# Environmental Benefits of Cold-in-Place Recycling

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## ABSTRACT

The conventional highway resurfacing technique, Mill and Overlay (M&O), partially removes the existing pavement and replaces it with asphalt derived from some recycled, but mostly virgin materials. Cold-in-Place Recycling (CIR) is an alternative highway resurfacing method that partially mills the existing pavement and uses it beneath a thinner layer of new asphalt. CIR has become widely used for convenience and cost benefits, but the environmental impacts are poorly quantified.

The objective of this study was to quantify the environmental life cycle benefits of using CIR for highway resurfacing instead of M&O. Material quantities and equipment used for CIR, and what would have been used in M&O in the same project, were provided by contractors for nine highway resurfacing projects in Wisconsin. With this information, a life cycle assessment (LCA) tool was used to determine the relative environmental impacts of the two methods with energy consumption, water usage, and carbon dioxide emissions chosen as the metrics of the LCA.

Results show an average environmental savings of 23% in energy consumption and carbon dioxide emissions and 20% in water consumption associated with highway resurfacing when using CIR instead of M&O. Additionally, CIR reduced virgin aggregate consumption by 37%. Environmental savings achieved by using CIR were found to be directly related to the reduction in volume of new HMA used, and to the reduction in transportation of materials to and from the site. Linear correlations that can be used to estimate savings of future CIR projects were projected.

*Keywords*: Cold-in-place recycling, Mill and overlay, Life cycle assessment, Highway resurfacing, Asphalt

## INTRODUCTION

The United States uses approximately 1.3 billion tons (1.2 billion tonnes) of aggregate every year, 58% of which is for road construction (*1*). Furthermore, 90% of aggregate used in road construction is virgin aggregate (*1*). With the increasing cost of virgin materials and the growing pressure towards more sustainable construction, the use of recycled materials in roads is becoming increasingly widespread. The triple bottom line of sustainability requires that a project be 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 conceived 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 (M&O) (*2*). 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, e.g., HMA, and by reducing the transportation of materials to and from the site (*3*). 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 (*4*).

### Literature Review

Despite the understanding of the benefits of CIR, there is insufficient literature that quantifies the environmental benefits of CIR with respect to the conventional M&O. One study by Turk et al. compared CIR and conventional construction on one road with an LCA tool, determining that CIR reduced acidification by 18%, reduced fossil fuel consumption by 15%, reduced primary energy consumption by 16% and reduced global warming potential by 1% when compared to conventional methods (*5*). This study, however, used cement in the process and looked at the use of recycled asphalt pavement (RAP) in the subbase layer, as opposed to using RAP in the surface wearing course layer of the road (*5*). 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 (*6*); however, this study is not directly applicable to Wisconsin due to differences in construction techniques. It is demonstrated by these studies that hauling distance to the nearest asphalt plant plays a significant role in environmental savings associated with CIR, but the other relevant impact factors are not discussed (*4*), (*5*), (*6*).

Studies by Robinette et al., Giani et al., Alkins et al., and Cross et al demonstrated that CIR had fewer environmental impacts than conventional methods; however, these studies evaluated equivalent, hypothetical 1-kilometer or 1-mile sections that are not representative of typical project lengths and do not encompass variability in actual construction **(***7*), (*8*), (*9*), (*10*). Alkins et al. only produced cumulative environmental savings and did not delineate the results by life cycle stage (*9*). Cross et al. assumed a 25-mile hauling distance to the HMA plant and 100-mile hauling distance to an asphalt emulsion plant, when industry data shows much shorter hauling distances are common (*10*). Other studies from Shatec Engineering Consultants and Chan et al. stated environmental savings when using CIR in place of M&O, but provided little evidence for the savings (*11*), (*12*). Upon review of these studies, it was determined that there is a gap in understanding the life cycle components attributing to cumulative environmental savings. Additionally, there is a lack of validation case studies to provide information relevant to construction.

## METHODOLOGY

To address the research gaps identified in the literature review, the Recycled Materials Resource Center (RMRC) at the University of Wisconsin-Madison has worked closely with the Wisconsin Department of Transportation (WisDOT) to quantify the relative environmental impacts of CIR and M&O. For this report, case studies of nine highway projects across Wisconsin that utilized CIR have been analyzed and compared to conventional M&O using LCA. The nine project locations are shown in Figure 1.

### M&O and CIR Processes

The first step in the M&O process, also called mill and fill, is to mill the existing pavement to a specified depth dependent on distress of the roadway; for the projects in this study, the milling depth was between 2 and 5 inches (5 to 12 cm). The milled material is then hauled to the nearest asphalt plant to be recycled, and 4 to 4.5 inches (10 to 11 cm) of new HMA produced from virgin (80%) and recycled (20%) materials is paved on top of the milled surface *(13)*.

Like M&O, the first step in the CIR process is to mill the existing roadway. In the nine cases studied here, and for most cases, milling depth is 2 to 4 inches (5 to 10 cm) (*2*). Depending on the distress of the roadway, however, some pre-milling may be necessary for a project. Generally, all the RAP generated during the milling of the existing road is used for reconstruction (*2*). After milling, the material is crushed and graded, a stabilizing agent (e.g. asphalt emulsion) is added, and the mixture is paved 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 anywhere from a few hours, up to several weeks, depending on conditions. The most common curing periods are 2-3 days (*3*). Traffic can drive on the CIR compacted base during the curing period. After curing, new HMA is paved as a wearing course layer; the wearing course needed in CIR construction is thinner, and therefore requires less virgin materials than M&O. A side-by-side road profile comparison of the M&O and CIR processes is illustrated in Figure 2.

It is also important to note that the CIR surface post compaction may exhibit a series of ripples in the pavement surface perpendicular to traffic, known as corrugations (*14*). These can disturb the ride quality and may require an additional layer of HMA overlay as a leveling layer to smooth the surface before paving the wearing course layer. Of the nine projects evaluated in this study, only STH 64 required a leveling layer, and environmental savings were still achieved. Although the CIR has a more involved construction process, it requires less new HMA and reduces transportation of materials to and from the HMA plant.

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 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 (*2*). 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. Only one project analyzed in this study 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.

Multi-unit recycling trains involve different machines for each of the different processes. 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 (*2*). 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.

## Environmental Impacts Analysis

To most effectively determine the environmental benefits associated with the implementation of the CIR process, a LCA of each the CIR and M&O 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 to assess the environmental and economic effects of pavement and road construction under the sponsorship of RMRC (*15*). 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 (kg), 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 (*15*).

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 included the benefits associated with the CIR process in place of M&O, 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 WisDOT and contractors. The nine projects were all constructed using CIR, with materials and equipment tracked by the contractors on site. Additionally, contractors were asked to provide hypothetical material quantities and equipment specifications for the nine projects if M&O construction was used. Productivity and fuel consumption data for the equipment were obtained from the equipment manufacturers (*16), *(*17*). For each project, two PaLATE scenarios were performed: one for the actual CIR construction, and another for the hypothetical M&O construction. For the eight projects that utilized a multi-unit recycling train, two PaLATE spreadsheets were needed to accommodate the equipment inputs, and thus the total CIR environmental impacts for the multi-unit recycling trains were the sum of the outputs of the two spreadsheets. Information used to perform LCAs included amount of HMA, tack coat, and surface area of milling for the CIR process and the hypothetical M&O, and additionally the asphalt stabilizing agent and surface area of the CIR layer for the CIR process. CIR thickness and HMA thickness varied by project to meet the design requirements of the road. 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 according to the standard procedures described in the PaLATE Manual (*18*). For this study, the impact assessment results only for energy use, water consumption, and carbon dioxide emissions from the PaLATE were compared for both CIR and M&O. Conclusions were drawn such that the results of this study can help future contractors and DOTs to estimate the savings associated with using CIR instead of M&O for their highway construction projects.

### Virgin Aggregate Reduction

M&O construction requires more virgin aggregate than CIR. Reduction in virgin aggregate consumption was also considered as a benefit and was evaluated. To find reduction in virgin aggregate consumption by using CIR in place of M&O, a simple volume reduction calculation was used:

$$VA_{reduction} = VA_{M\&O} - VA_{CIR} \tag{1}$$

### Assumptions

This research used the PaLATE database program with some updates, and used the following assumptions:

- All M&O projects were assumed to have depths of 4 - 5 inches and HMA Overlay of 4 - 4.5 inches.
- Mix design was assumed to be the same for the M&O 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 (*19*).
- 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.
- Water trucks were not included in the analyses because they were used in both the M&O alternative and the CIR process.
- Manufacturers fuel consumption and productivity specifications were unavailable for some of the older equipment used. Thus, comparable equipment research was conducted to choose an equivalent piece of machinery that had the most similar fuel consumption and productivity specifications. This allowed the use of the same equipment for each multi-unit recycling train project.
- Initial construction was not considered because each of the projects was completed on existing road. Maintenance materials, transportation, and construction were analyzed.
- It is noted that PaLATE calculates emission factors from national averages from 1996 – 2002.

## RESULTS

The variables that were subject to change with every project are listed in Table 1 for all the nine projects. Thickness of HMA for M&O 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 M&O all control the transportation and construction related environmental impacts.

Environmental parameters were assessed at the material production, transportation, and construction phases and combined as total percent reductions. The percent reductions within each of the environmental output categories due to the use of CIR instead of M&O for each project are illustrated in Figure 3. Percent reductions in environmental outputs behave relatively consistent throughout the nine projects. The average reduction in energy consumption and carbon dioxide emissions was 23% and in water usage 20%. The average reduction in virgin aggregate consumption was 37%.

A listing of savings in each project for each environmental parameter considered is provided in Table 2. The nine projects saved a total of 24,341,387 kWh (87,628,993 MJ) of energy, 30 tons (27 tonnes) of water, 5,029 tons (4,562 tonnes) of carbon dioxide emissions, and 81,694 tons of virgin aggregate (74,342 tonnes). 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 water savings equivalent to 158 bathtubs (*20*), (*21*), (*22*).

By using CIR, there is a significant reduction in material production-related emissions. The amount of environmental savings achieved through transportation- and construction-related activities is therefore only a fraction of the total environmental savings. The substantial environmental savings, then, comes from a reduction of virgin materials used in CIR due to the thinner HMA overlay. Figure 4 shows the cumulative percent savings from each life cycle stage of maintenance construction for the nine projects combined.

The CIR process is more demanding in the construction phase 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 (*4*), (*5*), (*6*). Figures 5, 6, and 7 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 factor in environmental savings when using CIR. This report has determined that HMA saved using CIR is the largest influential factor.

## ANALYSIS OF DATA AND OBSERVED TRENDS

To normalize the data and demonstrate the parameters in a project that will determine the savings, Figures 8-10 below were generated. These graphs represent a framework for the quantity of savings achieved by using CIR in place of M&O 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 an essentially linear trend, which demonstrates that the two key factors in CIR savings with respect to M&O are the reduction in HMA production and the 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 0.96. 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 M&O, whereas all other projects used much less HMA proportionally. The resource intensive nature of asphalt makes reduction of HMA a key factor in the environmental savings achieved by using CIR instead of M&O. 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.

## CONCLUSIONS

The nine projects in summation saved 24,341,387 kWh (87628993 MJ) in energy consumption, 5,029 tons (4562 tonnes) in carbon dioxide emissions, 30 tons (27 tonnes) in water usage, and 81,694 tons (74,112 tonnes) of virgin aggregate. It was determined that the environmental savings achieved by using CIR are directly related to the reduction in volume of hot mix asphalt used in thinner hot mix asphalt overlay, and to the reduction in transportation of reclaimed materials to and from site. Linear correlations using volume of hot mix asphalt avoided and hauling distance estimate the energy consumption, water usage, and carbon dioxide emission savings achieved when using CIR in place of conventional M&O for future highway resurfacing projects. They exhibit the environmental savings potential CIR holds for road rehabilitation projects in the future.

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## TABLE 1 Summary of Project Information.

| Project | M&O HMA (in) | CIR Base (in) | CIR HMA (in) | Road Width (ft) | Project Length (mi) | Hauling Distance (mi) | Excess RAP Hauled Away (tons)[1] | Recycling Train |
|---|---|---|---|---|---|---|---|---|
| **CTH H** | 4.5 | 4 | 3.5 | 30 | 9.5[b] | 5.3 | 0 | multi |
| **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 RL** | 4 | 3 | 2 | 30 | 8.10 | 10.3 | 8898 | multi |
| **STH 48 GB** | 4 | 4 | 2.25 | 24 | 12.5 | 4.3 | 10382 | multi |
| **STH 64** | 4 | 4 | 3 | 30 | 4.46[c] | 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 |

*Note: 1 in. = 2.54 cm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 ton = 0.907 tonnes*

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[a] *The asphaltic surface was too distressed to use for CIR, so it was hauled to the HMA plant.*

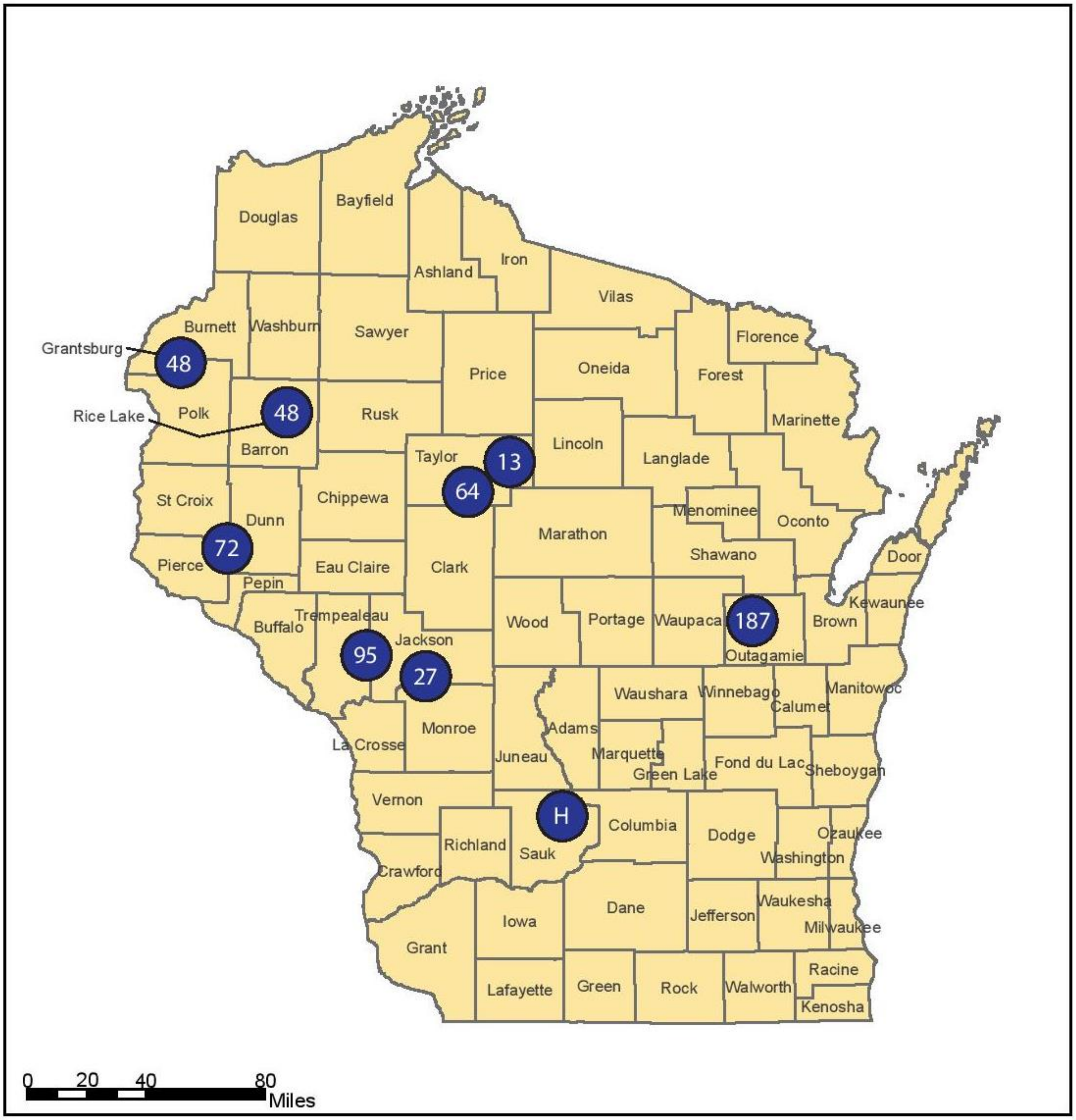
[b] *Originally a 12.3-mile project. 2.8 miles were constructed using single-unit recycling train and the remaining 9.5 were constructed using a multi-unit recycling train. This project was looked at as a 9.5-mile multi-unit project. The project quantities were adjusted.*

[c] *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 M&O due to inclement weather.*

## TABLE 2 Environmental Savings by Project.

| **Project** | **Energy Consumption (kWh)** | **Water Consumption (tons)** | **Carbon Dioxide Emissions (tons)** | **Virgin Aggregate (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 RL | 3,930,466 | 5.1 | 820 | 11,142 |
| STH 48 G | 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** |

*Note: 1 kWh = 3.6 MJ, 1 ton = 0.907 tonnes*



*Note: 1 mi =1.61 km*

**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)

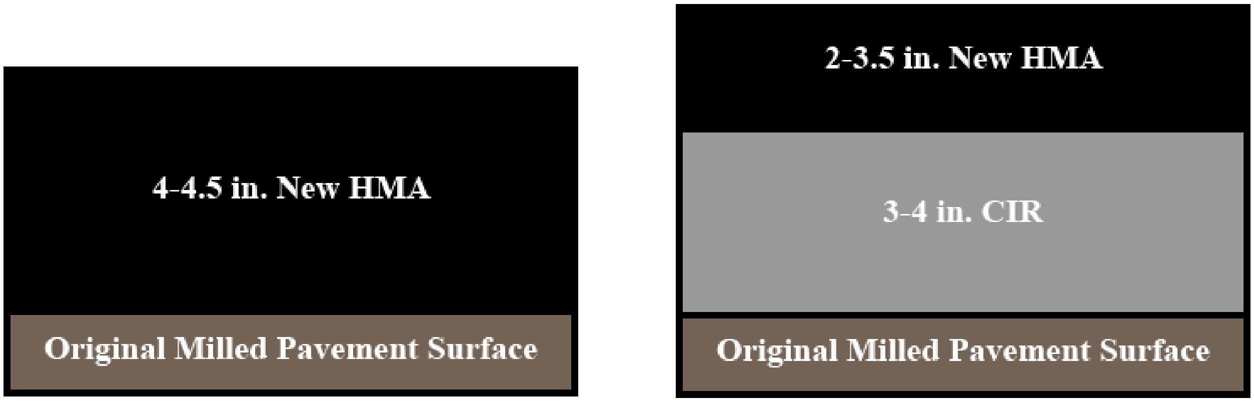
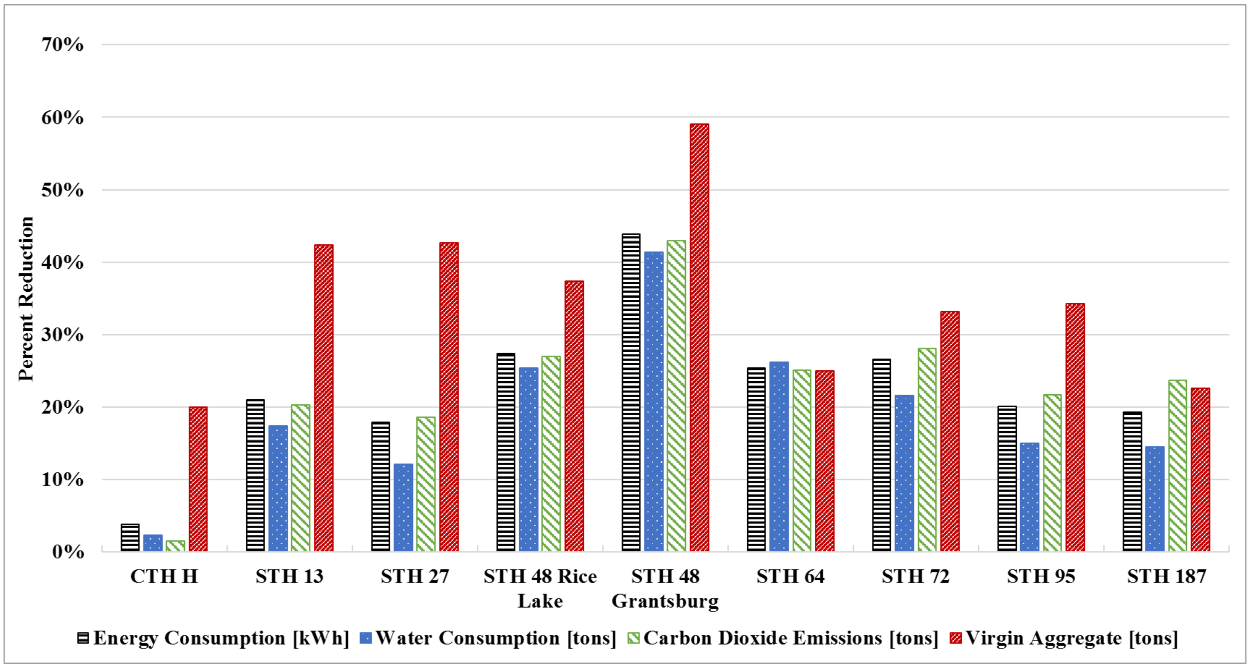


**FIGURE 2 Mill and overlay and cold-in-place recycling road profiles.**



*Note: 1 kWh = 3.6 MJ, 1 ton = 0.907 tonnes*

**FIGURE 3 Percent reductions achieved using CIR in place of M&O for each project.**

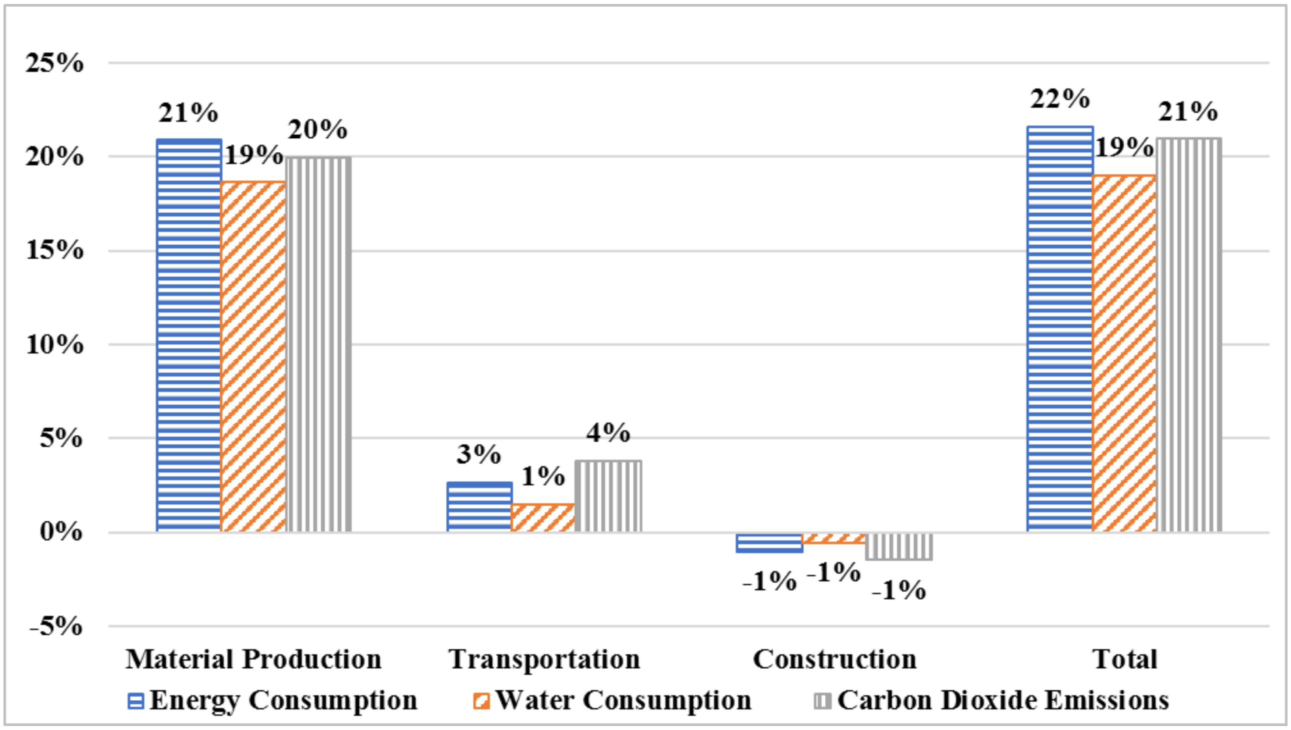
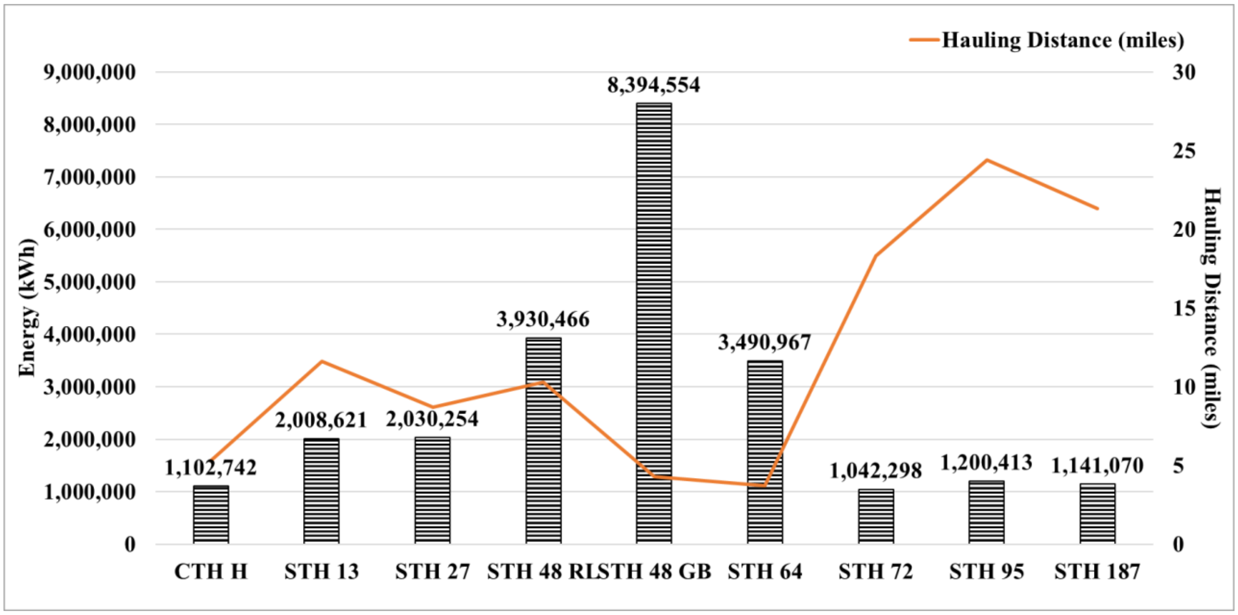
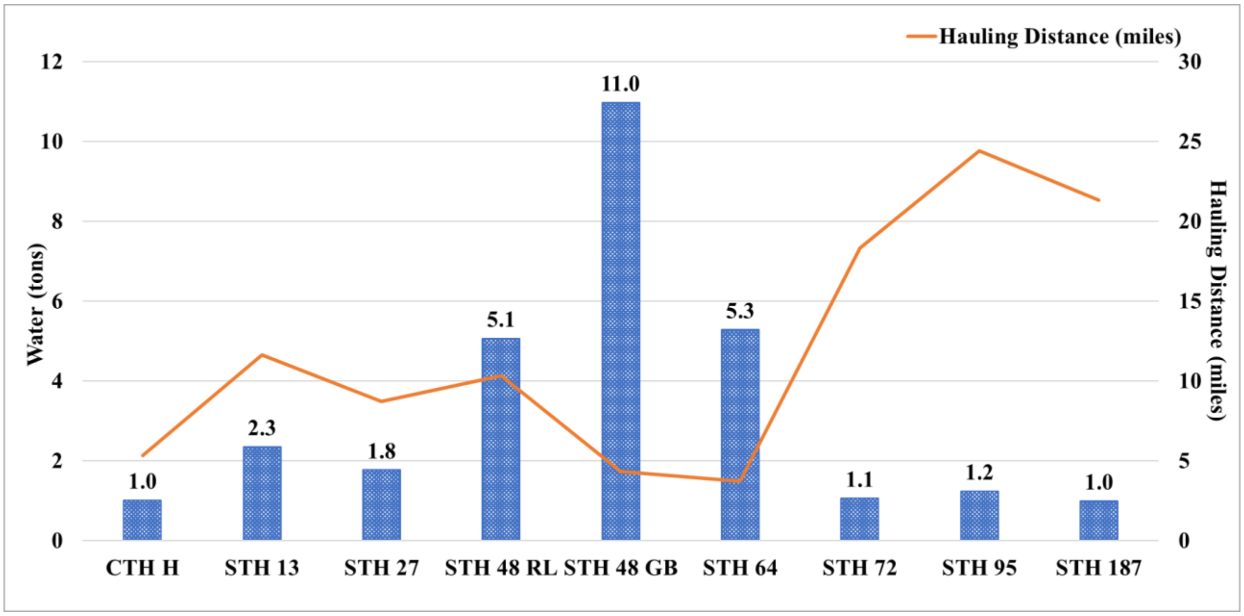


**FIGURE 4 Percent reductions achieved using CIR in place of M&O for each life cycle stage.**



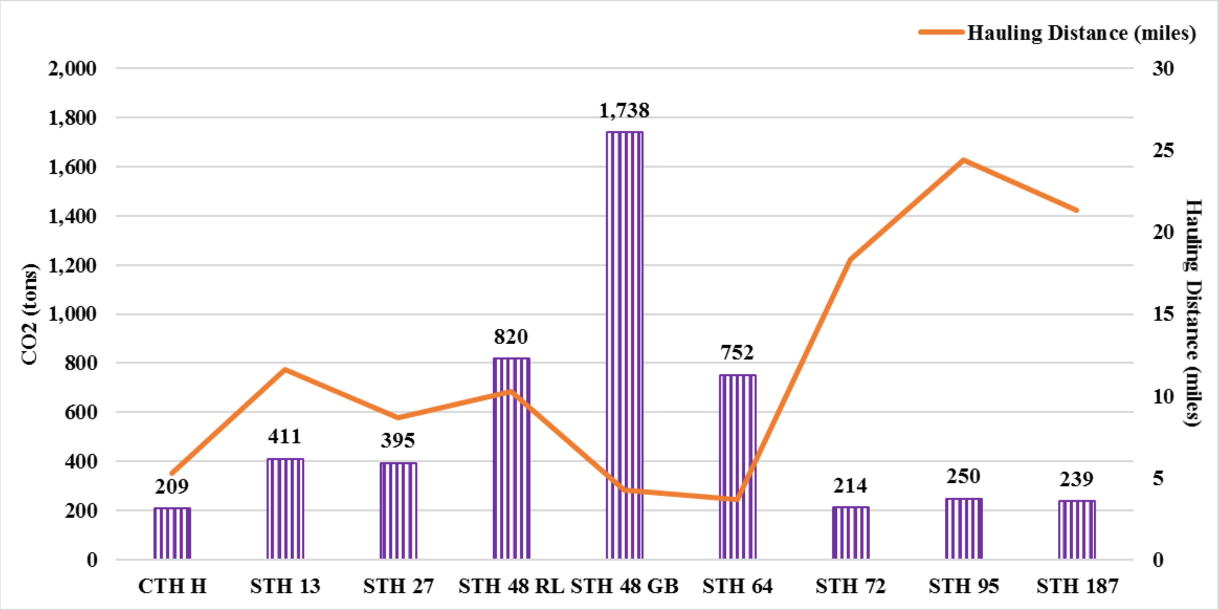
*Note: 1 kWh = 3.6 MJ, 1 mi = 1.61km*

**FIGURE 5 Energy savings achieved per project, plotted with hauling distance.**



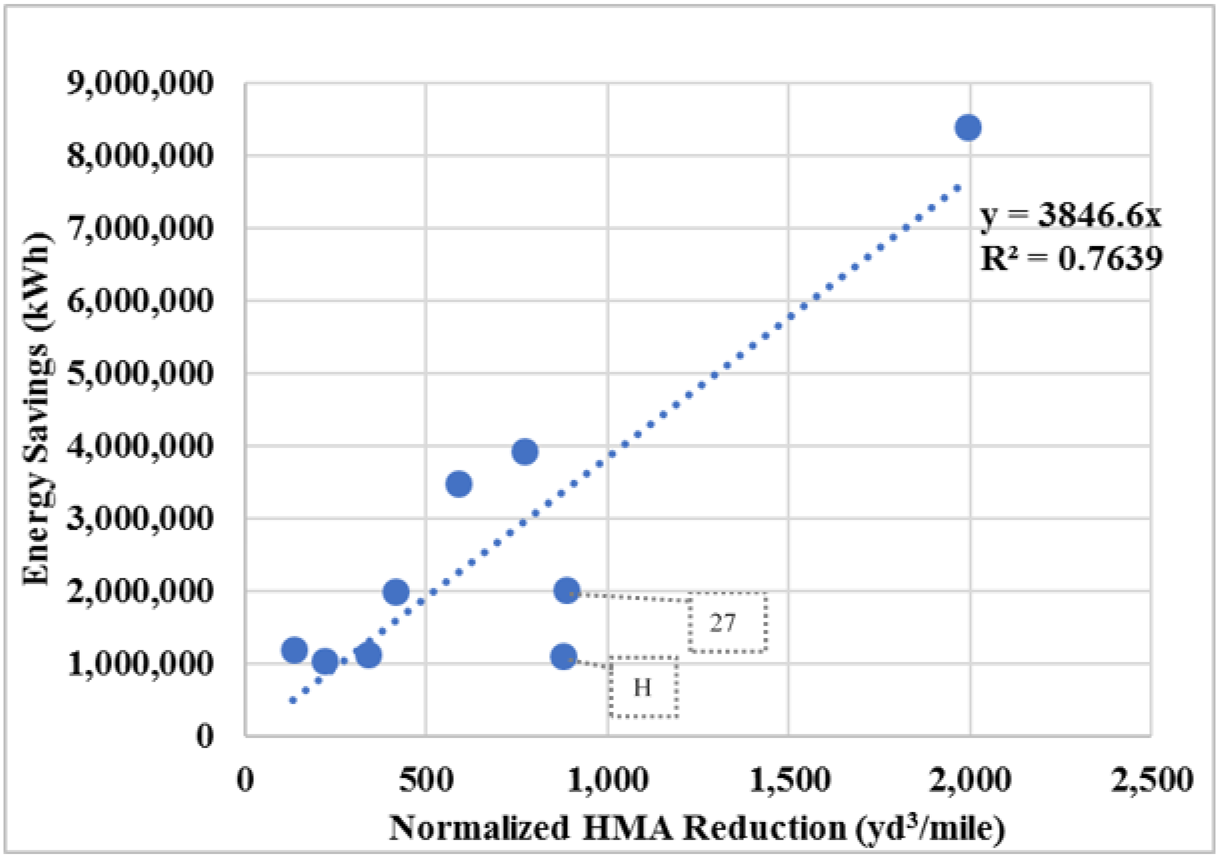
*Note: 1 ton = 0.907 tonnes, 1 mi = 1.61 km*

**FIGURE 6 Water savings achieved per project, plotted with hauling distance.**



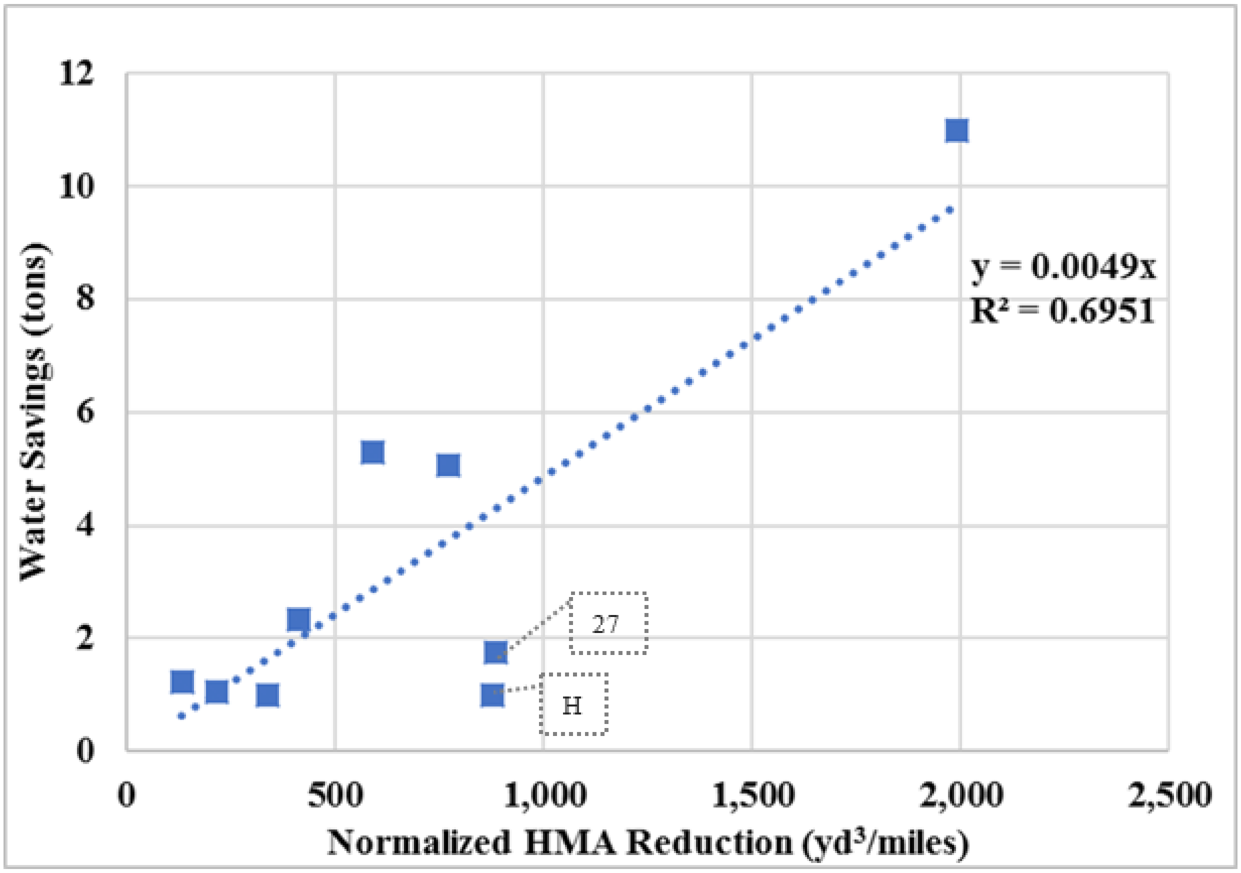
*Note: 1 ton = 0.907 tonnes, 1 mi = 1.61 km*

**FIGURE 7 Carbon dioxide emission savings achieved per project, plotted with hauling distance.**



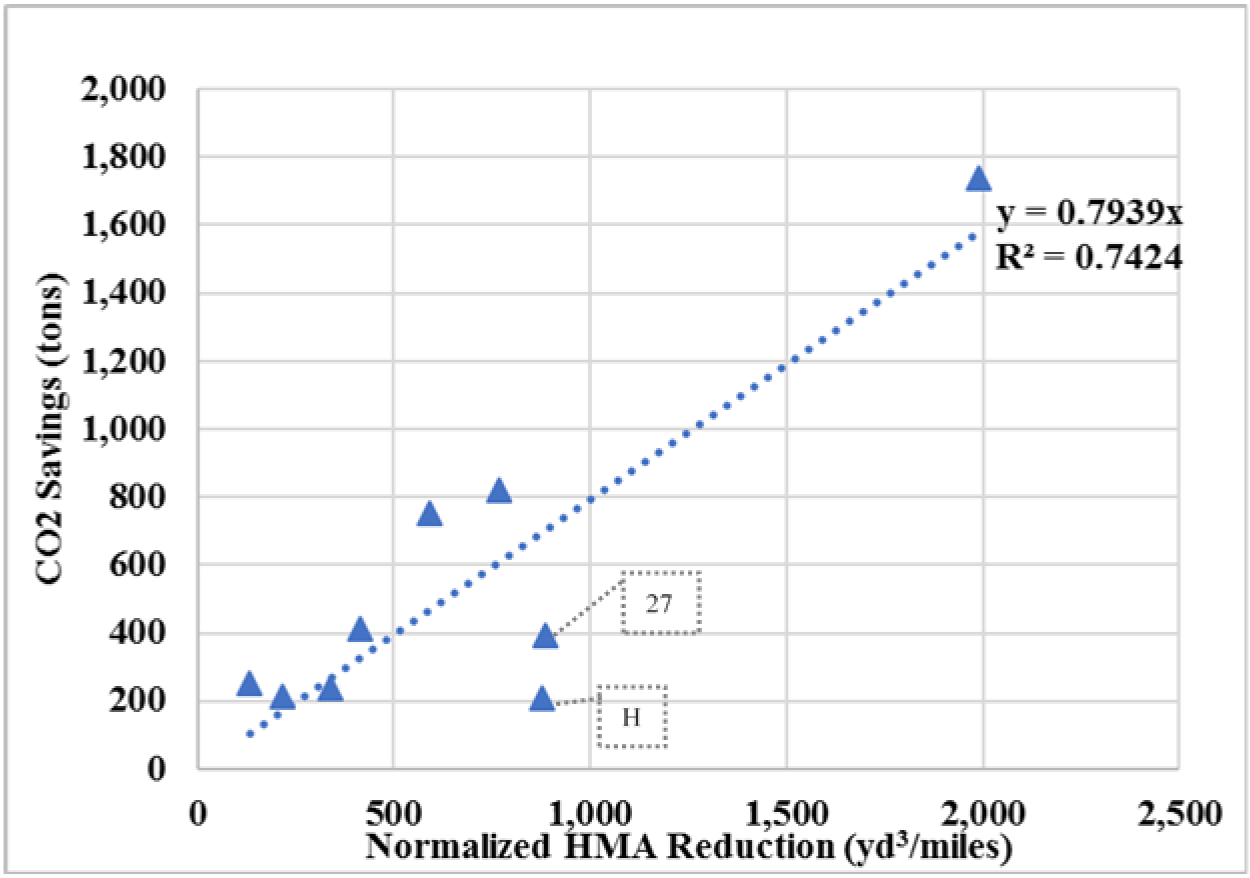
*Note: 1 kWh = 3.6 MJ, 1 yd$^3$/mile = 0.475 m$^3$/km*

**FIGURE 8 Energy savings predictions.**



*Note: 1 ton = 0.907 tonnes, 1 yd*$^3$*/mile = 0.475 m*$^3$*/km*

**FIGURE 93 Water savings predictions.**



***Note: 1 ton = 0.907 tonnes, 1 yd$^3$/mile = 0.475 m$^3$/km***

**FIGURE 10 Carbon dioxide savings predictions.**