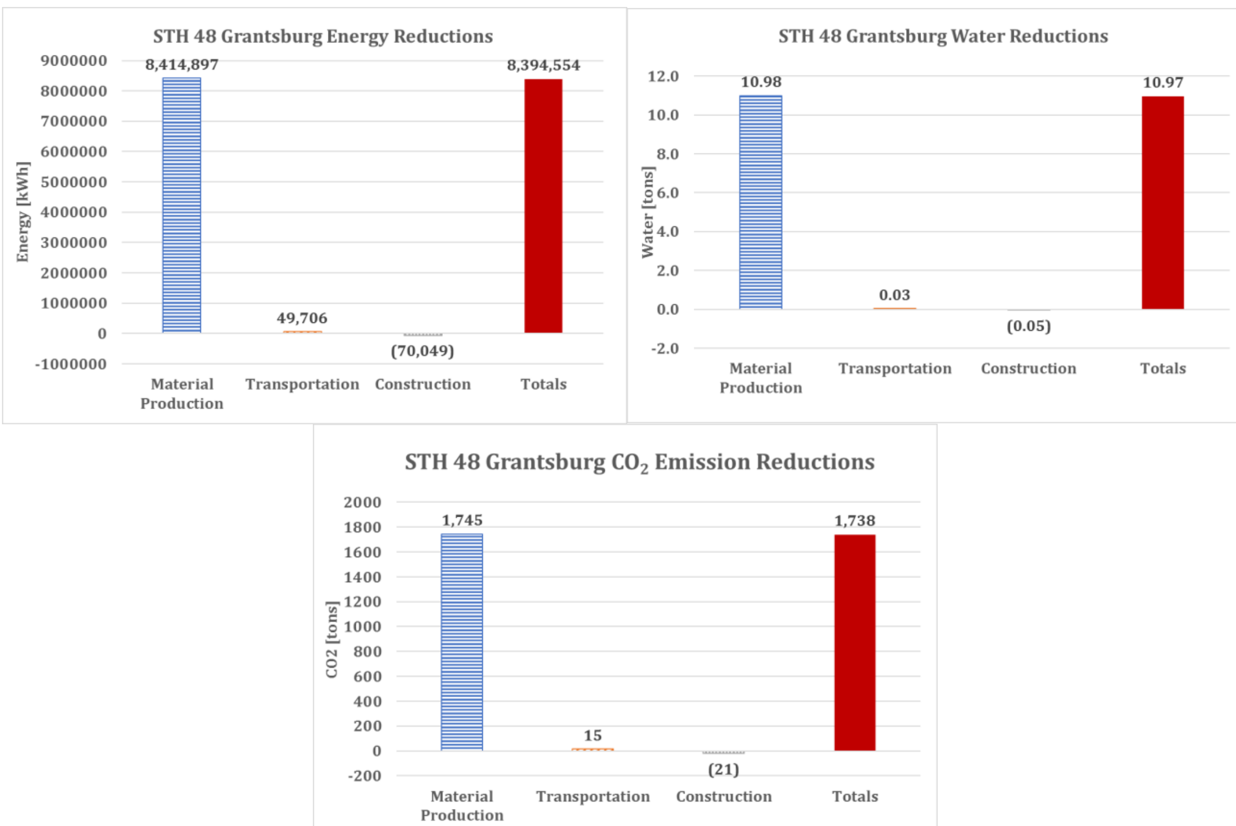

Figure 20. Environmental savings achieved at each phase of STH 48 Grantsburg.

When compared to Mill and Overlay these gross savings translate to a 44% reduction in energy used, 41% reduction in water consumption, and a 43% reduction in carbon dioxide emitted.

The percent reductions achieved in the STH 48 Grantsburg were the highest of any of the nine projects evaluated. This is likely because STH 48 Grantsburg was the longest of the projects with the biggest reduction in HMA overlay when using CIR in place of Mill and Overlay. Therefore, reduction in virgin materials on STH 48 Grantsburg was the largest of the nine projects, providing the most significant material production-related emission savings. The percent reductions achieved by each element of the process are illustrated in Figure 21 below. Additional project information can be found in Appendix F.

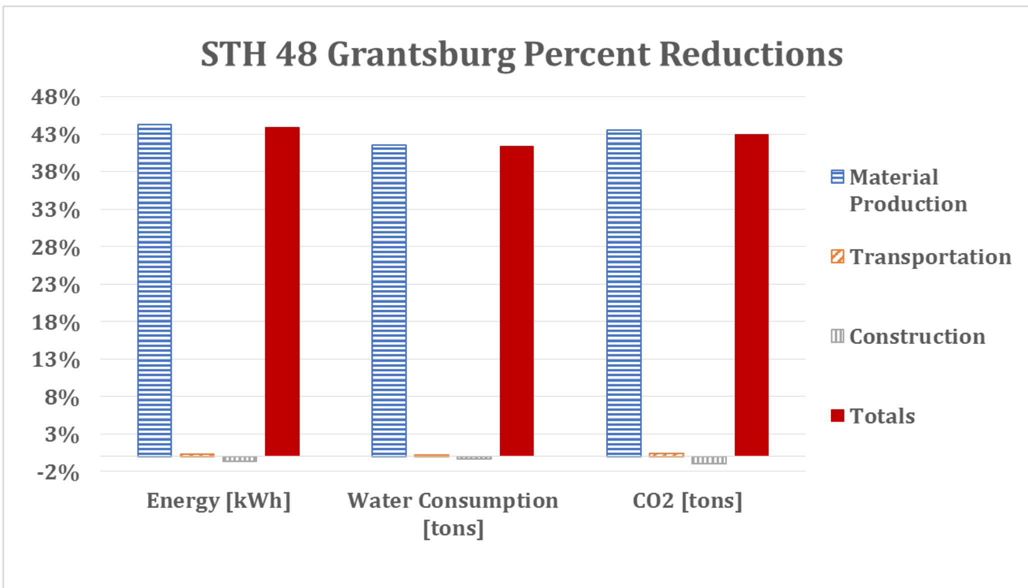

Figure 21. Percent reductions achieved in each phase of STH 48 Grantsburg.

Project 6: STH 64

This project was located on STH 64 in Taylor County, initially covering 13.3 miles from Gilman to Medford. Due to unfavorable weather conditions, 8.8 miles of this project were construction using conventional Mill and Overlay methods and the remaining 4.46 miles was constructed using CIR. In order to be consistent, the project was evaluated as a 4.46-mile project. Leveling layer. Completed in 2014 by WK using a multi-unit recycling train, the initial treatment was 4 inches of CIR under 3 inches of new HMA overlay with 5.8% asphalt binder. The hauling distance for this project was 3.7 miles.

The implementation of the CIR process for this project yielded a total energy savings of 3,490,967 kWh, reduced water usage by 5.3 tons, and reduced carbon dioxide emission by 752 tons. The breakdown of each savings can be found in Figure 22 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

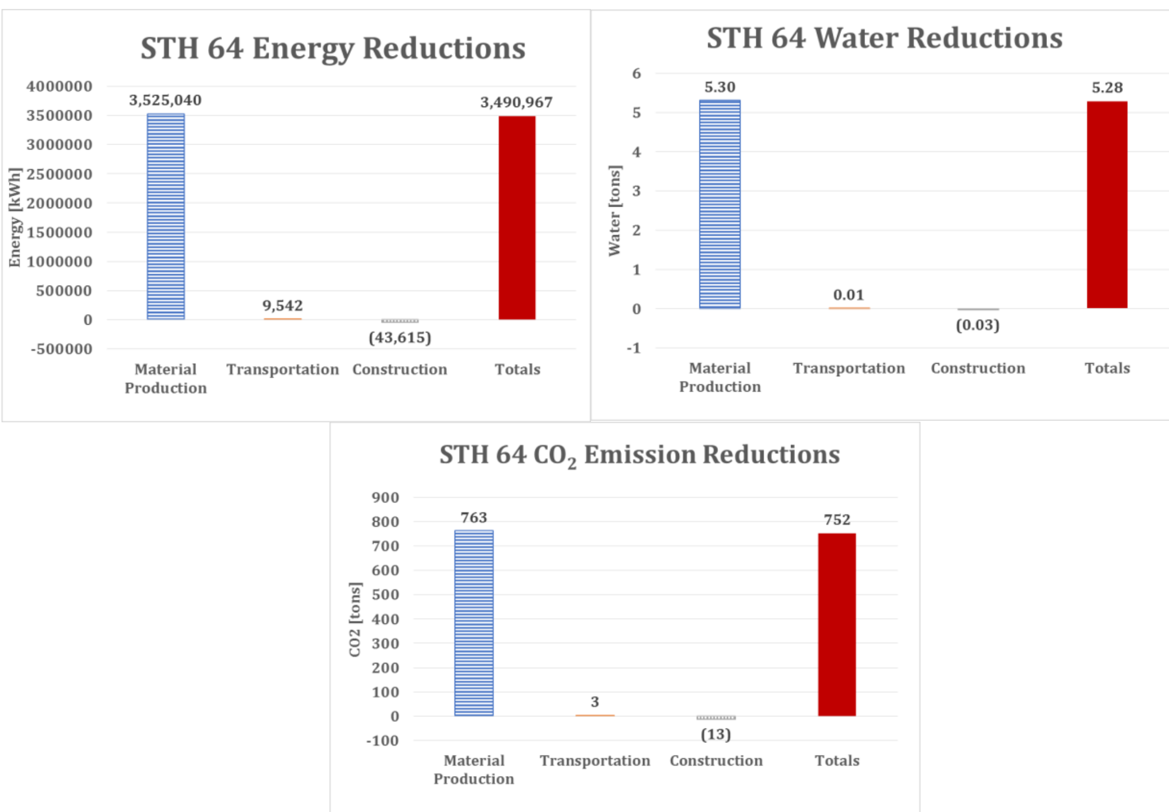

Figure 22. Environmental savings achieved at each phase of STH 64.

When compared to Mill and Overlay these gross savings translate to a 25% reduction in energy used, 26% reduction in water consumption, and 25% reduction in carbon dioxide emitted. The percent reductions achieved by each element of the process are illustrated in Figure 23 below. Additional project information can be found in Appendix G.

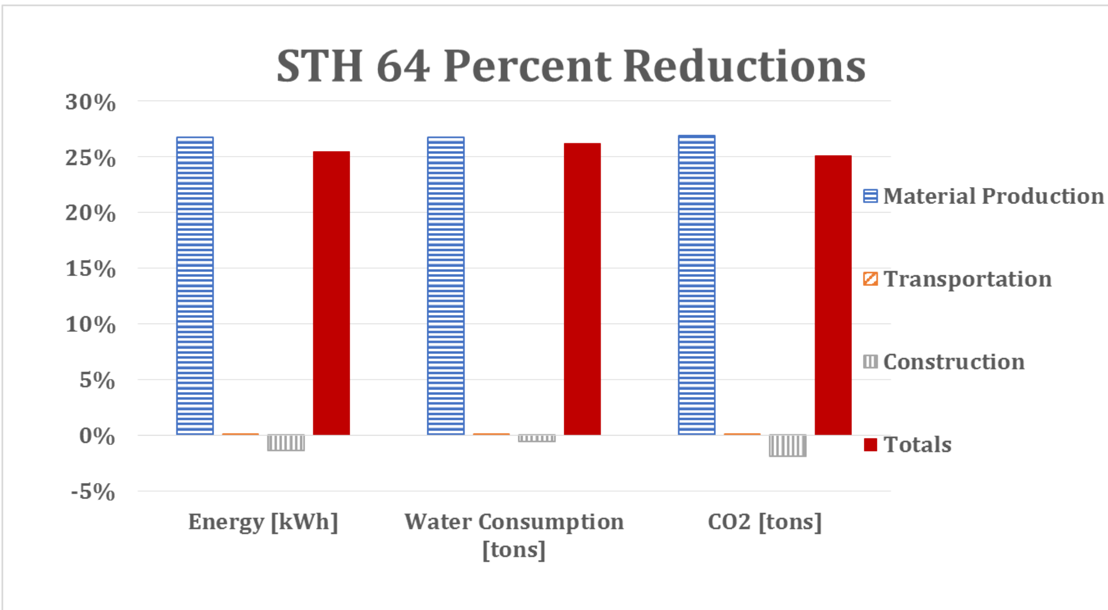

Figure 23. Percent reductions achieved in each phase of STH 64.

Project 7: STH 72

This project was located on STH 72 in Pierce County, covering 4.63 miles from Ellsworth to Elmwood. Complete in 2016 by WK and Mathy using a multi-unit recycling train, the treatment was 4 inches of CIR beneath 2.25 inches of new HMA overlay with 5.9% asphalt binder. The hauling distance for this project was 18.3 miles.

The implementation of the CIR process for this project yielded a total energy savings of 1,042,298 kWh, reduced water usage by 1.1 tons, and reduced carbon dioxide emission by 214 tons. The breakdown of each savings can be found in Figure 24 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

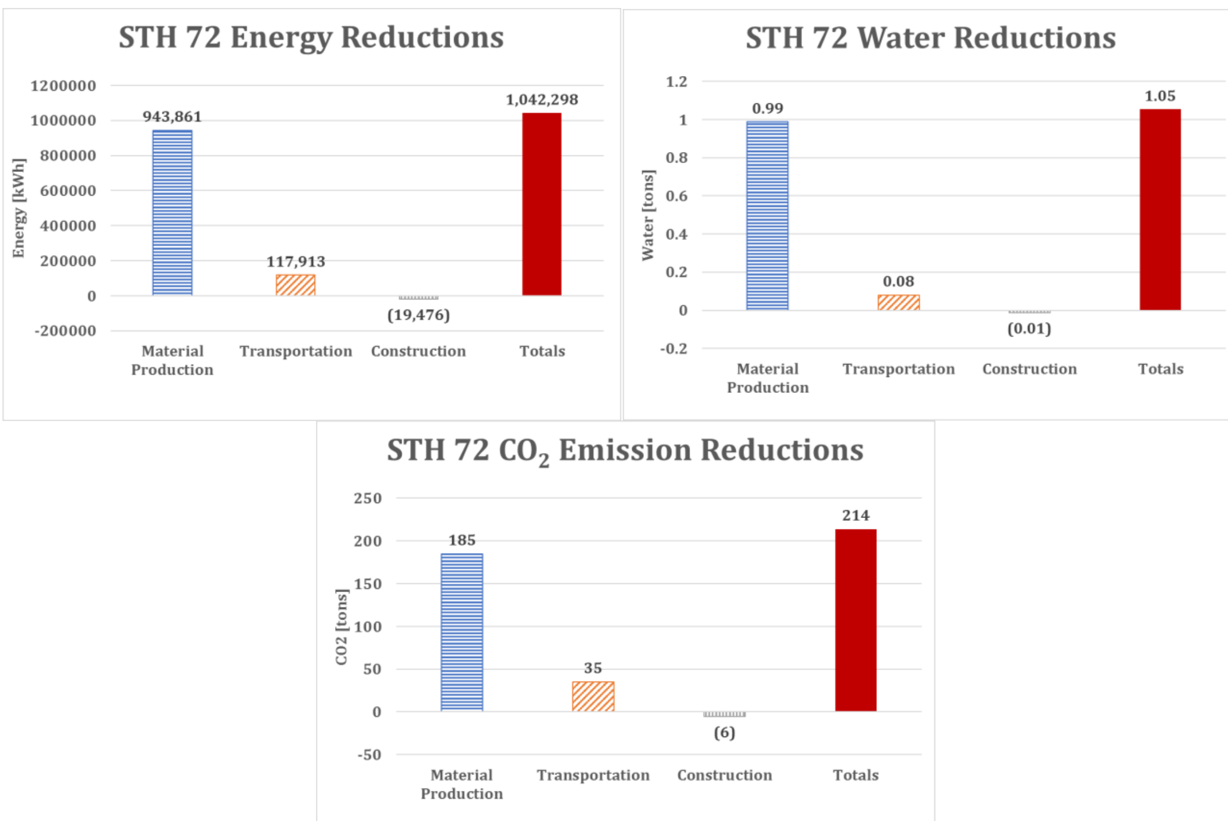

Figure 24. Environmental savings achieved at each phase of STH 72.

When compared to Mill and Overlay these gross savings translate to a 27% reduction in energy used, 22% reduction in water consumption, and 28% reduction in carbon dioxide emitted. percent reductions achieved by each element of the process are illustrated in Figure 25 below. Additional project information can be found in Appendix H.

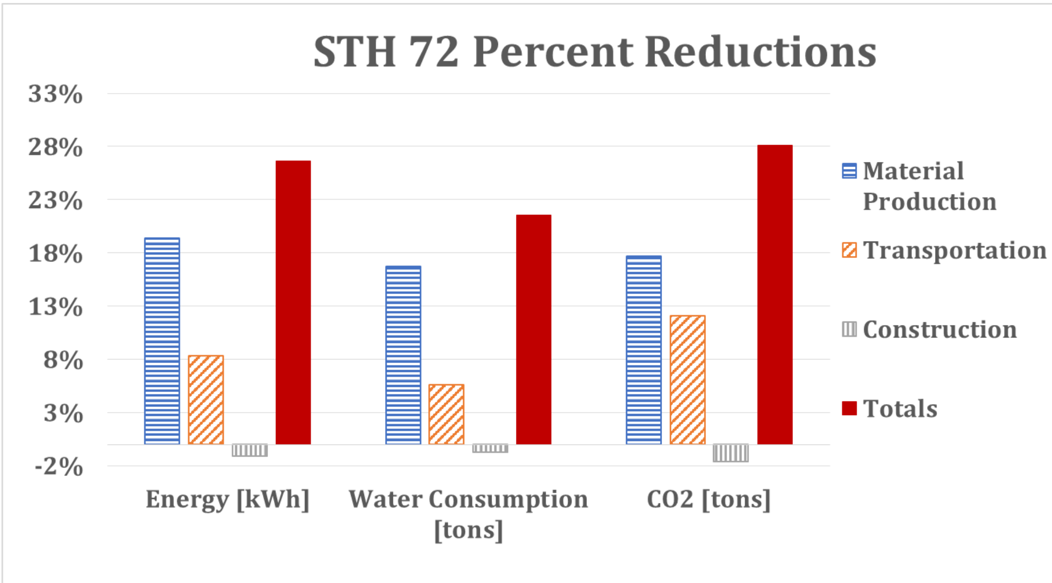

Figure 25. Percent reductions achieved in each phase of STH 72.

Project 8: STH 95

This project was located on STH 95 in Trempealeau County, covering 4.42 miles from Blair to Merrillan. Completed in 2015 by WK and Mathy using a multi-unit recycling train, the treatment was 4 inches of CIR under 2.5 inches of new HMA overlay with 5.75% asphalt binder. The hauling distance for this project was 24.4 miles.

The implementation of the CIR process for this project yielded a total energy savings of 1,200,413 kWh, reduced water usage by 1.2 tons, and reduced carbon dioxide emission by 250 tons. The breakdown of each savings can be found in Figure 26 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

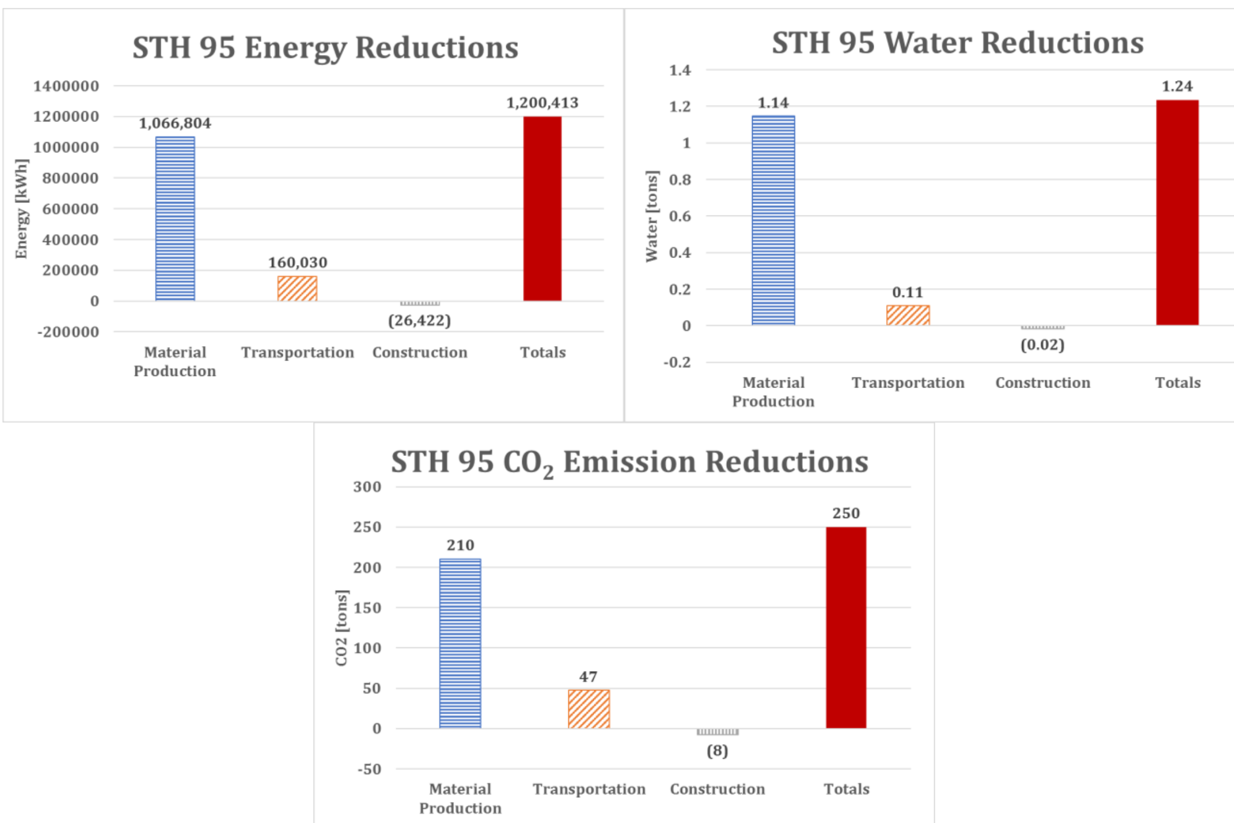

Figure 26. Environmental savings achieved at each phase of STH 95.

When compared to Mill and Overlay these gross savings translate to a 20% reduction in energy used, 15% reduction in water consumption, and a 22% reduction in carbon dioxide emitted. The percent reductions achieved by each element of the process are illustrated in Figure 27 below. Additional project information can be found in Appendix I.

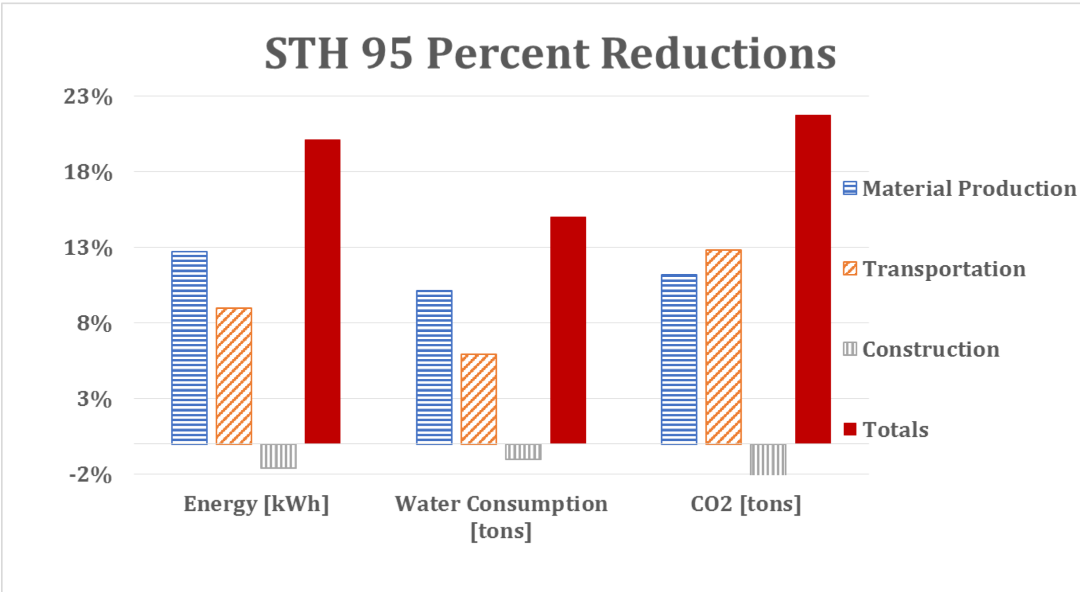

Figure 27. Percent reductions achieved in each phase of STH 95.

Project 9: STH 187

This project was located on STH 187 in Outagamie County, covering 9.84 miles from Shiocton to the North County Line. Completed in 2016 by Mid States Reclamation and Northeast Asphalt, the treatment consisted of 3 inches of CIR under 2.5 inches of new HMA overlay with 5.46% asphalt binder. This project was completed using a multi-unit recycling train. The hauling distance for the project was 21.3 miles.

The implementation of the CIR process for this project yielded a total energy savings of 1,141,070 kWh, reduced water usage by 1 ton, and reduced carbon dioxide emission by 239 tons. The breakdown of each savings can be found in Figure 28 below. Most of the savings for each measure are realized in material production, some in transportation, and very little or negative savings come from the construction phase.

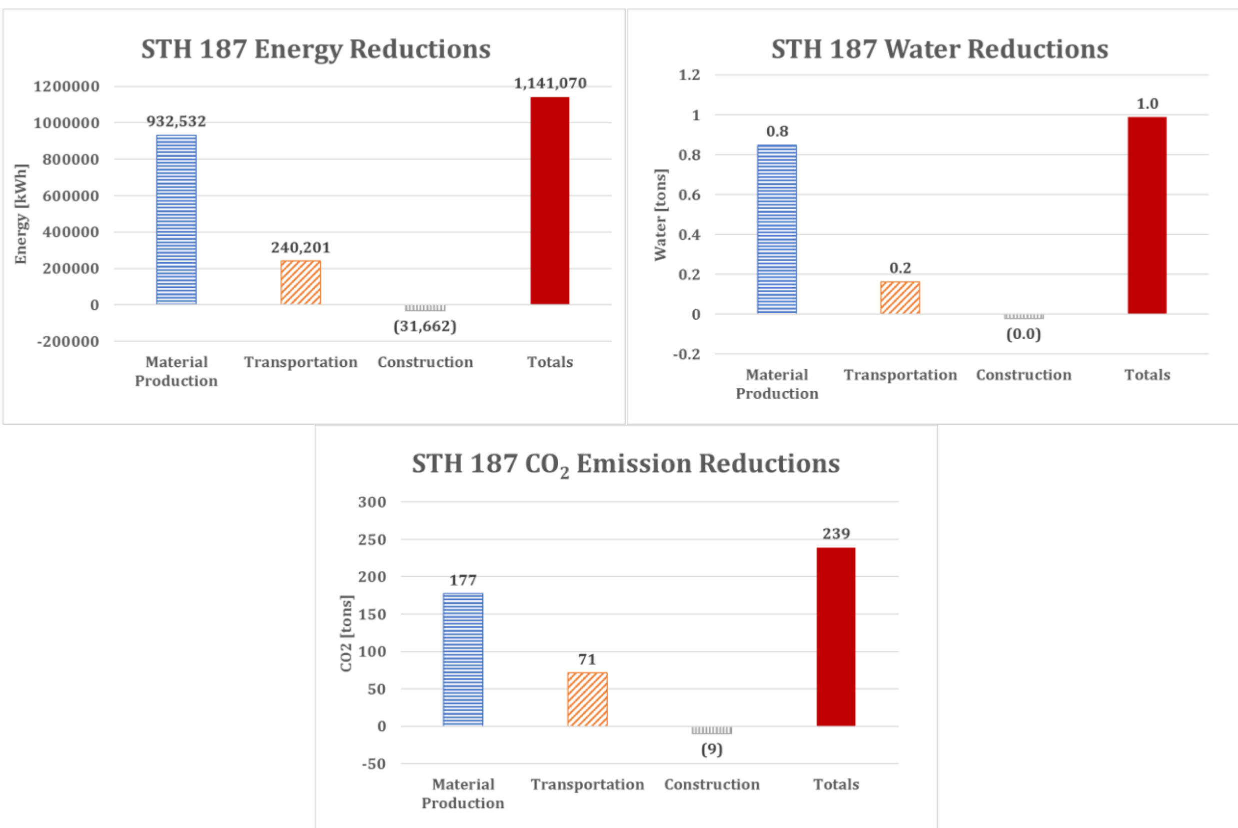

Figure 28. Environmental savings achieved at each phase of STH 187.

When compared to Mill and Overlay these gross savings translate to a 19% reduction in energy used, 15% reduction in water consumption, and 24% reduction in carbon dioxide emitted. The percent reductions achieved by each element of the process are illustrated in Figure 29 below. Additional project information can be found in Appendix J.

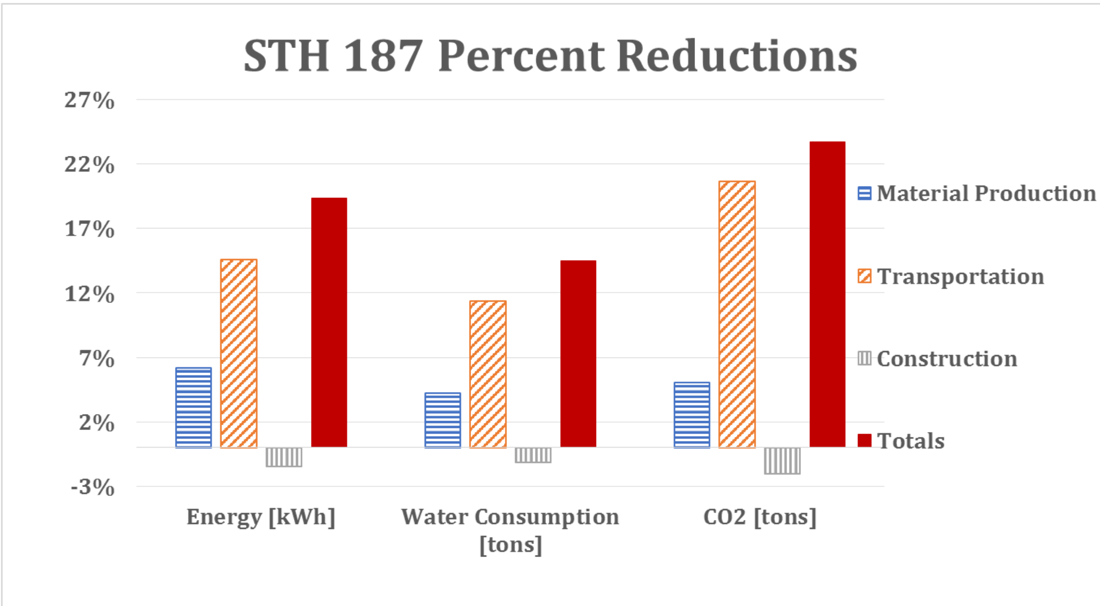

Figure 29. Percent reductions achieved in each phase of STH 187.

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Appendix

Appendix A.

Table 3. Densities used in the LCA Model.

Material	Density [tons/CY]
Virgin Aggregate	**2.23**
Asphalt cement	**0.84**
RAP	**1.85**
Milled	**1.83**
Asphalt Stabilizing Agent	**0.84**

PaLATE Calculations

The following steps and calculations were used to convert the project quantities provided by contractors as inputs for the LCA PaLATE model.

Step 1. Enter the project specifications into the PaLATE spreadsheet's "Design" page

- Width (ft)
- Length (miles)
- Depth (inches)

Step 2. Calculate the volume (CY) of virgin aggregate, asphalt cement, RAP, CIR, HIPR, and RAP to landfill quantities using the data provided by the construction plans for Mill and Overlay. The title of the following calculations refers to their input cell name in PaLATE.

Mill and Overlay Quantity Calculations:

Virgin Aggregate (CY)= $\frac{[HMA\ Type\ E3\ (tons)]}{\left[Virgin\ aggregate\ density\left(\frac{tons}{CY}\right)\right]} \times 0.8$

Asphalt cement (CY)[h]= $\frac{[PG\ 58.28\ (tons) or\ Asphalt\ binder (tons)]}{\left[Asphalt\ cement\ density\ \left(\frac{tons}{CY}\right)\right]} + Tack\ Coat\ (CY)$

[h] PaLATE calls this "Bitumen"

$$\text{RAP (CY)} = \frac{[HMA\ Type\ E3\ (tons)]}{[Virgin\ aggregate\ density(\frac{tons}{CY})]} \times 0.2$$

HIPR, CIR, and RAP from site to landfill (CY)

$=Pulverize\ and\ Relay\ or\ Surface\ Milling\ (SY) \times Wearing\ Course\ 1\ Depth\ (yd)$

Step 3. Enter each into the PaLATE spreadsheet's "Maintenance" page. See project specific Appendices B-J for inputs.

Step 4. Enter the project equipment provided by the construction companies into the PaLATE spreadsheet "Equipment" page. See project specific Mill and Overlay Equipment Inputs and CIR Equipment Inputs below.

Step 5. Gather the environmental outputs from the "Environmental Results" page.

Step 6. Repeat this process using the data provided by the construction plans for CIR.

CIR Run 1 Quantity Calculations:

Virgin Aggregate (CY): *See Mill and Overlay Virgin Aggregate Calculation*

Asphalt cement (CY): *See Mill and Overlay Asphalt cement Calculation*

RAP (CY)*: See Mill and Overlay RAP Calculation*

HIPR (CY)= *Pulverize and Relay or Surface Milling (SY)×Wearing Course 1 Depth (yd)*

CIR (CY), Also used in Full-depth Reclamation= *CIR (SY)×Wearing Course 2 Depth (yd)*

RAP from site to landfill (CY); *See CIR Run 1 HIPR Calculation for projects where pavement was too distressed to reuse, otherwise value is 0.*

CIR Run 2 Quantity Calculations:

HIPR (CY)*: See CIR Run 1 CIR Calculation*

CIR (CY)*: See CIR Run 1 CIR Calculation*

Weighted Percent Reduction Calculation

Step 1. Calculate the Weighted Overall impact of the Material Production savings

Weighted Overall Impact of Material Production Savings=

$$\frac{[Energy\ usage\ in\ Material\ Production\ (Mill\ and\ Overlay) - Energy\ usage\ in\ Material\ Production\ (CIR)]}{(Total\ Energy\ Usage\ Mill\ and\ Overlay - Total\ Energy\ Usage\ CIR)}$$

Step 2. Calculate Weighted Percent Reduction for the Material Production Savings

Material Productions Energy usage=

$$\frac{[Energy\ usage\ in\ Material\ Production\ (Mill\ and\ Overlay) - \ Energy\ usage\ in\ Material\ Production\ (CIR)]}{[\ Energy\ usage\ in\ Material\ Production\ (Mill\ and\ Overlay)]} \times Weighted\ Overall\ Impact\ of\ Material\ Production\ Savings$$

Step 3. Repeat Steps 1 and 2 for Transportation Savings

Step 4. Repeat Steps 1 and 2 for Construction Savings

Step 5. Add the Weighted Percent Reductions to get the total Percent Reduction Savings for that environmental parameter (i.e. Energy Usage)

Step 6. Repeat Steps 1-5 for Water Usage, and Carbon Dioxide Emissions.

Equipment Specifications

Mill and Overlay Equipment

Equipment varied by project and this was accounted for in PaLATE Equipment inputs. Refer to the project specific Appendix below for the project specific PaLATE Equipment inputs for Mill and Overlay. Note that the Equipment pieces from the *Rubblization* Activity through the HMA production in the equipment tables below remained the same for all Mill and Overlay and CIR Equipment Assemblages in PaLATE.

CIR Equipment

Below are the Equipment packages entered into the “Equipment” tab of the PaLATE spreadsheet for the CIR PaLATE file of each of the projects. After much investigation into productivity and fuel consumption specifications of CIR equipment provided for each project, it was decided that each multi-unit recycling train would be assumed to have the same equipment. For multi-unit recycling projects, an additional PaLATE spreadsheet was needed to account for all of the equipment. Table 4 and Table 5 are the equipment package for CIR Run 1 and Run 2, respectively. Table 6 is the equipment package used for the single-unit recycling project, STH 27. Note that the Equipment pieces from the *Rubblization* Activity through the HMA production in the equipment tables below remained the same for all Mill and Overlay and CIR Equipment Assemblages in PaLATE.

Table 4. Multi-unit recycling train PaLATE Equipment Run 1.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	United Machinery RAP Crusher	174	125	17
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	CMI T5-400	425	1846	5
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Rubblization	Multi head breaker	Badger MHB Breaker	350	520	76
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Milling	Milling machine	Wirtgen W2200	875	1100	156
Grinding	Grinding machine	CBI Magnum Force Shingle	1050	115	161
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350	520	76
	Wheel loader	John Deere 644E	160	490	40
Crushing Plant	Excavator	John Deere 690E	131	225	34
	Wheel loader	John Deere 624E	135	225	35
	Dozer	Caterpillar D8N	285	225	71
	Generator	Caterpillar 3406C TA	519	225	98
Excavation, placing and compaction	Excavator	John Deere 690E	131	315	34
	Vibratory soil compactor	Dynapac CA 262D	174	1832	28
Tire Recycling	Shredder + Granulator + Classifier + Aspirator	Wendt Corporation	630	3	105
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10	1	7
HMA Production	Asphalt mixer	Uncontrolled Batch-Mix		227	

Table 5. Multi-unit recycling train PaLATE Equipment Run 2.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen 120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Rubblization	Multi head breaker	Badger MHB Breaker	350	520	76
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Milling	Milling machine	Wirtgen W2200	875	1100	156
Grinding	Grinding machine	CBI Magnum Force Shingle	1050	115	161
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350	520	76
	Wheel loader	John Deere 644E	160	490	40
Crushing Plant	Excavator	John Deere 690E	131	225	34
	Wheel loader	John Deere 624E	135	225	35
	Dozer	Caterpillar D8N	285	225	71
	Generator	Caterpillar 3406C TA	519	225	98
Excavation, placing and compaction	Excavator	John Deere 690E	131	315	34
	Vibratory soil compactor	Dynapac CA 262D	174	1832	28
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630	3	105
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10	1	7
HMA Production	asphalt mixer	Uncontrolled Batch-Mix		226.7956796	

Table 6. Single-unit recycling train PaLATE Equipment.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 3800 CR	950	1713	75
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen 120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Rubblization	Multi head breaker	Badger MHB Breaker	350	520	76
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Milling	Milling machine	Wirtgen W2200	875	1100	156
Grinding	Grinding machine	CBI Magnum Force Shingle	1050	115	161
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350	520	76
	Wheel loader	John Deere 644E	160	490	40
Crushing Plant	Excavator	John Deere 690E	131	225	34
	Wheel loader	John Deere 624E	135	225	35
	Dozer	Caterpillar D8N	285	225	71
	Generator	Caterpillar 3406C TA	519	225	98
Excavation, placing and compaction	Excavator	John Deere 690E	131	315	34
	Vibratory soil compactor	Dynapac CA 262D	174	1832	28
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630	3	105
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10	1	7
HMA Production	asphalt mixer	Uncontrolled Batch-Mix		226.7956796	

Example Project Savings Projection

The purpose of this portion of the study is to provide a framework for contractors in Wisconsin to estimate the potential energy, water, and carbon dioxide saving for their single-unit and multi-unit recycling train CIR projects. If a contractor wishes to make this estimation, they must divide the volume of HMA being avoided in using CIR instead of Mill and Overlay [CY] by the hauling distance to the nearest HMA plant from the midpoint of the project [miles]. This ratio is the normalized HMA reduction, the x-variable, in the linear relationships provided in Figures 9-11.

Table 7. Example Project Specifications

Hauling Distance (miles)	Project Length (miles)	Road Width (ft)	Mill and Overlay HMA Thickness (inches)	CIR HMA Thickness (inches)	
10	5	30	4.5	2	
N/A	**8800**	**10**	**0.125**	**0.0556**	**Converted to yards**

$$Volume\ of\ Mill\ and\ Overlay\ HMA = Length \times Width \times Thickness$$

$$= (8800\ yards) \times (10\ yards) \times (0.125\ yards)$$

$$= 11000\ CY$$

$$Volume\ of\ CIR\ HMA = (8800\ yards) \times (10\ yards) \times (0.0556\ yards)$$

$$= 4893\ CY$$

$$Volume\ of\ HMA\ Avoided = (Volume\ of\ Mill\ and\ Overlay\ HMA) - (Volume\ of\ CIR\ HMA)$$

$$= 11000 - 4893 = 6107\ CY$$

$$Xvariable = \frac{Volume\ of\ HMA\ Avoided}{(Hauling\ Distance)}$$

$$= \frac{6107\ CY}{10\ miles}$$

$$= 610.7\ CY\ per\ mile$$

Estimated Energy Savings, using equation given in Figure 9.

$$Energy\ savings = 3620.6 \times Xvariable = 3620.6 \times (610.7) = 2{,}211{,}100\ kWh$$

Estimated Water Savings, using equation given in Figure 10.

$$Water\ savings = 0.0047 \times Xvariable = 0.0047 \times (610.7) = 2.9\ tons$$

Estimated Carbon Dioxide Savings, using equation given in Figure 11.

$$Carbon\ Dioxide\ savings = 0.7522 \times Xvariable = 0.7522 \times (610.7) = 459.4\ tons$$

Appendix B. CTH H Project Information

Table 8. General Project Information for CTH H.

Project: CTH H (Reedsburg to Wisconsin Dells)	
Project ID	8957-00-70
Construction Year	2015
County	Sauk
Contractor	Mathy
Project Length (miles)	9.5
Hauling Distance (miles)	5.3
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4.5
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	3.5
RAP Hauled Away during CIR (CY)	0
Asphalt binder (%)	5.2

Table 9. Equipment Information for CTH H.

Mill and Overlay HMA Process (4.5 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Compaction Rollers	Hamm 3412
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
CIR Recycling Train (Multi Unit)	Wirtgen CR3800
Water Tank	3000-Gal Freightliner
Asphalt Tank	Etnyre
2 Compaction Rollers	Hamm GRW 18, Cat CB 534
Paver	Cedarapids CR551
Cold-in-Place Recycling HMA Process (3.5 in)	
Equipment Description	**Equipment Used**
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 10. Material Quantities provided by Mathy for CTH H.

Material	Provided Quantity	
	Mill and Overlay	CIR
HMA Type E-3 (tons)	55,579	44,445
PG 58-28 (tons)	3,057	2,291
Pulverize and Relay (SY)	216,480	216,480
Tack Coat (Gal)	9,053	9,053
Cold-in-Place Recycling (SY)		20,440
Tack Coat (Gal)		9,053
Asphaltic Stabilizing Agent (tons)		747

Table 11. Material Quantity PaLATE Inputs for CTH H.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	15,400	12,315	
Asphalt cement (CY)	2,845	2,141	
Asphalt Emulsion (CY)		687	
RAP (CY)	3,850	3,079	
HIPR (CY)	20,900	16,256	17,537
CIR (CY)	20,900	17,537	17,537
Full-depth Reclamation (CY)		17,537	
RAP from site to landfill (CY)	20,900	0	

Table 12. CTH H Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670	4800	120
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 13. PaLATE Outputs for CTH H.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	16,435,917	15,329,080	22.9	21.9	3,469	3,259
Transportation	118,190	36,342	0.1	0.0	35	11
Construction	83,255	169,199	0.1	0.1	25	50
Total	**16,637,362**	**15,534,620**	**23.0**	**22.0**	**3,529**	**3,320**

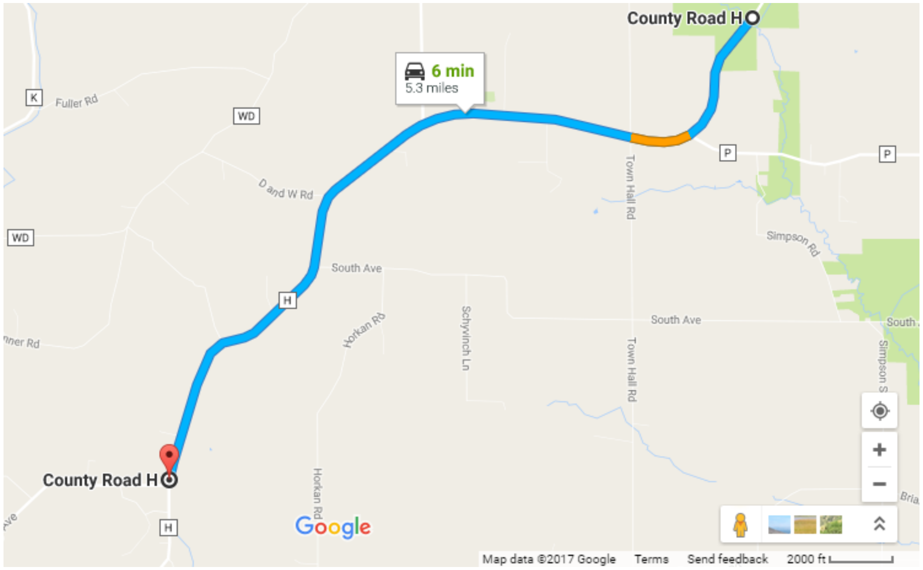

Figure 30. CTH H Hauling Distance Map.

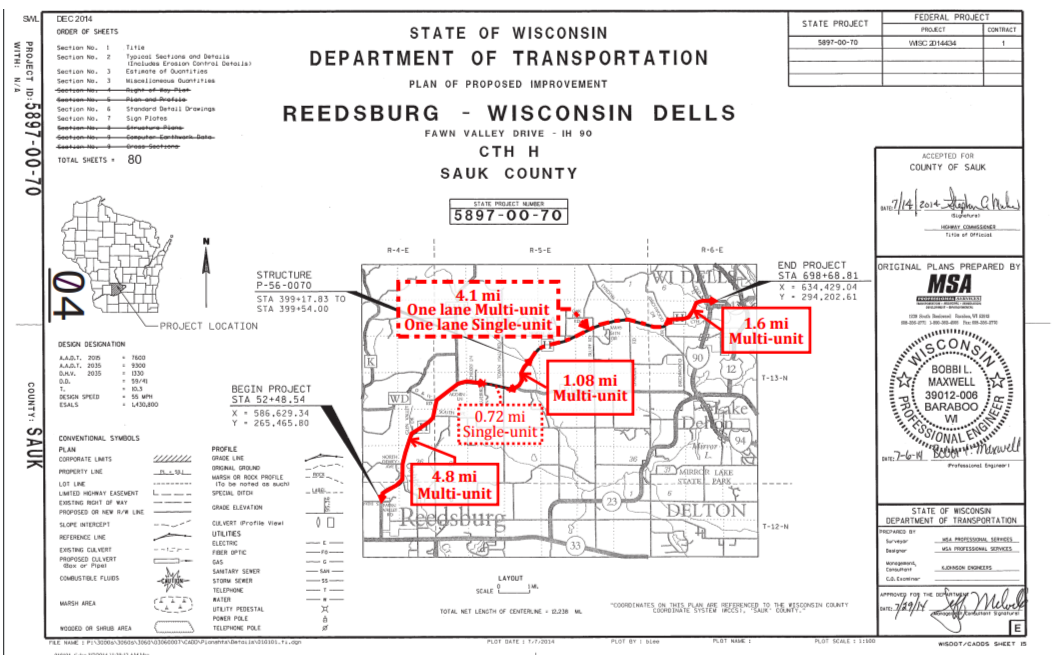

Figure 31. Justification for CTH H Hauling Distance.

Figure 31 is meant to justify the decision to evaluate CTH H as a 9.5-mile multi-unit recycling train project with a hauling distance at the middle of the original 12.3-mile project. This graphic shows the portions of the project that were completed using a multi-unit recycling train, a single-unit recycling train, and a lane of each. Because the multi-unit portions were not isolated on one end of the project, the hauling distance was assumed to be from the midpoint of the 12.3-mile project for the 9.5-mile multi-unit recycling train analysis completed in the report.

Appendix C. STH 13 Project Information

Table 14. General Project Information for STH 13.

Project: STH 13 (Medford to Westboro)	
Project ID	1610-03-62
Construction Year	2016
County	Taylor
Contractor (CIR)	WK
Contractor (Mill and Overlay)	Mathy
Project Length (miles)	5.64
Hauling Distance (miles)	11.6
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	2.3
RAP Hauled Away during CIR (CY)	5,811[i]
Asphalt binder (%)	6.3

[i] Existing pavement was too distressed for reuse.

Table 15. Equipment Information for STH 13.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
Compaction Roller	Hamm GRW18
Asphalt Paving Machine	Cedarapids CR551
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Supplemental Milling Machine	Roadtec RX700 7' Milling Machine
Portable RAP Crusher	United Machinery Crusher Model 660 HB
Asphalt Injection System	Bear Cat Injection System
Water Truck	Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller and CatCB64 Vibratory 84" Roller
Paver	CAT AP1055 F Asphalt Paver
Cold-in-Place Recycling HMA Process (2.25 in)	
Equipment Description	**Equipment Used**
2Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 16. Quantities provided by Mathy (HMA) and WK (CIR) for STH 13.

Material	Provided Quantity	
	Mill and Overlay	CIR
2.0" Surface Milling (SY)	104,600	104,600
Tack Coat (Gal)	7,744	7,744
Asphaltic Surface (tons) *	11,235	1,710
HMA Pavement Type SMA Special (tons)	11,235	11,235
HMA Pavement Type SMA Compaction Acceptance (tons)	11,235	11,235
Asphalt Stabilizing Agent (tons)		549
CIR (SY)		98,200

Table 17. PaLATE Inputs for STH 13.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	8,061	4,644	
Asphalt cement (CY)	1,722	880	
Asphalt Emulsion (CY)		654	
RAP (CY)	2,015	1,161	
HIPR (CY)	11,622	5,811	10,911
CIR (CY)	11,622	10,911	10,911
Full-depth Reclamation (CY)		654	
RAP from site to landfill (CY)	11,622	5,811	

Table 18. STH 13 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670	4800	120
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 19. PaLATE Outputs for STH 13.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	9,626,280	7,675,110	13.6	11.3	2,043	1,649
Transportation	140,829	31,987	0.1	0.02	42	9.5
Construction	45,241	96,670	0.03	0.07	14	29
Total	**9,812,350**	**7,803,767**	**13.8**	**11.4**	**2,099**	**1,687**

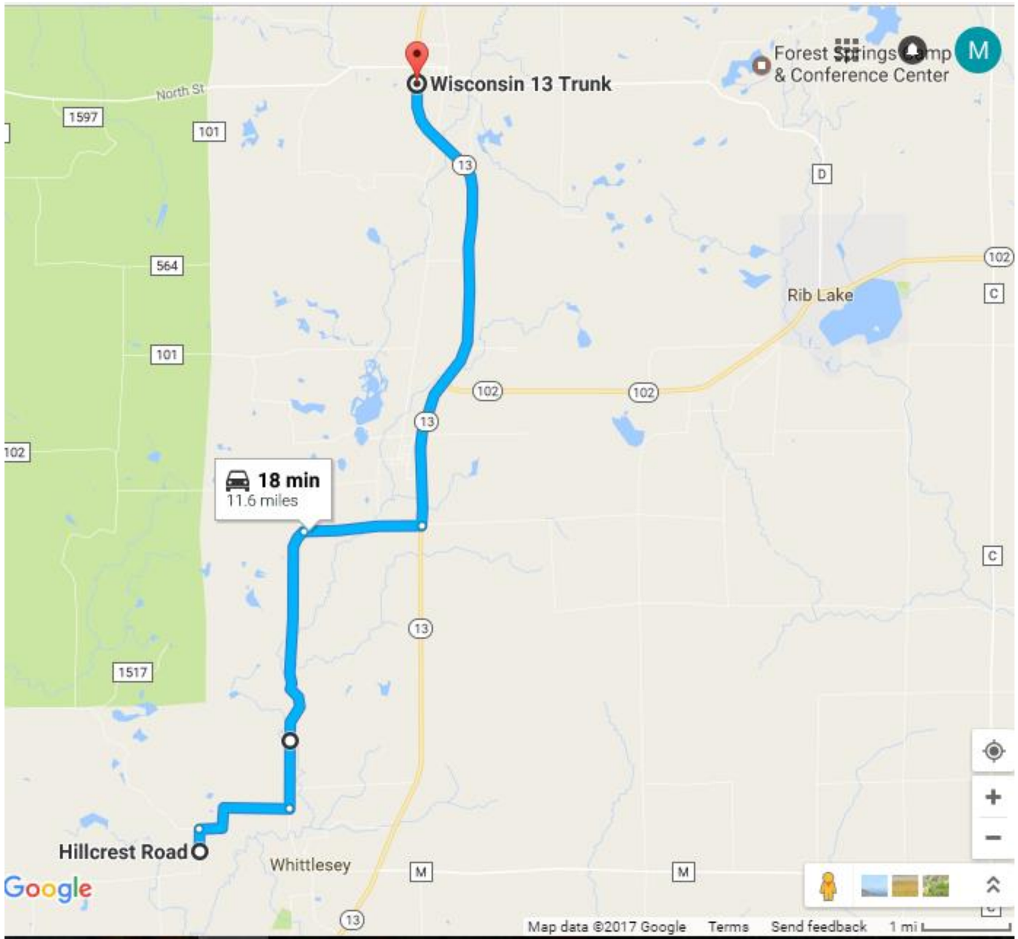

Figure 32. STH 13 Hauling Distance Map.

Appendix D. STH 27 Project Information

Table 20. General Project Information for STH 27.

Project: STH 27 (Sparta to Black River Falls)	
Project ID	7062-05-71
Construction Year	2016
County	Jackson
Contractor	Mathy
Project Length (miles)	9.00
Hauling Distance (miles)	8.7
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	2.25
RAP Hauled Away during CIR (CY)[j]	9,206
Asphalt binder (%)	5.4

[j] Existing pavement was too distressed for reuse.

Table 21. Equipment Information for STH 27.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
Compaction Roller	Hamm GRW18
Asphalt Paving Machine	Cedarapids CR551
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine (12.5' wide)	Wirtgen CR3800
Supplemental Milling Machine (up to 4')	Wirtgen W120
Water Truck	3000-gGl Freightliner
2 Asphalt Tankers	Etnyre
2 Compaction Rollers	Hamm GRW 18, Cat CB 534
Paver	Cedarapids CR552
Cold-in-Place Recycling HMA Overlay Process (2.25 in)	
Equipment Description	**Equipment Used**
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 22. Quantities provided by Mathy for STH 27.

Material	Provided Quantity	
	Mill and Overlay	CIR
HMA Type E-3 (tons)	36,456	20,911
5-6 inch Milling (SY)	165,709	165,709
Tack Coat (Gal)	9,779	9,779
Asphalt Stabilizing Agent (tons)		801
CIR (SY)		142,598
Asphalt binder (tons)		1,136

Table 23. PaLATE Inputs for STH 27.

Material	Input Quantity	
	Mill and Overlay	CIR
Virgin Aggregate (CY)	13,078	7,502
Asphalt cement (CY)	2,407	1,401
Asphalt Emulsion (CY)		954
RAP (CY)	3,270	1,875
HIPR (CY)	18,412	9,206
CIR (CY)	18,412	15,844
Full-depth Reclamation (CY)		15,844
RAP from site to landfill (CY)	18,412	9,206

Table 24. STH 27 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670	4800	120
	Vibratory soil compactor	Dynapac CA 262D	150	1832	38
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 25. CIR PaLATE Outputs for STH 27.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	13,804,879	11,886,920	19.2	17.5	2,912	2,551
Transportation	167,915	38,352	0.1	0.03	50	11
Construction	71,806	89,074	0.05	0.06	21	27
Total	**14,044,600**	**12,014,346**	**19.3**	**17.6**	**2,984**	**2,588**

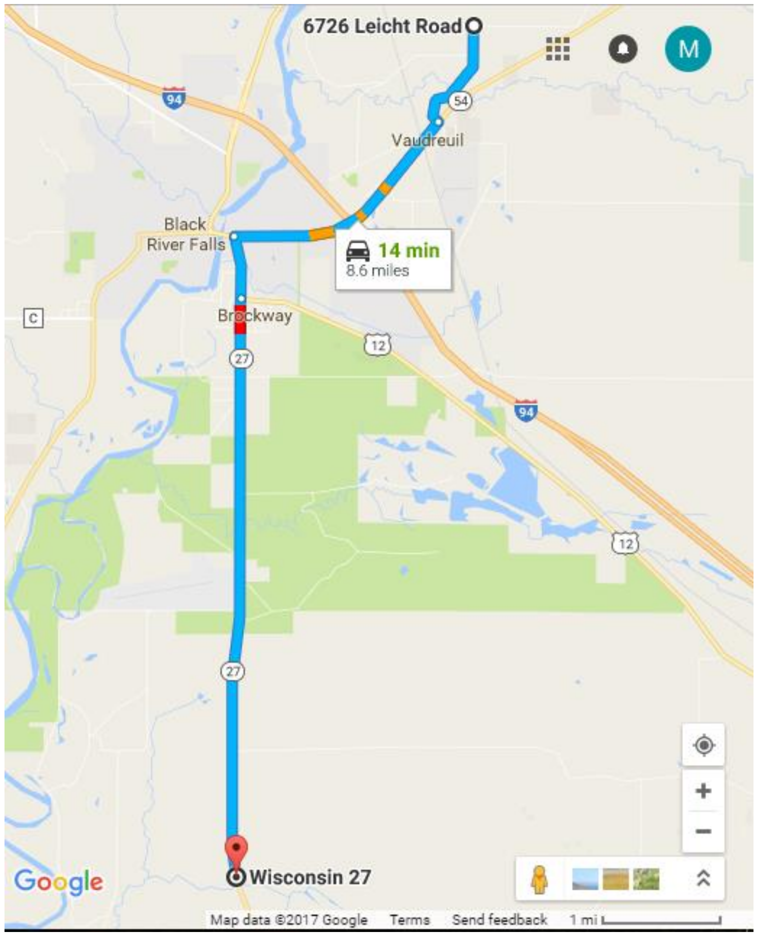

Figure 33. STH 27 Hauling Distance Map.

Appendix E. STH 48 Rice Lake Project Information

Table 26. General Project Information for STH 48 Rice Lake.

Project: STH 48 (Rice Lake to Birchwood)	
Project ID	8570-03-70
Construction Year	2015
County	Barron
Contractor (CIR	WK
Contractor (HMA)	HMA
Project Length (miles)	8.1
Hauling Distance (miles)	10.3
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	3
Cold-in-Place Recycling HMA Thickness (inches)	2
RAP Hauled Away during CIR (CY)[k]	8,898
Asphalt binder (%)	5.6

[k] Existing pavement was too distressed for reuse.

Table 27. Equipment Information for STH 48 Rice Lake.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (3 in)	
Equipment Description	**Equipment Used**
Milling Machine	Roadtec RX900 12.5" Milling Machine
Supplemental Milling Machine	Roadtec RX700 7' Milling Machine
Portable RAP Crusher	United Machinery Crusher Model 660 HB
Asphalt Injection System	Bear Cat Injection System
Water Truck	Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller, CatCB64 Vibratory 84" Roller
Paver	CAT AP1055 F Asphalt Paver
HMA Overlay Process (2 in)	
Equipment Description	**Equipment Used**
Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 28. Quantities provided by Mathy (HMA) and WK (CIR) for STH 48 Rice Lake.

Material	Provided Quantity	
	Mill and Overlay	CIR
Surface Milling (SY)	160,160	160,160
HMA Type E-3 special (tons)	37,233	23,305
Tack Coat (Gal)	9,176	9,176
Asphalt Stabilizing Agent (tons)		293
CIR (SY)		104,333
Asphalt binder (tons)		1,293

Table 29. PaLATE Inputs for STH 48 Rice Lake.

Item	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	13,357	8,361	
Asphalt cement (CY)	2,505	1,585	
Asphalt Emulsion (CY)		348	
RAP (CY)	3,339	2,090	
HIPR (CY)	17,796	8,898	8,694
CIR (CY)	17,796	8,694	8,694
Full-depth Reclamation (CY)		8,694	
RAP from site to landfill (CY)	17,796	8,898	

Table 30. STH 48 Rice Lake Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 31. CIR PaLATE Outputs for STH 48 Rice Lake.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	14,320,139	10,455,858	19.9	14.9	3,024	2,224
Transportation	197,342	111,889	0.1	0.08	59	33
Construction	71,654	90,976	0.05	0.06	21	27
Total	**14,589,135**	**10,658,723**	**20.1**	**15.1**	**31,03**	**2,284**

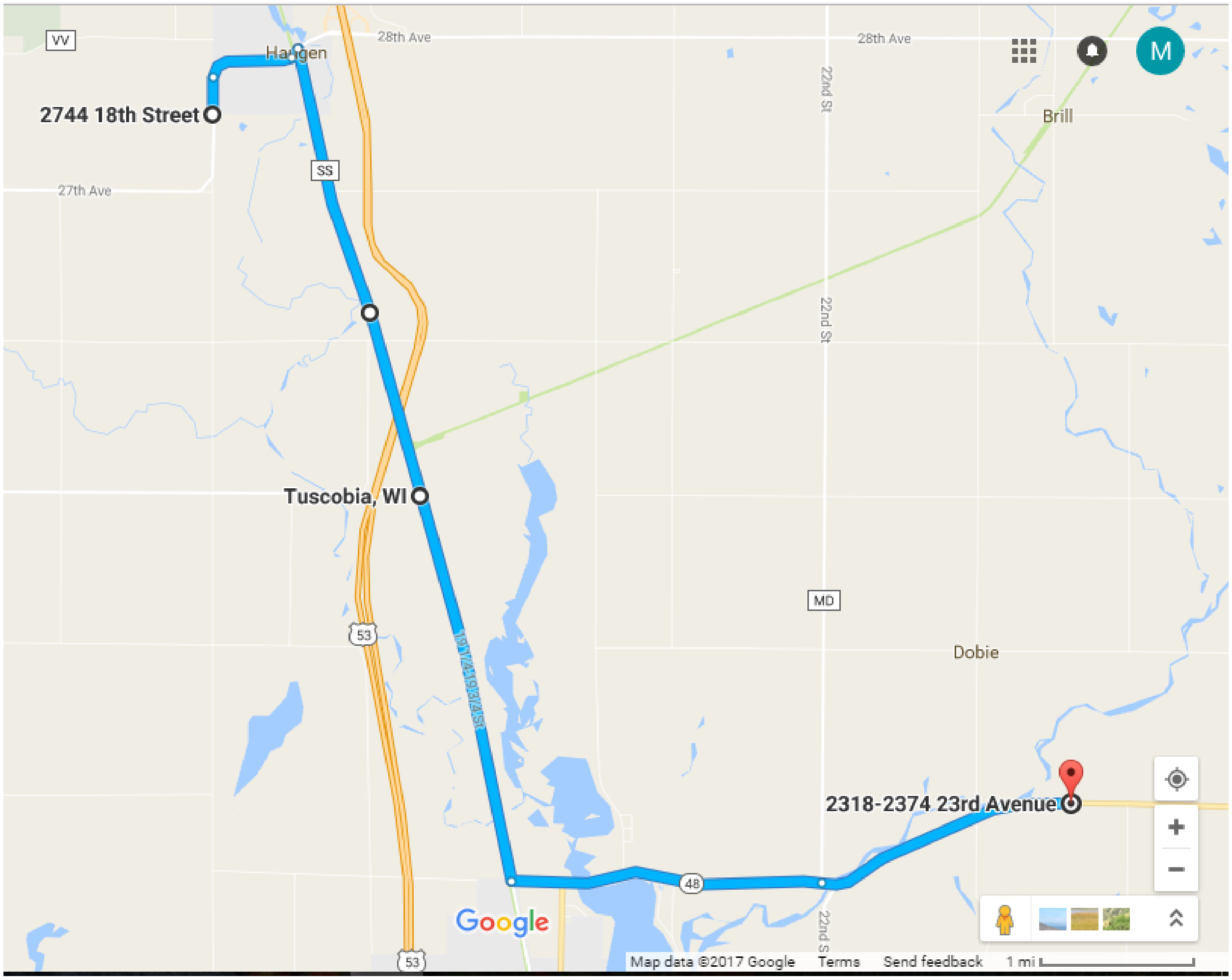

Figure 34. STH 48 Rice Lake Hauling Distance Map.

Appendix F. STH 48 Grantsburg Project Information

Table 32. General Project Information for STH 48 Grantsburg.

Project: STH 48 (Grantsburg to Frederic)	
Project ID	8845-14-60
Construction Year	2012
County	Burnett/Polk
Contractor (CIR)	WK (CIR)
Contractor (HMA)	Mathy (HMA)
Project Length (miles)	12.5
Hauling Distance (miles)	4.3
Road Width (feet)	24
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	2.25
RAP Hauled Away during CIR (CY)[1]	10,382
Asphalt binder (%)	5.5

[1] Existing pavement was too distressed for reuse.

Table 33. Equipment Information for STH 48 Grantsburg.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Roadtec RX900 12.5" Milling Machine
Supplemental Milling Machine	Roadtec RX700 7' Milling Machine
Portable RAP Crusher	United Machinery Crusher Model 660 HB
Asphalt Injection System	Bear Cat Injection System
Water Truck	Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller, CatCB64 Vibratory 84" Roller
Paver	CAT AP1055 F Asphalt Paver
Cold-in-Place Recycling HMA Overlay Process (2.25 in)	
Equipment Description	**Equipment Used**
Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 34. Quantities provided by Mathy (HMA) and WK (CIR) for STH 48 Grantsburg,

Material	Provided Quantity	
	Mill and Overlay	CIR
Asphaltic Surface Milling (SY)	220,000	166,118
HMA Type E-3 (tons)	50,400	20,648
Asphaltic Material PG 58-34 (tons)	2,772	1,130
Tack Coat (Gal)	4,309	4,309
Asphalt Stabilizing Agent (tons)		580
CIR (SY)		160,975
Asphalt binder (tons)		1,130

Table 35. PaLATE Inputs for STH 48 Grantsburg.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	18,081	7,407	
Asphalt cement (CY)	3,321	1,368	
Asphalt Emulsion (CY)		690	
RAP (CY)	4,520	1,852	
HIPR (CY)	18,458	10,382	17,886
CIR (CY)	18,458	17,886	17,886
Full-depth Reclamation (CY)		691	
RAP from site to landfill (CY)	18,458	10,382	

Table 36. STH 48 Grantsburg Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 37. PaLATE Outputs for STH 48 Grantsburg.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	19,058,644	10,643,747	26.5	15.5	4,020	2,276
Transportation	97,724	48,017	0.07	0.03	29	14
Construction	86,909	156,958	0.06	0.1	26	47
Total	**19,268,393**	**10,848,721**	**26.6**	**15.6**	**4,075**	**2,337**

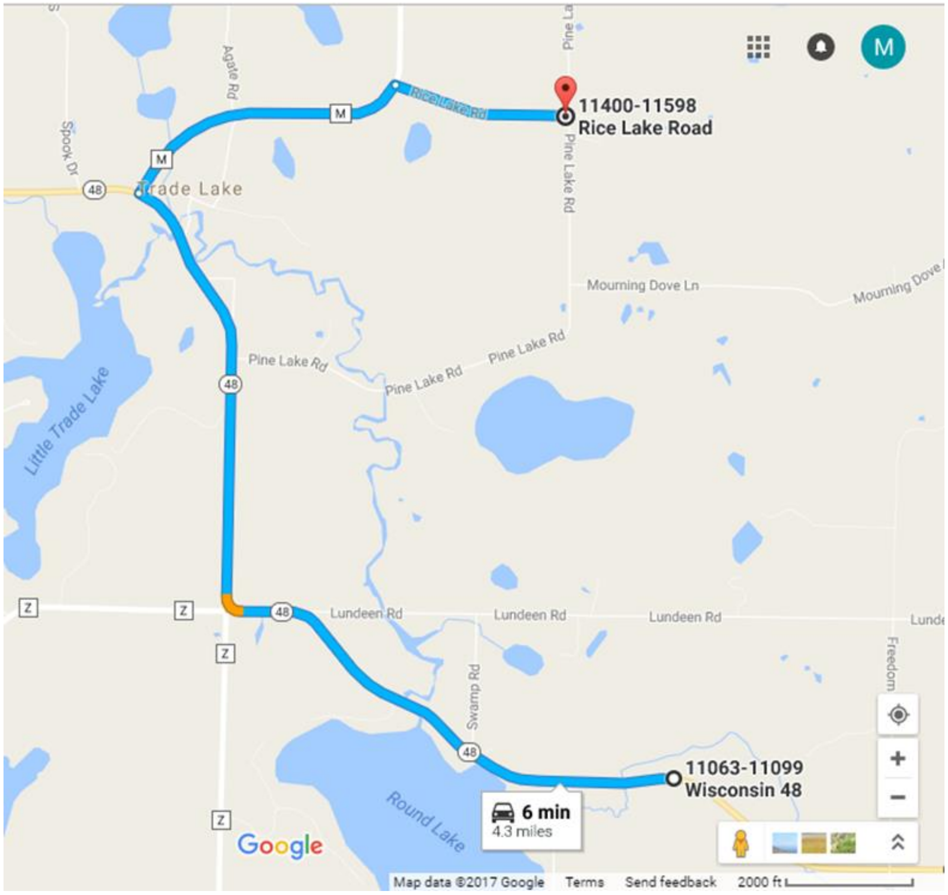

Figure 35. STH 48 Grantsburg Hauling Distance Map.

Appendix G. STH 64 Project Information

Table 38. General Project Information for STH 64.

Project: STH 64 (Gilman to Medford)	
Project ID	8220-05-72
Construction Year	2014
County	Taylor
Contractor (CIR	WK
Contractor (HMA)	Mathy
Project Length (miles)	4.46
Hauling Distance (miles)	3.7
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	3
HMA Hauled Away during CIR (CY)[m]	5,426
Asphalt binder (%)	5.8

[m] Existing pavement was too distressed for reuse.

Table 39. Equipment Information for STH 64.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	CMI PR1000 12' Milling Machine
Supplemental Milling Machine	Roadtec RX60 7' Milling Machine
1 Portable RAP Crusher	United Machinery Crusher Model 660 HB
Injection System and Relaying Equipment	CMI Single Lane Autograder TS-400 with Blau Knox Paving Screed (Extendo Matt) and CMI Injection System
1 Water Truck	1 Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller and Hamm HD130HV Vibratory 84" Roller
Cold-in-Place Recycling HMA Overlay Process (2.25 in)	
Equipment Description	**Equipment Used**
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 40. Quantities provided by Mathy (HMA) and WK (CIR) for STH 64.

Material	Provided Quantity	
	Mill and Overlay	CIR
Surface Milling (SY)	78,546	78,546
HMA Type E-3 special (tons)	20,340	15,255
Tack Coat (Gal)	4,726	4,726
Asphalt Stabilizing Agent (tons)		384
CIR (SY)		78,546
Asphalt binder (tons)		1,213

Table 41. PaLATE Inputs for STH 64.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	7,297	5,473	
Asphalt cement (CY)	2,540	1,467	
Asphalt Emulsion (CY)		457	
RAP (CY)	1,824	1,368	
HIPR (CY)	8,727	6,546	8,727
CIR (CY)	8,727	8,727	8,727
Full-depth Reclamation (CY)		8,727	
RAP from site to landfill (CY)	8,727	6,545	

Table 42. STH 64 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	none	0	1	0
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 43. PaLATE Outputs for STH 64.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	13,315,078	9,790,038	19.9	14.6	2,872	2,110
Transportation	38,276	28,734	0.03	0.02	11.4	8.5
Construction	39,845	83,459	0.03	0.1	11.9	24.9
Total	**13,393,199**	**9,902,231**	**19.9**	**14.7**	**2,895**	**2,143**

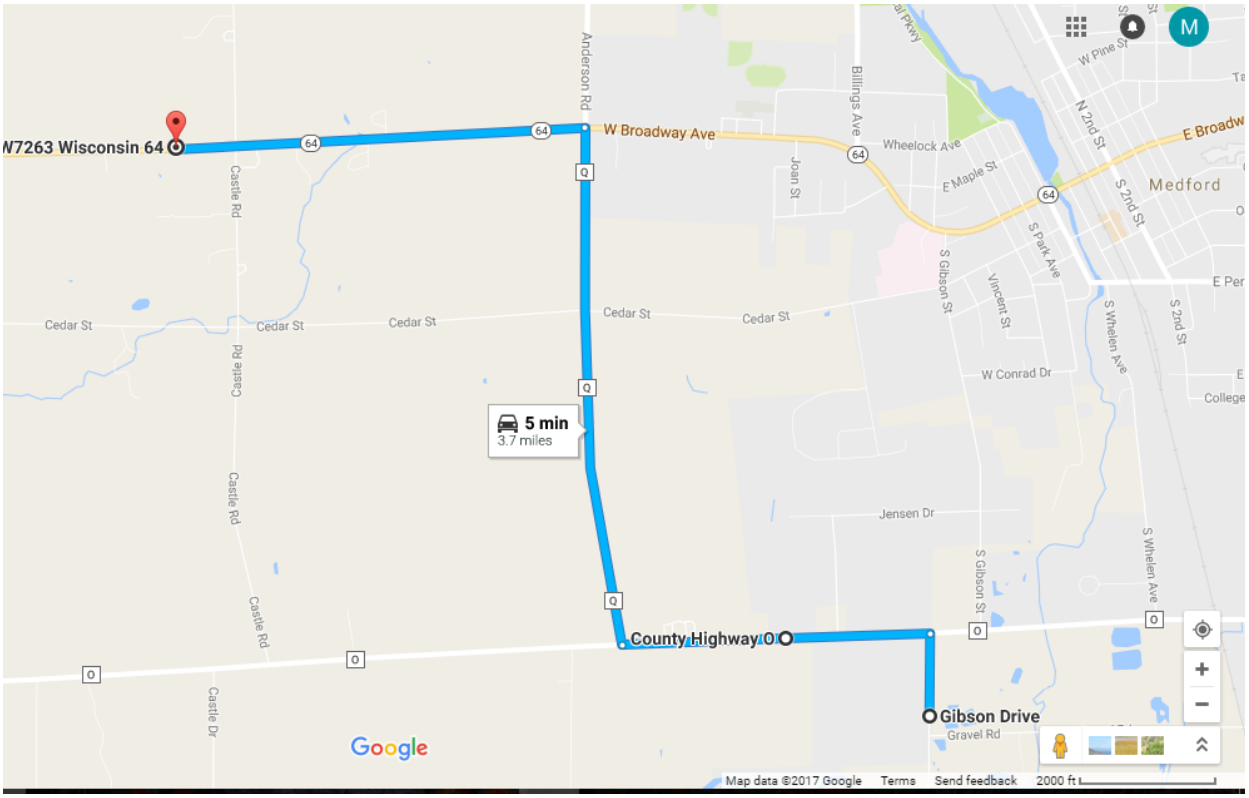

Figure 36. STH 64 Hauling Distance Map

Appendix H. STH 72 Project Information

Table 44. General Project Information for STH 72.

Project: STH 72 (Ellsworth to Elmwood)	
Project ID	7105-06-70
Construction Year	2016
County	Pierce
Contractor (CIR)	WK
Contractor (HMA)	Mathy
Project Length (miles)	4.63
Hauling Distance (miles)	18.3
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	2.25
HMA Hauled Away during CIR (CY)	0
Asphalt binder (%)	5.9

Table 45. Equipment Information for STH 72.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Roadtec RX900 12.5" Milling Machine
Supplemental Milling Machine	Roadtec RX700 7' Milling Machine
Portable RAP Crusher	United Machinery Crusher Model 660 HB
Asphalt Injection System	Bear Cat Injection System
Water Truck	Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller, CatCB64 Vibratory 84" Roller
Paver	CAT AP1055 F Asphalt Paver
Cold-in-Place Recycling HMA Overlay Process (2.25 in)	
Equipment Description	**Equipment Used**
Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack Coat Application Truck	Etnyre

Table 46. Quantities provided by Mathy (HMA) and WK(CIR) for STH 72.

Material	Quantity Provided	
	Mill and Overlay	CIR
2.5 inch Milling (SY)	72,500	72,500
Tack Coat (Gal)	9,400	9,400
HMA Pavement Type 5 MT 58-34H (tons)	8,964	4,790
HMA Pavement Type SMA Special (tons)	8,964	
HMA Pavement Type SMA Compaction Acceptance	7,185	
E-3 Mix (tons)		7,185
Asphalt Stabilizing Agent (tons)		174
CIR (SY)		63,395

Table 47. PaLATE Inputs for STH 72.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	6,431	4,296	
Asphalt cement (CY)	675	382	
Asphalt Emulsion (CY)		207	
RAP (CY)	1,608	1,074	
HIPR (CY)	8,056	4,028	5,283
CIR (CY)	8,056	5,283	5,283
Full-depth Reclamation (CY)		5,283	
RAP from site to landfill (CY)	8,056	0	

Table 48. STH 72 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Dynapac F30C	196	2400	49
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 49. PaLATE Outputs for STH 72.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	4,405,908	3,462,047	5.52	4.54	903	718
Transportation	159,864	41,951	0.1	0.03	47	12
Construction	32,483	51959	0.02	0.04	9.7	16
Total	**4,598,255**	**3,555,,957**	**5.65**	**4.60**	**960**	**746**

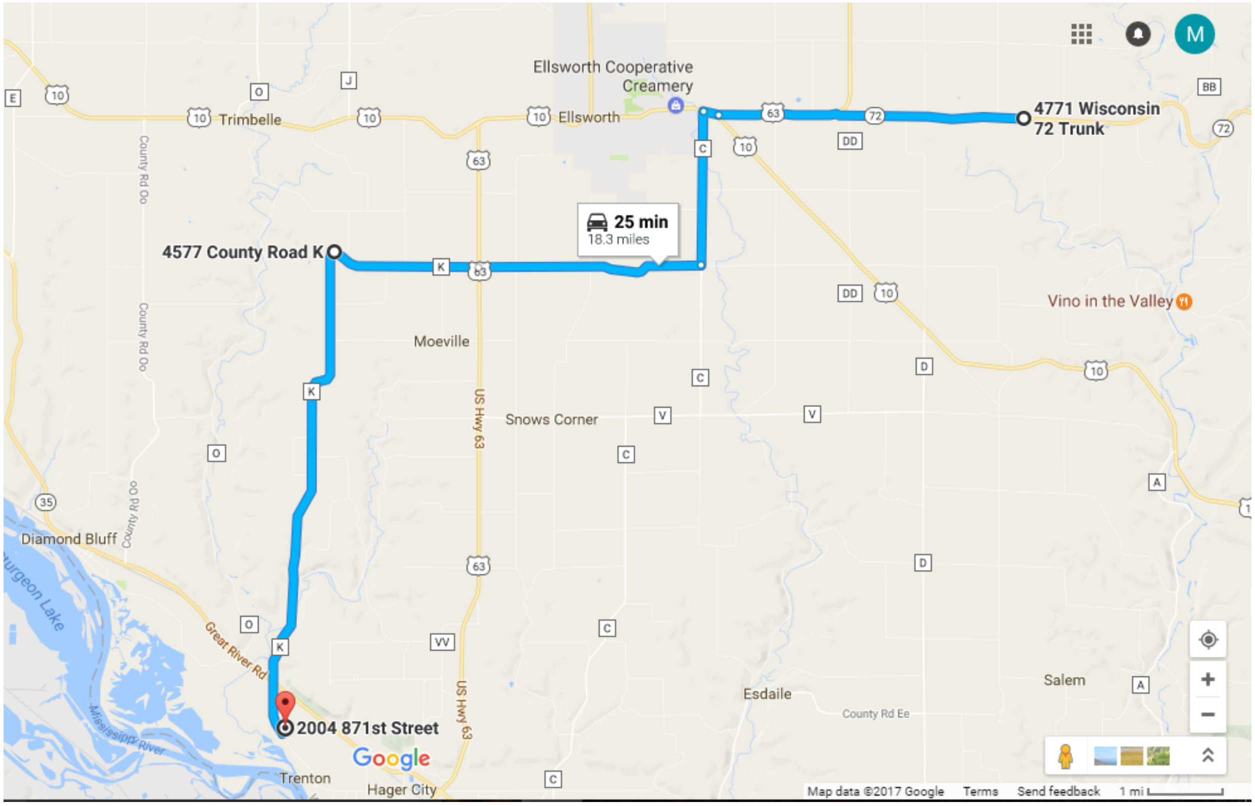

Figure 37. STH 72 Hauling Distance Map.

Appendix I. STH 95 Project Information

Table 50. General Project Information for STH 95.

Project: STH 95 (Blair to Merrillan)	
Project ID	7560-06-70
Construction Year	2015
County	Trempealeau
Contractor (CIR)	WK
Contractor (HMA)	Mathy
Project Length (miles)	4.42
Hauling Distance (miles)	24.4
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	4
Cold-in-Place Recycling HMA Thickness (inches)	2.5
HMA Hauled Away during CIR (CY)	0
Asphalt binder (%)	5.8

Table 51. Equipment Information for STH 95.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
Supplemental Milling Machine	Wirtgen W120
2 Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack coat application Truck	Etnyre
Cold-in-Place Recycling Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Roadtec RX900 12.5" Milling Machine
Supplemental Milling Machine	Roadtec RX700 7' Milling Machine
Portable RAP Crusher	United Machinery Crusher Model 660 HB
Injection System and Relaying Equipment	CMI Single Lane Autograder TS-400, CMI Injection System
Water Truck	1 Mack Water Truck
2 Asphalt Tankers	2 Etnyre Asphalt Tank Trailers
2 Compaction Rollers	Cat PS360 Pneumatic Roller, Hamm HD130HV Vibratory 84" Roller
Cold-in-Place Recycling HMA Overlay Process (2.5 in)	
Equipment Description	**Equipment Used**
Compaction Rollers	Cat CB66, Dynapac CC624
Asphalt Paving Machine	Cedarapids CR552
Tack coat Application Truck	Etnyre

Table 52. Quantities provided by Mathy (HMA) and WK (CIR) for STH 95.

Material	Provided Quantity	
	Mill and Overlay	CIR
HMA Type E-3 (tons)	18,813	12,365
PG 58-34P (tons)	1,082	688
5-6 inch Milling (SY)	81,460	81,460
Tack Coat (Gal)	5,702	4,922
Asphalt Stabilizing Agent (tons)		330
CIR (SY)		58,630
Asphalt binder (tons)		711

Table 53. PaLATE Inputs for STH 95.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	6,749	4,436	
Asphalt cement (CY)	1,316	843	
Asphalt Emulsion (CY)		393	
RAP (CY)	1,687	1,109	
HIPR (CY)	9,051	5,657	6,514
CIR (CY)	9,051	6,514	6,514
Full-depth Reclamation (CY)		6,514	
RAP from site to landfill (CY)	9,051	0	

Table 54. STH 95 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	Cedarapids CR552	260	857	15
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 55. Mill and Overlay PaLATE Outputs for STH 95.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	7,471,649	6,404,845	10	9.3	1,580	1,370
Transportation	237,494	77,464	0.2	0.05	70	23
Construction	36,416	62,838	0.02	0.04	11	19
Total	**7,745,559**	**6,545,146**	**11**	**9.4**	**1,661**	**1,412**

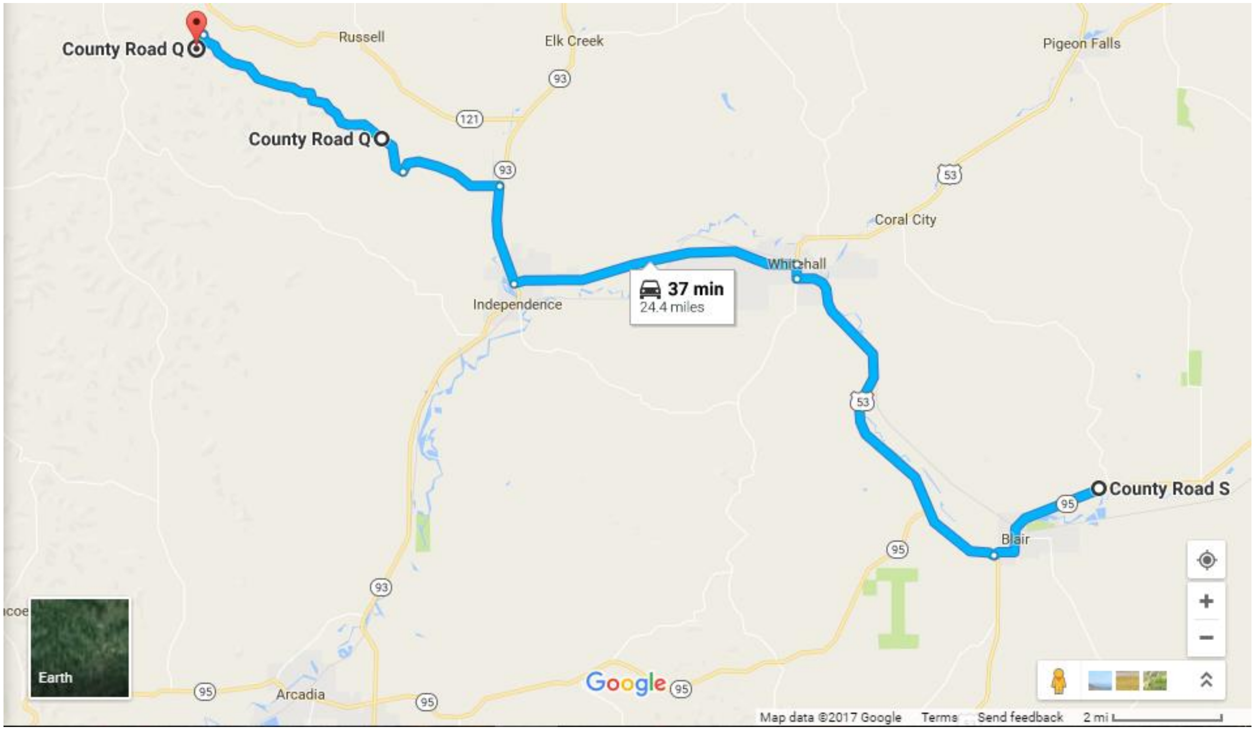

Figure 38. STH 95 Hauling Distance Map.

Appendix J. STH 187 Project Information

Table 56. General Project Information for STH 187.

Project: STH 87 (Shiocton to North County Line)	
Project ID	6520-03-60
Construction Year	2016
County	Outagamie
Contractor (CIR)	Mid States Reclamation
Contractor (HMA)	Northeast Asphalt
Project Length (miles)	9.8
Hauling Distance (miles)	21.3
Road Width (feet)	30
Mill and Overlay HMA Thickness (inches)	4
Cold-in-Place Recycling Thickness (inches)	3
Cold-in-Place Recycling HMA Thickness (inches)	2.5
RAP Hauled Away during CIR (CY)[n]	5,575
Asphalt binder (%)	5.5

Table 57. Equipment Information for STH 187.

Mill and Overlay HMA Process (4 in)	
Equipment Description	**Equipment Used**
Milling Machine	Wirtgen 250
2 Compaction Rollers	SW 850 SAKAI, BW 138 AD-5 BOMAG
Asphalt Paving Machine	P7170 VOLVO
Material Transfer Vehicle	Ingersoll Shuttlebuggy

[n] Existing pavement was too distressed for reuse.

Tack Coat Application Truck	Freightliner with Tack Body and Spray Bars
Skid Steer	JD 318D
Broom Tractor	Ford Tractor with Belly Blade and Broom Attachment
Water Truck	Freightliner with approx 2000-Gal Tank and Parts Body
Cold-in-Place Recycling Process (3 in)	
Equipment Description	**Equipment Used**
Milling Machine (12.5' wide)	CMI / TEREX 1050
CIR Recycling Train (Multi-Unit System - involves, milling and crushing unit)	Crusher/Pug Mill Made by: Nesbett
Water Tank	7500 Gal Semi Trailer and Tractor
Asphalt Tank	Emulsion Trailer with Heating Capabilities
2 Compaction Rollers	Hamm HD 130, Hamm GRW18 (50,000# pneumatic)
Asphalt Paving Machine	Wirtgen Vision - 5200 2i
Material Transfer Device	Cedar Rapids - Pickup Machine
Cold-in-Place Recycling HMA Overlay Process (2.5 in)	
Equipment Description	**Equipment Used**
2 Compaction Rollers	SW 850 SAKAI, BW 138 AD-5 BOMAG
Asphalt Paving Machine	P7170 VOLVO
Material Transfer Vehicle	Ingersoll Shuttlebuggy
Tack Coat Application Truck	Freightliner with w/ Tack Body and Spray Bars
Skid Steer	JD 318D
Broom Tractor	Ford Tractor with Belly Blade and Broom Attachment
Water Truck	Freightliner with approx 2000-G gal Tank and Parts Body

Table 58. Quantities provided by NE Asphalt (HMA) and Mid States Reclamation (CIR) for STH 187.

Material	Provided Quantity	
	Mill and Overlay	CIR
2.5 inch Surface Mill (SY)	133,800	133,800
HMA Type E-3 (tons)	32,281	24,999
Asphaltic Material PG 58-28 (tons)	1,763	1,360
Tack Coat (Gal)	9,366	13,891
Asphalt Stabilizing Agent (tons)		376
CIR (SY)		125,238
Asphalt Binder (tons)		2,845

Table 59. PaLATE Inputs for STH 187.

Material	Input Quantity		
	Mill and Overlay	CIR Run 1	CIR Run 2
Virgin Aggregate (CY)	11,581	8,968	
Asphalt cement (CY)	2,145	1,666	
Asphalt Emulsion (CY)		448	
RAP (CY)	2,895	2,242	
HIPR (CY)	14,867	5,575	8,697
CIR (CY)	14,867	8,697	8,697
Full-depth Reclamation (CY)		8,697	
RAP from site to landfill (CY)	14,867	5,575	

Table 60. STH 187 Mill and Overlay PaLATE Equipment Inputs.

Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity (tons/hr)	Fuel Consumption (liters/hr)
Concrete Paving	Slipform paver	Wirtgen SP250	106	564	20
	Texture curing machine	Gomaco T/C 400	70	187	20
Asphalt Paving	Paver	Cedarapids CR552	260	857	15
	Pneumatic roller	Dynapac CP132	100	668	26
	Tandem roller	Inersoll rand DD110	125	285	33
Cold in Place Recycling	CIR recycler	Wirtgen 250i	979	1713	141
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0
Full Depth Reclamation	Asphalt road reclaimer	none	0	1	0
	Vibratory soil compactor	none	0	1	0
Hot In Place Recycling	Heating machine	Wirtgen W120	280	1713	25
	Asphalt remixer	none	0	1	0
	Pneumatic roller	none	0	1	0
	Tandem roller	none	0	1	0

Table 61. Mill and Overlay PaLATE Outputs for STH 187.

Process	Energy Consumption (kWh)		Water Consumption (tons)		CO2 Emissions (tons)	
	Mill and Overlay	CIR	Mill and Overlay	CIR	Mill and Overlay	CIR
Material Production	12,288,249	11,355,717	17	16	2,593	2,416
Transportation	346,836	106,635	0.2	0.1	103	32
Construction	61,075	92,737	0.04	0.1	18	28
Total	**12,696,160**	**11,555,090**	**17**	**16**	**2,714**	**2,475**

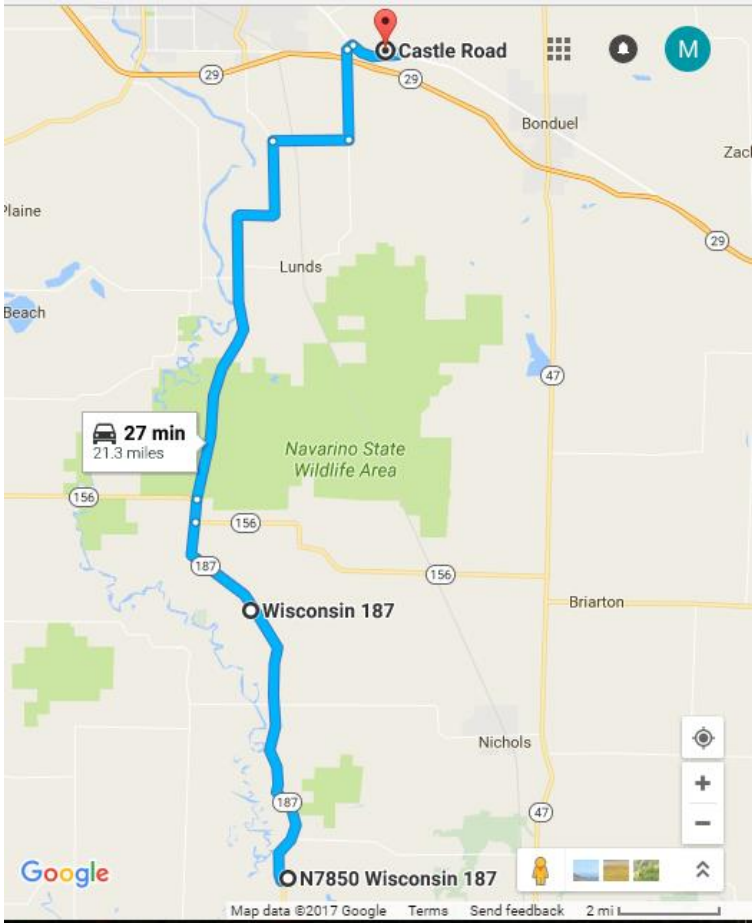

Figure 39. STH 187 Hauling Distance Map.