Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation

Final Report

CLEAR ROADS

research for winter highway maintenance

Bolton & Menk, Inc.

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16. Abstract (Limit: 250 words)

This study investigates how roadside vegetation management can enhance winter road maintenance by leveraging solar radiation to improve pavement conditions. The research addresses a gap in quantitative guidance on the effects of tree canopy shading during winter. A multi-phase approach was employed, including a literature review, a national survey of transportation agencies, desktop analysis of submitted data, and a controlled field study in Minnesota. Findings from field monitoring reveal that shaded pavement segments were up to 20°F colder than sun-exposed areas, prolonging snow and ice persistence by an average of 5.2 hours and potentially increasing salt usage. Conversely, sunlit pavement demonstrated faster recovery to bare conditions and potential material savings exceeding 50 pounds per lane-mile under certain conditions. The project culminated in a Vegetation Management Guide and a spreadsheet-based Shadowcasting Model to help agencies quantify solar radiation benefits of vegetation management in shade-prone segments and prioritize vegetation removal or pruning while balancing safety and community considerations. Recommendations for future research include validation of results in other regions, integration with drainage and pavement design, and refinement of remote sensing tools for shade mapping. These findings provide actionable strategies for improving winter road safety, reducing maintenance costs, and supporting sustainable operations.

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Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation
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Executive Summary

This report presents the findings of the CR23-04 research project, "Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation," conducted by Bolton & Menk, Inc. in partnership with the University of Minnesota's Saint Anthony Falls Laboratory (SAFL). The study was initiated to address a critical gap in winter road maintenance planning: the lack of quantitative guidance on how roadside vegetation impacts pavement conditions during winter and how strategic vegetation management can improve safety, efficiency, and sustainability. Having quantitative assessments of the benefits of solar radiation at the road surface will help maintenance agencies prioritize and communicate with the general public.

The project combined a comprehensive literature review, a national survey of winter maintenance agencies, desktop analysis of vegetation removal sites, and a controlled field instrumentation study in Minnesota. Key findings demonstrate that tree canopy shading significantly reduces pavement temperatures, prolongs snow and ice persistence, and increases salt application rate recommendations. Field data revealed that sun-exposed pavement can be up to 20°F warmer than shaded segments, with a 5.3-hour faster return to bare pavement and potential salt savings exceeding 50 pounds per lane-mile in certain conditions.

The study culminated in the development of a Vegetation Management Guide for Winter Roads, offering practical recommendations for identifying shade-prone road segments, prioritizing vegetation removal, or pruning, and implementing best practices while balancing environmental and community considerations. The guide includes tools such as a Shadowcasting Model to quantify solar exposure and support decision-making.

Future research suggestions that could extend the value of this project include multi-year and multi-region validation of findings, integration of vegetation management with drainage and pavement design, ecological impact assessments, and refinement of remote sensing tools for shade mapping. These efforts will further enhance the ability of transportation agencies to optimize winter maintenance strategies and communicate the benefits of vegetation management to stakeholders.

Introduction

Winter highway maintenance is profoundly influenced by a road's exposure to sunlight. In sun-exposed areas, solar radiation warms the pavement, which helps prevent snow from bonding and makes deicing chemicals more effective. Conversely, where overhanging trees cast shade on the pavement, road surface temperatures stay lower, ice lingers longer, and maintenance crews must apply more salt and make more passes to keep the road safe. Some agencies actively maintain roadside vegetation to increase sun exposure and improve winter driving conditions. However, prior to this project, there was little formal guidance or quantified evidence on the winter maintenance benefits of vegetation removal. This lack of documented benefits sometimes led to public resistance against tree removal—communities often value roadside trees for aesthetics, wildlife habitat, and other benefits and may oppose their removal without clear justification.

Project CR23-04 was initiated to fill this knowledge gap by scientifically evaluating how managing roadside vegetation (through trimming or removal) impacts winter road conditions. The ultimate goal was to equip transportation agencies with data and guidance to balance road safety and mobility with environmental and community values. In essence, the project set out to turn anecdotal evidence ("sunny roads are easier to maintain") into concrete information that agencies can use to make informed decisions and better explain the rationale for vegetation management to stakeholders.

Project Scope

In summary, the project's planned activities included an initial literature review which would then inform primary research. The primary research efforts included a mix of a maintenance professional survey via questionnaire, field experimentation, and development of a Vegetation Guide. The researchers decided that since quantitative tools for assessing shade on road surfaces did not seem accessible, a workbook to supplement the guidance in the manual would be helpful. By structuring the work this way, the team ensured that insights gained from the data would directly feed into practical recommendations.

State DOTs and local agencies were engaged via surveys, meetings, and review opportunities throughout, to align the research with real-world needs.

Literature Review Findings

The literature review surveyed existing research and guidance on three main topics: (a) how roadside vegetation affects road surface conditions in winter, (b) the practice of vegetation management by transportation agencies, and (c) any known side effects of removing or trimming roadside trees. The full literature review report is included as Appendix A.

Key findings from the review are summarized below:

- **Direct research on winter shading is uncommon.** The review found very few scientific studies directly quantifying the impact of tree shade on winter pavement icing or temperatures. Many papers have modeled pavement temperatures with solar radiation as a factor, but only a small subset explicitly considered shading from trees or terrain. In other words, while it's well established that sunlight warms pavements, there was almost no published quantitative field data on how shade from trees can worsen ice or how much tree removal may help. Most information prior to this was anecdotal or based on practitioners' observations.

- **Many agencies publish guidance for general roadside vegetation maintenance.** FHWA and several state DOTs have published guidelines or manuals on roadside vegetation management, but typically these focus on safety (clear zones to remove fixed-object hazards) or general maintenance (controlling invasive species, preserving sightlines) and disregard winter operations. Where winter is mentioned, aspects are only mentioned qualitatively. For example, the FHWA's "Vegetation Control for Safety" guide (2008) advises trimming overhanging branches before winter to prevent them from dropping snow/ice onto the road, but it does not quantify benefits to pavement conditions. State manuals (e.g., Minnesota's roadside vegetation handbook) recommend an integrated vegetation management plan and note that shaded roads can have persistent icy spots, yet specific criteria for tree removal are not well-defined beyond safety concerns. In short, agencies recognize the winter shading problem but lack empirical thresholds that relate vegetation management to winter road condition.

- **Mixed findings on the effects of roadside vegetation.** Scientific studies show somewhat contradictory impacts of roadside trees, indicating the issue is complex. Some examples that illustrate mixed findings include:

    - **Safety and Operations.** Transportation engineers often view roadside trees as a winter liability – they create shade that can lead to icy patches and overhanging branches may obstruct plowing. Accident analyses have shown that trees close to the road can increase crash severity. Many state DOTs reported in surveys that fallen leaves from canopy trees clog drains and require extra maintenance.

    - **Pavement Condition:** Much research suggests that shade is beneficial during warm seasons. By reducing sun exposure, trees can mitigate certain pavement distresses in summer and even slow down freeze-thaw damage. Tree canopies keep pavement cooler in extreme heat and reduce UV radiation, which might extend asphalt life. They also intercept precipitation, which can reduce the total water reaching the pavement.

  - **Evidence Gap – Winter Surface Ice:** Crucially, one recent study which attempted to measure snow and ice on pavement under tree canopy vs. open sky found no strong correlation between tree cover and ice thickness (Naik et al., 2020). Most ice formation was due to vehicles compacting snow or nighttime re-freeze of meltwater puddles, rather than shade. In their controlled trials, deciduous branches (even leafless) intercepted some snowfall (about 13% less snow under trees) but did not measurably prevent or prolong ice on the road surface. This counterintuitive result implies other factors (such as drainage and traffic) might outweigh the direct effect of shade on icing. The Ohio Department of Transportation suggested future research should evaluate the role of drainage upkeep versus tree removal. This finding points to the importance of a holistic approach: managing roadside vegetation is one tool, but it should be combined with good drainage and prompt plowing for best results.

- **Community and Environmental Aspects:** The literature also reviewed the broader context of roadside vegetation. Trees provide many benefits: aesthetic appeal to road corridors, wildlife habitat and corridors, snow fencing, and cooling of adjacent areas in summer. There is also evidence that tree-lined roads can have a traffic calming effect in suburban areas, causing drivers to intuitively slow down. However, negatives include greater corrosion and pollution from heavy salt use in shaded areas, as well as the obvious safety hazard of large trees close to the road. Some publications even argue for more roadside vegetation in certain forms (Galantinho et al., 2022) to support biodiversity. This underscores that vegetation management requires strategic planning.

In summary, the literature review confirmed that improving winter road sunlight exposure is a plausible strategy but one that had not been rigorously quantified before. There was broad agreement that shaded winter roads tend to have worse conditions, yet the specific benefits of vegetation removal remained largely undocumented prior to this project. The review also highlighted the need to consider the trade-offs: removing trees may aid winter maintenance but could have other costs or consequences (environmental, visual, etc.), so guidance should help agencies decide where and how much vegetation management makes sense. These insights set the stage for the project field research and were later incorporated into the guidance document to ensure it addressed balancing factors to the benefits of vegetation management.

Primary Research

Our primary research includes findings from an online questionnaire about vegetation management efforts of maintenance agencies, field measurement of solar radiation and pavement temperatures along road segments, and desktop analysis of shade conditions based on field measurements. The analyses were also informed by records from the maintenance agency responsible for the road segment where our instruments were located.

Online Survey

Early in the project, the team reached out to winter maintenance professionals within the network of Clear Roads member states to evaluate existing vegetation management practices. The survey was used to identify locations of vegetation management as well as the motivations, especially if enhancing winter performance of the road surface was an intended outcome. Locations spanned the U.S. and represented a wider range of climates and regions than anticipated. Respondents included a winding Vermont interstate segment, a north-south Arizona mountain highway, hilly Pennsylvania river valleys, and passes through mountains and forests at far northern latitudes in Washington, Montana, and Maine. Each site report included details like date of removal, which shoulder was maintained, dominant vegetation type, intended outcome, and whether the maintenance agency would be able to share material or road condition data.

Survey findings provided some clear pattens among respondents. More than 90% of respondents indicated that improved winter performance was an intended outcome of vegetation removal. A majority of sites reported that deciduous forests (57%) or mixed forests (31%) were the predominant canopy type causing problematic shade. Most of the vegetation management efforts took place in late fall or early winter. While vegetation management records indicated a wide range of placement and road orientation combinations, the most common placement for vegetation causing problematic shade was to the south of east-west roadways. The next most common grouping was to either side of north-south roadways. The survey questions and results are provided in Appendix B.

Field Site Selection & Measurement

While responses were being collected from across the nation, the Minneapolis, Minnesota-based research team was searching for sites nearby that could represent rural shaded roads where vegetation management practices may affect road surface conditions. This involved independently reviewing data products that characterized road corridors and land cover within a reasonable distance of the research team, as well as asking for contributions from local highway agencies. The latter approach proved promising since maintenance agencies could indicate areas where shade was truly problematic and provide maintenance data.

The field monitoring site selected was contributed by Anoka County Highway Maintenance. Anoka CR-13, also referred to as 229th Ave NW, is a relatively flat, east/west, two-lane asphalt roadway crossing through low-density residential and agricultural land use.

The project team's dedicated field monitoring site allowed for collection of high-resolution data. One monitoring site was located along a short sunny segment next to a small wetland. Two monitoring sites were located along dense evergreen heavily shaded segments in close proximity, approximately one mile apart, ideal for side-by-side comparison in the same weather events. In December 2024, the team installed instruments at both the "sunny site" and the "shaded site". The shaded sites were set up as a primary site and a secondary site, which allowed for pavement temperature measurement quality control in the shaded area.

The sunny site and primary shaded site were each outfitted with an infrared pavement temperature sensor aimed at the road, a mini weather station (measuring air temperature, humidity, wind, and solar radiation), and a time-lapse camera to observe surface conditions. The sensors fed data to a cloud-based logger continuously, while the cameras stored photos locally. Monitoring captured the core winter months with data collected from December 6, 2024 through April 2025. The intent was to directly measure pavement temperature differences between the sites and account for driving variables. The single corridor field observation method provided a natural experiment where weather conditions and maintenance approaches were analogous at each site, and shading was one of very few differences.

By mid-February 2025, about 10 weeks of field data were collected, encompassing a variety of conditions, so a mid-project presentation was given to the technical advisory panel. By that time, the team recorded 69 days of clear skies as well as several storms. They examined the data for patterns, particularly daily temperature curves, and response during precipitation. The analysis included pairing the pavement temperature measurements with records of precipitation timing and intensity (from a nearby official weather station) to see, for example, how each site fared during a snow event. They also computed potential salt application rates using standard guidelines to infer how much salt would be needed to melt snow/ice at each site's observed pavement temperatures.

Desktop Analysis & Key Findings from Monitoring

The monitoring data revealed clear differences between the sun-exposed and shaded road segments.

Thermal Benefits of Sunlight

Post-season analysis confirmed a significant thermal advantage for the sunlit pavement. On clear cold days, the black asphalt in the open sun would warm well above the air temperature, whereas the shaded asphalt remained near ambient air temperature. Data from early January showed the pavement at the sunny site peaking around 20°F (11°C) higher than the shaded site during midday hours. For example, one day the sunny pavement reached ~40°F while the shaded pavement stayed near 20°. The largest differences were observed late morning through early afternoon when the sun's energy was strongest. This finding is intuitive but now quantified: tree shade can keep a road section 20 degrees colder than an adjacent sunny section. Such a temperature gap can mean the difference between wet pavement and ice. Following snowfalls, it is common for maintenance agencies to do spot treatment. These sunny locations would be much less likely to need treatment.

The team noted that during one light snow event, the sunny zone's pavement rose above 32°F toward the end of the event, enough to start melting off the snow, while the shady zone stayed below freezing the entire time. In practical terms, the sunny stretch began self-clearing once the sun came out, whereas the shaded stretch needed deicer and/or plowing, or remained snow-covered. This directly demonstrates the benefit of sun exposure: it can undercut compacted snow and help break the bond between ice and pavement, as the report later explains in the Vegetation Management Guide.

Cloudy Conditions

One unexpected observation was that on cloudy days, the difference between the sites shrank – and at times the shaded site even received slightly more diffuse radiation than the open site. The team noted instances where the instrumentation showed the shaded area getting equal or greater sky radiation under overcast skies. This might occur because the open site loses long-wave radiation, which is sensible heat, to the sky while a forest canopy might partially trap or reflect that radiation. The practical insight is that the advantage of tree removal is most pronounced on clear sunny days. Under heavy cloud cover or at night, both sunny and shaded segments behave similarly. While the county was conducting maintenance operations, pavement temperature analysis suggested that material use could be reduced in sunny areas approximately 33% of the time. This was based on application rates in published Clear Roads guidance. At those times, the average rate difference based on pavement temperature would be 50 pounds per lane mile. However, there were short periods of time where more than 200 pounds per lane mile difference would be supported.

Snow and Ice Persistence

Across multiple snow events, the automated photos consistently showed the sun-exposed pavement regaining bare conditions faster. On average, the sunny segment dried 5.2 hours sooner than the shaded segment after snowfall, despite both generally receiving the same plowing and treatment. For example, if both sites were plowed and salted, the wet pavement on the sunny side might completely dry in ~20 hours, whereas the shaded road remained wet/icy for ~25.5 hours. Nine snow events were observed during the monitoring period, and in every case the sunny portion recovered noticeably faster. Rain events were also observed, and the pattern was the same with slightly less difference (clearing an average 0.8 hours faster in sunny sites). This finding is significant for operations: it means a road crew could potentially stop re-treating a sunny area sooner, or not have to come back to re-salt, whereas the adjacent shaded segments might need extra applications to be cleared. Over a season, these amount to a substantial difference in safety and sustainability.

The full data analysis for "Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation" report is included as Appendix C.

Vegetation Management Guide & Shadowcasting Model

One of the primary deliverables of this project is the **"Vegetation Management Guide for Winter Roads."** This guide translates the research findings into practical guidance for highway agencies and local road authorities. It is essentially a best-practices manual on how to leverage vegetation management to improve winter road conditions, support regional sustainability, and work with community considerations.

The guide is written for roadside vegetation managers, maintenance engineers, and planners. Its purpose is to give them a tool to identify where roadside trees are likely to cause winter issues and how different approaches to management may influence road conditions. The guide explicitly aims to help quantify the benefits of vegetation management for winter operations, so managers can make informed decisions about tree removal or pruning and communicate those decisions to stakeholders. The tone is non-technical and solution oriented.

The guide is organized into chapters that cover background, the effects of vegetation on winter roads, methods to assess problem areas, and recommended management practices. It uses the project literature review and field monitoring efforts to explain the potential benefits of a vegetation management program and refers to publicly available literature sources to introduce common approaches in forestry. It also presents tools that can be used to evaluate potential vegetation removal sites and prioritize efforts across an agency. One of those tools, the Shadowcasting Model, is an Excel-based modeling tool for evaluating solar radiation on pavement surface based on geolocation, road orientation, placement of vegetation, and local topography.

The Vegetation Management Guide and Shadowcasting Model can be accessed on the Clear Roads project website: https://www.clearroads.org/project/23-04/.

Conclusions

This research project was able to quantify many of the differences between road surfaces affected by shade and those which are well-exposed to the sun. It also identified the breadth of regions where shade is seen as problematic to winter road conditions. The literature review showed that while vegetation and pavement heating are frequently studied, these fields largely ignore application to road maintenance operations, despite the potential for substantial benefits.

Recommendations for Further Research

While this project has advanced the understanding of vegetation management to benefit winter road conditions, it also highlights areas where further research would be valuable:

- **Long-Term and Multi-Site Studies.** The controlled data from one winter in Minnesota showed clear benefits of sun exposure. The winter of 2024-2025 was near average temperatures for the study area, but very low snowfall, 29.4” compared to a 10-year average of 54.0”. A logical next step is to verify and expand these findings across multiple winters and diverse geographic locations. Future studies could instrument roads in different climate zones – for example, a high-elevation western US site with more winter sun but drier snow, or a Northeast forested highway – to see if the magnitude of benefits (e.g. 20°F differences, 5-hour clearing improvements) hold universally.

  Does removing trees ever *worsen* conditions due to wind-driven snow? Our data hints that blowing snow needs consideration, but dedicated studies could quantify if additional snow fence measures are needed when trees are removed in certain locales.

  The Task 3 deliverables identified a regression-based prediction for pavement temperature that used average daily air temperature and average daily solar radiation. GIS was used to apply that equation across the lower 48 states using public air temperature and solar radiation data from climate models. See Figures 1-3 (Jasinski, M. F., 2018). Future studies could test how the pavement temperature prediction methods presented within the Task 3 deliverable, which rely on regression equations informed by empirical observations, may vary based on changes in the prevalence and strength of solar radiation as well as differences in air temperature. Further work could evaluate how the model works when applied to other areas.

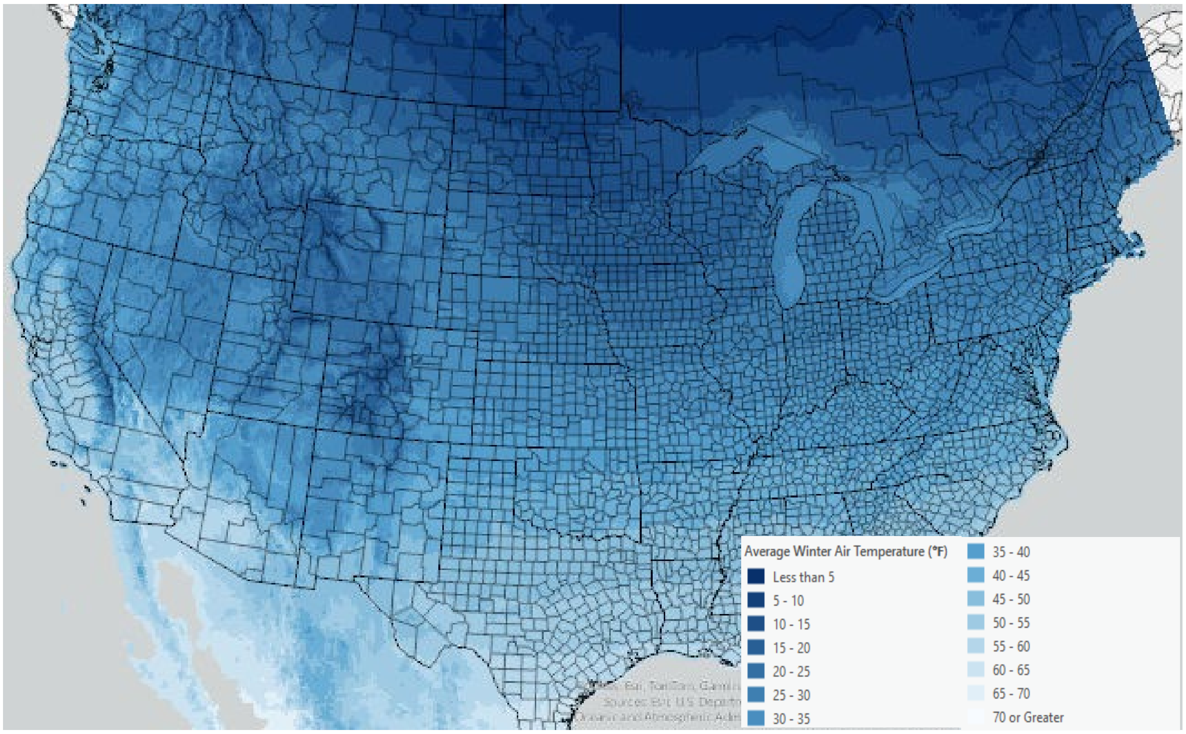

Figure 1. Average winter air temperatures (°F) (Jasinski, M. F., 2018).

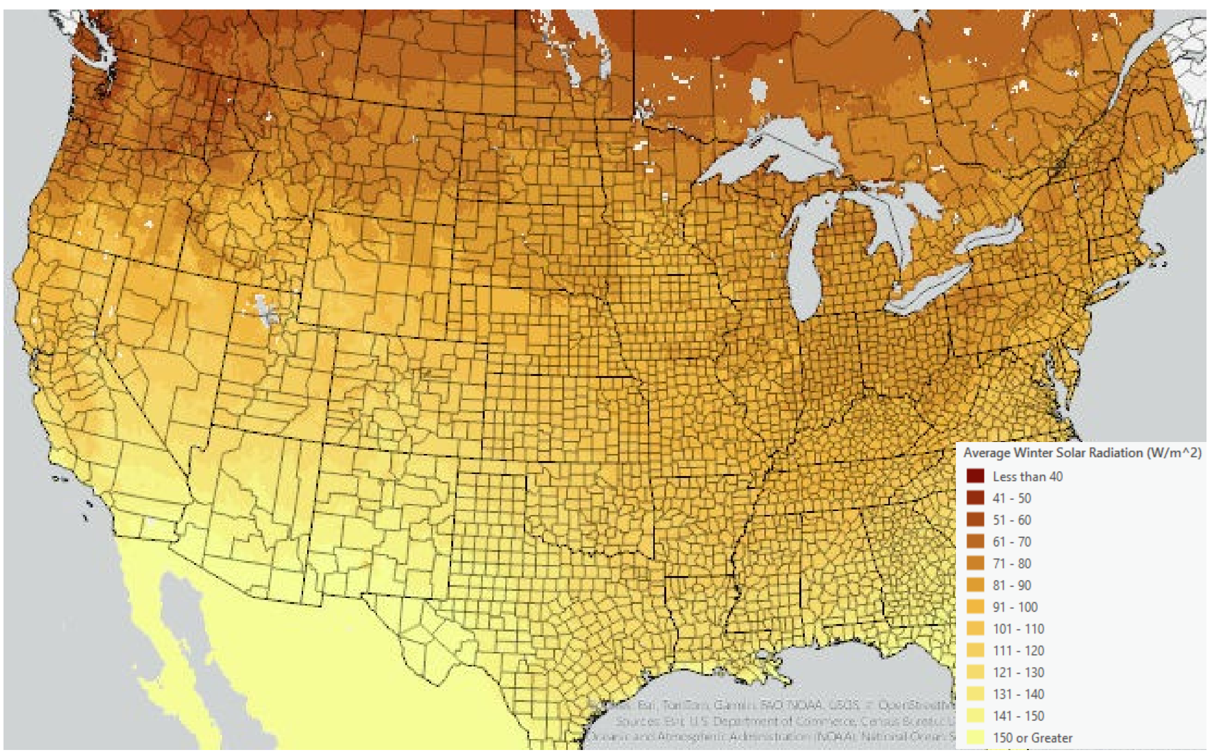

Figure 2. Average Winter Solar Radiation (W/m^2) (Jasinski, M. F., 2018).

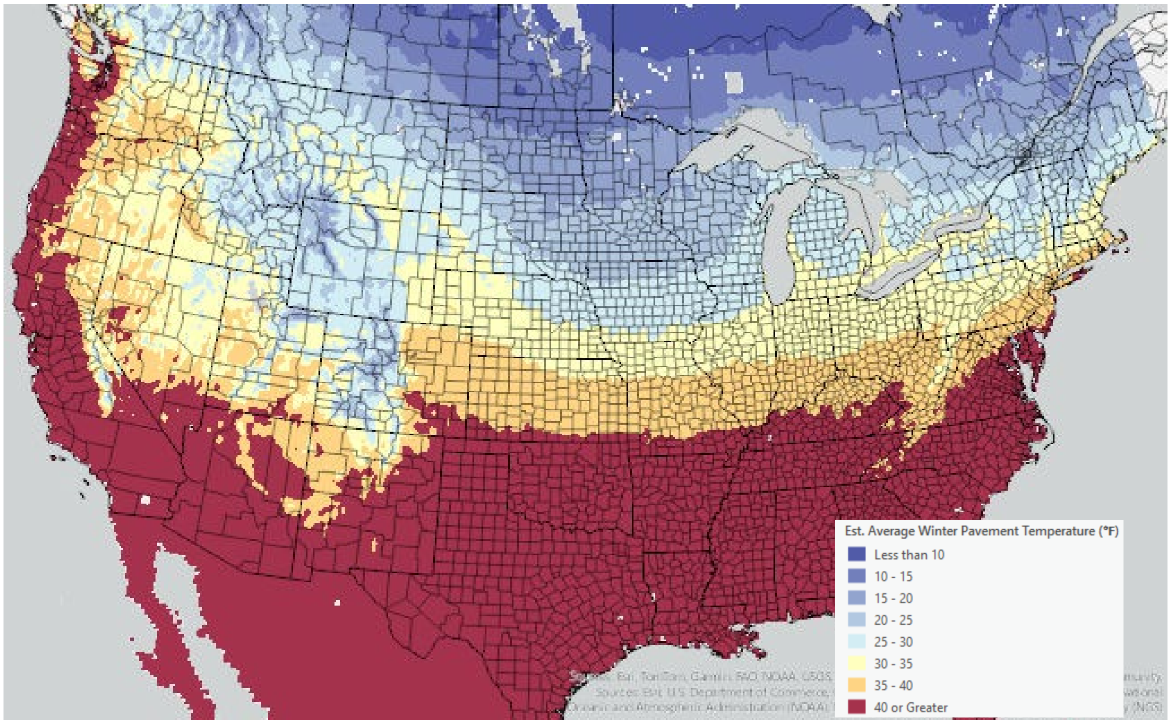

Figure 3. Estimated average winter pavement temperature (°F) (Jasinski, M. F., 2018).

- **Refinement of Shadow Modeling Tools.** The project delivered a first-generation Shadowcasting spreadsheet-based modeling tool, but further refinement or development of more accessible tools (e.g., a GIS plugin that auto-calculates winter shadow zones from LiDAR data) could aid practitioners. Future research could involve creating or validating remote sensing methods to identify shade-prone road segments over large areas. High-resolution LiDAR or even simple fish-eye photos (as one study did for urban roads) might automate the detection of where critical shadows occur. Research and development in this area could result in a mapping application that highlights trouble spots on a map for a given date/time – especially useful for DOTs in planning vegetation management programs.
- **Human Factors and Public Acceptance.** It could be valuable to research the effectiveness of communication strategies around roadside tree removal. How do different explanations or educational materials affect public support? Since community pushback is often a barrier, social science research (surveys or focus groups in communities where tree removal is proposed) could identify messaging that resonates (for example, focusing on reduced salt pollution might win over environmentally minded residents, while emphasizing safety and traction might persuade drivers). This is a practical area to explore so that science and technology-based recommendations can be implemented with public buy-in.
- **Vegetation Management Guide.** The Vegetation Management Guide produced as part of this project provides science-based information on vegetation management to increase solar

radiation and improve winter road conditions based on this research and available literature. An ongoing MnDOT-funded University of Minnesota research study, Effect of Tree Shade on Winter Maintenance Operations, is expected to provide additional data that will help inform vegetation management practices. Based on the research findings, an update to the Vegetation Management Guide may be warranted.

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Appendix A. Literature Review

Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation

Literature Review

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1. Literature Review

1.1 Introduction

This report is the deliverable for Task 2 of the research project "Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation," which was funded by Clear Roads. The report is a review of published literature related to roadside vegetation management, its side effects, the effect of solar radiation on winter pavement conditions, and other topics related to the project such as road shading due to vegetation and the corresponding impacts of shading on the road.

Many studies have investigated computer modeling of pavement temperatures with most incorporating solar radiation through an energy balance approach. Those that incorporate shading of the road surface due to vegetation are more relevant to this project than those that do not and, therefore, will be reviewed in greater detail. Regarding roadside vegetation management, the Federal Highway Administration (FHWA), and many states (e.g., Colorado, Georgia, Minnesota, Montana, Nebraska, New York, Washington, etc.) have published guidance on the topic. While this document reviews guidance from the FHWA and the State of Minnesota, not all state guidance documents are reviewed herein because some states, like Georgia, are rarely impacted by snow and ice and others, like Montana, say little about vegetation or trees with respect to snow and ice removal and/or prevention. Finally, most scientific publications on the impact of vegetation management have investigated the impact on plants and/or animals and, thus, will be summarized only briefly.

Reviewed publications are organized in the following sections of this report:

- Modeling Road Temperatures
- Shading
- Management of Roadside Vegetation
- Impact of Vegetation Management

1.2 Modeling Road Temperatures

Many researchers have developed models to predict pavement temperatures (Adwin at al., 2021). Models may be one-dimensional (Asaeda et al., 1993; Hermansson, 2004; Herb et al., 2008; Herb et al., 2009) or multi-dimensional (Yavuzturk et al., 2005; Yavuzturk and Ksaibati, 2006; Liu et al., 2010). They may predict only the surface temperature or model a vertical temperature profile. Some predict daily maximum temperatures only (Solaimanian and Kennedy, 1993), while others predict daily maximum and minimum temperatures (Salem, 2015) or a continuous sub-daily temperature time series (Herb et al. 2008, 2009). Regardless of the capabilities or desired output, many use an energy balance method that models heat transfer to and from the pavement. The typical modes of heat transfer included are solar radiation, long-wave and thermal radiation to and from the pavement surface and the atmosphere, convection due to heat transfer between the pavement surface and the air (or water) that is in contact with the pavement, and pavement internal conduction.

Herb et al. (2009), for example, used a one-dimensional finite difference heat transfer model and field measurements to model pavement temperature as a function of depth. A sensitivity analysis showed that the incorporation of a wind sheltering coefficient into the model was indeed important. This supports the notion that wind sheltering from trees is an important factor that affects pavement temperatures. While the model accurately predicted pavement temperatures when there was no snow, accuracy dropped during snowy winter months. Accuracy was improved when the model varied albedo with the season, but accuracy was still less than months without snow. Although these errors were smaller below the pavement surface, they were shown to possibly last for weeks.

Solaimanian and Kennedy (1993) used a simpler method to predict the maximum pavement temperature by using only maximum air temperature and hourly solar radiation. Their method, which used an energy balance at the surface of the pavement, estimated the resulting equilibrium surface temperature. Assumptions regarding thermal properties of the asphalt concrete were incorporated into the model. The accuracy of the method, which was tested by comparing results to field temperature measurements, predicted the pavement surface temperature within 3°C in 83% of the comparisons.

Using a different approach, Chao and Zhang (2018) conducted a regression model using the partial least squares method via analysis on the pavement temperature data and environmental data from a nearby weather station. The study concluded that environmental factors that affect pavement temperature include air temperature, relative humidity of the air, cloud cover, wind speed, and precipitation. While shading by vegetation was outside the scope of the study, shading by cloud cover was found to be an important variable, and thus it is reasonable to assume that shading by vegetation would also be important. A different regression model developed by Salem (2015) predicted daily minimum and maximum pavement temperatures based only on air temperature, wind speed, and solar radiation.

Opara and Zielinksi (2017) used the average air temperature from the seven previous days as a pseudo-observation of the road subsurface temperature. This study was based on the Model of the Environment and Temperature of Roads (METRo, v.3.3.0) that Environment Canada distributes as open-source software. This software predicts the road surface temperature by accounting for energy fluxes to and from the surface while also accounting for water accumulation. The model needs initial pavement conditions, which must be obtained from a nearby meteorological station, to run. It was concluded, however, that the prediction of the pavement surface temperature is possible without roadside meteorological weather data. Instead, averaged past weather data from the previous days can serve as the pseudo-observations of initial temperatures. Average air temperature from the preceding seven days was an adequate pseudo-observation for the surface and subsurface temperatures of the pavement but there was a loss of accuracy. This method initially increased the forecast error by an average of 1.2 °C (with standard deviation of 1.7 C) but the error decreased in the subsequent hours.

Kršmanc et al. (2012) reviewed the METRo model by comparing model results to field measurements in Slovenia during the winter. The review was primarily focused on the road surface temperature. It was concluded that the model accuracy was generally satisfactory but predicted temperatures were too high at some sites, especially around noon. To improve the model Kršmanc et al. (2012) made the following recommendations:

- Include a user option to input anthropogenic flux predictions (this is already done in the METRo version 3.2.7),

- Include water freezing point predictions as an optional input,
- Include the number of vehicle passages as an optional input,
- Include sky-view factor as optional input,
- Include the depth of a subsurface temperature sensor as an optional input,
- Include subsurface road temperature measurements on bridge locations, and
- Provide the ability to add new road layer types with optional physical properties.

Lekea and Steyn (2023) investigated the accuracy of three pavement temperature models. The models examined were: SHRP Superpave Model, the Viljoen Model (which used local pavement temperature data to develop temperature prediction equations for asphalt pavements in South Africa), and the Diefenderfer Model (Diefenderfer et al., 2006) that predicts daily maximum or minimum pavement temperatures using daily maximum or minimum ambient temperatures, the day of the year, and the depth of pavement temperature. That model was further developed by Diefenderfer et al. (2003) to include the daily amount of solar radiation at a given location, thus enabling the model to predict pavement temperatures at any location. Lekea and Steyn (2023) found that the models performed better at predicting maximum temperature as compared to minimum temperature predictions, which were highly variable. It was concluded that assumptions incorporated into minimum temperature models need to be revised to improve accuracy.

Nantasai and Nassiri (2019) used a linear regression method to model the surface of pervious concrete pavement (PCP). The study investigated frost durations at PCP near-surface depths with the intent of informing winter maintenance operations. First, the near-surface temperature of PCP was predicted using the Enhanced Integrated Climatic Model (EICM), a one-dimensional finite difference-based software model that requires detailed input parameters. By comparing field measured temperatures over an entire winter season to EICM predicted temperatures, it was concluded that the temperatures were accurately predicted, especially near the surface. The input parameters, however, needed to be adjusted to incorporate the porosity of the PCP. Then, Nantasai and Nassiri (2019) developed a linear regression model correlating the near-surface temperatures with ambient temperature, relative humidity, wind speed, and solar radiation. The regression equation accurately predicted the PCP near-surface temperature.

Adwan et al. (2021), who conducted a review of 38 pavement temperature models and categorized them as numerical, analytical, or statistical models, concluded that most models provide reasonable predictions for both minimum and maximum pavement temperatures. It was concluded that analytical methods were simpler, and only straight-forward boundary conditions were required. Conversely, some models were deemed unnecessarily complicated and required several variables as input. Adwan et al. (2021) also believed that some equations are not suitable for routine use and recommended further study on the topic.

1.3 Shading

Of particular interest to this project are shading and the temperature models that incorporate the effect of shading. This section first reviews studies that have investigated the impact of shading on pavement temperatures and then reviews models that incorporate shading. Although not all the models covered in this section incorporate shading due to vegetation or are specifically geared towards pavement temperatures, the shading aspect makes the work relevant to the project. Also, most studies that have investigated the shading of deciduous trees have done so under leaf-on conditions. The current study is focused on winter conditions when shading by deciduous trees would be less.

1.4 General Impacts of Shading

Van Dam et al. (2015) reviewed the social and environmental impacts of pavement. The impact of pavement shading by buildings and trees on pavement heating was discussed. The most important factor when the pavement is exposed to direct solar radiation is its albedo, which is the fraction of the incident solar radiation that is reflected by the surface. Thus, in addition to latitude, shading by buildings, trees, and cloud cover is important when considering pavement heating. There are, however, many other factors that influence the impact trees have on pavement and pavement surface temperature such as interception of precipitation and evapotranspiration (Rahman et al., 2014). The effect is also dependent on the tree species and season and the size of the tree canopy, tree density, and the leaf area index (Gardner and Sydnor, 1984; Rahman et al., 2014; Li, 2016).

The decrease in solar radiation due to tree shading for different tree species and for summer versus winter was investigated by Yates and McKennan (1989). They used direct measurement with a light meter to measure solar attenuation and used crown density measured via photographs and a dot matrix method developed by Wagar and Heisler (1986) to predict solar attenuation. Yates and McKennan found that the dot matrix method gave results very close to the direct measurements made using a light meter.

Zeng et al. (2023) investigated the potential of using parameters derived from streetview photographs to explain road surface temperature (RST) variations in an urban central district in a hot and humid climate. The parameters included view factors (VFs), sunlit/shaded status (the ratio of the sunlit to shaded values in a picture, ranging from zero to one), and sunlit hours. VFs measured the amount of building (BVF), sky (SVF), or green (GVF) in a photograph. Resulting correlations between RST variations and SVF and GVF reached 0.92 and -0.93, respectively, at around 11:25 AM. BVF showed a weak correlation with RST and had both positive and negative influences depending on the time of the day. Streetview correlations of GVF, SVF and sunlit ratio were stronger than the traditional parameters of building coverage ratio, floor area ratio, and mean height (of buildings, etc.). Multiple linear regressions showed that VFs derived from Street View photographs explained from 59% to 82% of the spatial variation in daily maximum RST. There have been many studies and scientific publications on the impact of shading on pavement temperature. Much of the information on the effect of shading on road conditions, however, is not backed by scientific study. For example, a website on roadway icing and weather hosted by the University of Washington (Mass and Steed, 2024) states, in part, that:

> *"Shading of road surfaces by trees, hills, and other objects greatly influence the potential for, and longevity of, roadway ice. At night, overhanging trees or other road covers can lessen the potential for frost by blocking the loss of infrared heat to space. This is why cars rarely frost up under carports. On the other hand, if an area does frost up or get covered with ice, shading due to trees or hillsides can delay melting well into the late morning or allow ice to remain all day. A number of fatal accidents have occurred on State roadways when drivers hit unexpected areas of ice protected by*

> *shade. Areas shaded by hillsides can start to cool rapidly hours before sunset, resulting in icing before dark. Such icing was associated with a recent fatal accident on Interstate 90 near the town of Thorp."*

Personal communication with Dr. Mass, however, revealed that references corresponding to this statement are not available. Rather, the above quoted text was based on their observations.

In the first known scientific study of the impact of tree shading on pavement, McPherson and Muchnick (2005) paired 48 street sections in Modesto, CA into 24 high- and low- shade pairs. Field data was used to determine the value of the Pavement Condition Index (PCI) and a Tree Shade Index (TSI) for each section. The PCI used a six-step protocol to incorporate pavement distress type, amounts of distress, and severity of distress. The greater the PCI, the better the condition of the pavement. Similarly, the greater the TSI, the greater the amount of shade that trees provided to the section. Statistical analysis revealed that a larger PCI value was associated with a greater TSI value, indicating that tree shade was responsible for less rutting, shoving, and fatigue cracking, among other distress, in the pavement sections.

Further analysis revealed that an unshaded pavement section required six slurry seal applications over 30 years whereas an identical section planted with 12 crape myrtles (14 ft crown diameter) required five, and a section shaded with six Chinese hackberry trees (45 ft crown diameter) required only 2.5. It has been questioned, however, how relevant these results from Modesto, CA are to locations with different climates.

Matlack et al. (2022) documented pavement heating over a daily cycle by measuring pavement temperature under and near 13 street-side trees in a residential neighborhood in the Ohio Valley. The pavement temperature differences were compared with tree canopy coverage and other aspects including tree size, species, aspect, and canopy density. In this study, aspect was defined as the compass direction from the trunk of the tree to the pavement section under analysis.

Unshaded pavement temperatures increased by 29–34 °C but tree-shaded pavement temperatures increased by only 8–15 °C. Tree shaded pavement had intermittent heating (when the sun rose and set) that was dependent on tree crown geometry, aspect, and position of nearby trees. Overall, pavement temperatures did not vary significantly with tree size or canopy porosity but rather were dependent on tree location and crown geometry. Overall, results suggest that lower tensile stresses develop in tree-shaded pavements and that shading may reduce corresponding pavement damage. While the previous two studies were conducted under summer conditions, Druschel (2020) investigated the impact of shading on winter maintenance of roadways in Minnesota. One objective of this study was to investigate MnDOT's winter treatment of difficult pavement conditions and determine the benefits and costs (including environmental impacts) of different treatment methods. Ten low-volume traffic road sections that often-developed difficult icy conditions were monitored over the winter of 2019-2020 as were nine control sites that had similar traffic volumes and roadway designs but were not likely to develop difficult conditions.

At each site, instruments collected roadway level air temperature, dew point, and light intensity and cameras took time-lapsed photographs to document road conditions (Druschel, 2020). The amount of deicing materials dispensed, the amount and type of precipitation, and the wind speed and direction were also recorded at each site. Over the study period, trucks applied deicing materials 909 times at the 19 study sites. There were only 255 times (28%) in which a truck applied more than the typical amount of deicing material to treat a difficult road condition. Drifting snow, blow ice formation (when snow blows onto the road and melts), and black ice received normal applications and amounts of deicing material. The effectiveness of these normal applications was enhanced by vehicle traffic due to the tires working the deicing materials into the ice.

Areas that needed extra deicing salts included bridge decks and shaded roadway segments (such as beneath overpasses, Druschel, 2020). At one location under a bridge, the shaded road segment was 28 °F colder than the unshaded portion four feet away. Sites with extreme temperature differences such as this were deemed to need occasional extra deicing treatment. It was concluded that extra deicing treatment was needed far less frequently than expected and that minimal extra deicing material was applied when needed. The most important variable with respect to the amount of salt applied was operator judgement. Recommendations included enhanced training for operators and communication between operators to share their experiences.

With respect to shading, Druschel (2020) evaluated two sites for the effect of shading on the amount of deicer applied. The sites were 1) US 169 in Garden City (AADT = 2800) that runs north-south and has a high bank and shading trees on the west side, and 2) MN 30 in New Richland (AADT = 1300) that runs east-west and has shading trees on the south side. Salt application was vastly different at these two sites. Garden City had 24 deicer applications the entire winter (8,350 lbs./lane mile) with 9 of the applications (38%) using extra material. The 8,350 lbs./lane mile was the lowest recorded for all the 19 sites. New Richland had 68 applications (22,550 lbs./lane mile) with 42 (62%) receiving extra deicing material. Over half of the total deicer applied at this site was due to one storm sequence in late November. The high percentage of extra treatment applications at New Richland occurred uniformly throughout the winter whereas at Garden City it occurred primarily in February. It was theorized that the shading along the south side of the road in New Richland necessitated extra treatment for the entire winter as this was the only location that had a consistent percentage of extra application. The study concluded that, because the total amount of deicer applied at New Richland was approximately the same as the amounts at a nearby drifting study location (except for one storm in late November) and that only the percent of the times that extra application was used was different, the non-shaded road segments at New Richland were salted less than the nearby drifting sites. In other words, based on a comparison of the frequency of higher application rates, it was concluded that the non-shaded road segments were salted less than nearby sites where segments were prone to drifting.

Naik et al. (2017) investigated shaded and unshaded pavement conditions on a rural highway in Ohio to observe the effects of tree canopies on the pavement. The study also included a literature review and interviews with transportation professionals and researchers. Based on surveys and communication with transportation professionals, most respondents believed that trees cause pavement distress. It is believed that road moisture is not necessarily from rain and snow but also from condensation dripping from trees year-round. Transportation personnel believed shaded road sections are the first to freeze and the last to thaw, creating increased hazards for motorists. Trees were also associated with falling debris, which can block drainage systems, cause road closures, injuries, and fatal accidents, and trees can make it difficult to see road markings in foggy conditions. They believe that shaded pavement experiences accelerated degradation due to moisture remaining on the pavement surface for longer durations and that shaded roads require more maintenance, including needing more deicing materials in the winter. In general, they believe management of roadside trees includes trimming and/or removal.

Overall findings by Naik et al. (2017) included the following:

- Tree canopy management guidance is lacking.
- There is little or no research providing any empirical or scientific evidence into the effects of tree canopy overtop or alongside the roadway.
- Trees are valued in Ohio communities because they contribute to property values, climate moderation, retail business activity, and they are aesthetically pleasing. As such, they have substantial support in public meetings.
- Based on accident data, transportation engineers and maintenance crews consider roadside trees within the 60-foot Right-of-Way a threat to driver safety.
- Pavement condition data in a select site and anecdotal evidence from DOT personnel, suggest that roadside trees may contribute to pavement degradation.
- Based on published research that present methods that indirectly estimate the impact of roadside trees on pavement degradation and road conditions, trees potentially protect pavement by blocking environmental/climate impacts. As previously discussed, trees can extend pavement life by moderating temperature fluctuations, diverting moisture, and blocking sunlight.
- Trees may also promote pavement degradation by reducing or delaying evaporation and reducing temperature cycles.
- Although trees are dangerous in crashes, there is evidence that suggests trees in urban/suburban areas have a calming effect.
- There is a clear contradiction between the experiences of transportation engineers and conclusions of published research. Published research, however, has not fully addressed or explained the relationship between trees and pavement degradation, road conditions, and road safety.

Baek and Choi (2022) investigated and quantitatively compared shading matrices from three-dimensional models and fisheye photographs for efficient operation of solar powered vehicles. Skymaps were developed that incorporated the geometry of nearby obstacles (either buildings or trees). Sun-path diagrams, which tracked the position of the sun by time of day and season, were overlaid on the skymaps. Month-by-hour shading matrices were then calculated. Mean squared error (MSE) was used to determine the quantitative differences between the sun-path diagrams and the skymaps. Both shading matrices (3D models and fisheye images) accurately represented the shading caused by buildings. For shading caused by trees, however, fisheye images were more accurate. Although this study was geared towards optimizing solar powered vehicle use in urban areas, results may be applicable to roadside vegetation management.

Li and Ratti (2018) investigated the spatial distribution of shade provided by street trees in Boston, Massachusetts. Street shade was quantified by the sky view factor (SVF), which was determined using Google Street View panoramic images. The overall SVF was assumed to be based on effects from both trees and buildings, and only trees and buildings. SVFs were also determined by incorporating only buildings and the difference between the two SVFs was assumed to be a measure of the shade provided by trees. Results indicated that trees decreased the SVF by 24.6% in Boston. Li et al. (2018) performed a similar analysis on downtown Boston. It was determined that, in this location, trees decreased SVF by 18.5%.

Postgård and Lindqvist (2001) analyzed road thermal maps and data from road weather field stations in Sweden. The main objectives were to investigate the time duration needed, after the arrival of a warm front, for air and road surface temperatures to adjust from clear to overcast conditions and if there are any differences in those times for air and road surfaces. It was determined that existing weather conditions prior to the front arrival, temperature differences at the time of arrival, time of arrival, wind speed, and precipitation all impact the time of adjustment. Unsurprisingly, air temperature reacts more quickly to a front arrival than the road surface temperature. After sundown road surface temperatures may be affected by previous shading for up to four hours after the arrival of a front and, overall, areas that are shaded by topography or trees have the coldest temperatures while open areas have the warmest. Conclusions included temperature changes from clear to overcast conditions are complex and that temperature adjustments depend on the preceding weather, timing of front arrival, precipitation, and wind speed.

1.5 Management of Roadside Vegetation

Literature related to and addressing the management of roadside vegetation is summarized in this section.

The Federal Highway Administration published a report to guide maintenance of roadside vegetation (Eck and McGee, 2008). This document suggests that, in preparation for winter, dead limbs and overhanging branches be removed in the fall so that snow and ice accumulation in the coming months does not cause them to fall on the roadway. Although no references are cited, the guide also states that trees casting shadows on the road can cause the formation of isolated ice patches, which, during freeze-thaw cycling, can lead to crashes. Other guidance is as follows:

- If time and money for brushing are limited, work should be completed on the west and south side of roads first.
- Cutting taller vegetation can increase the amount of sunlight that reaches the road surface, which helps improve ice control.
- In areas that receive abundant snowfall, it is recommended to provide enough clear space (i.e., no vegetation) for snow storage.

Johnson (2008) authored a roadside vegetation management handbook published by Minnesota Department of Transportation. The book presents eight best management practices that were identified via surveys, discussion with transportation experts, research, and a review of the literature. Those practices are:

1) Develop an integrated roadside vegetation management plan,
2) Develop a public relations plan,
3) Develop a mowing policy and improved procedures,
4) Establish sustainable vegetation,

5) Control prohibited and restricted noxious weeds,
6) Manage living snow fences,
7) Use integrated construction and maintenance practices, and
8) Manage roadside vegetation for wildlife and vehicle safety.

Living snow fences are defined as intentionally selected and planted vegetation that manages drifting snow and where it accumulates. The handbook discusses the design and maintenance of four types of living snow fences, Twin Shrub Row, Community Shelterbelt, Deciduous Trees Windbreak, and Standing Corn Rows and states that maintenance of snow fences impacts their effectiveness. Wildlife and vehicle safety focuses solely on minimizing deer and vehicle collisions.

Lechtenberg et al. (2015) calculated incremental benefit to cost (B/C) ratios of three safety treatment options for trees on low volume roads (< 500 vehicles per day) with speed limits of at least 55 mph. Trees were grouped by type, diameter, and distance from the road. Altogether, there were 120 scenarios investigated. The three options were 1) do nothing, 2) tree removal, and 3) guardrail installation. In all cases, B/C ratios for tree removal were equal to or greater than one and guardrail installation was not more cost effective than tree removal or the do-nothing option. Thus, based on these results, there is little justification for guardrail installation or in keeping trees. Overall, tree removal was considered the safest option and the primary alternative when trees are far from other fixed objects on the roadside.

Some literature reviewed the effect of roadside vegetation management on animals. For example, Galantinho et al. (2022) investigated the impact on wood mice due to roadside vegetation management for roads with traffic counts less than 20,000 vehicles per day. The study found that the benefit of road verges (i.e., a strip of land between the road and a line of vegetation running parallel to the road) is reduced when landowners create firebreaks in the verges. To reduce this impact, and the risk of road kills, the authors suggested better communication and agreement between landowners and road managers on when and where, or if, firebreaks should occur. It was also concluded that maintaining strips of undisturbed vegetation on road verges can optimize their positive impact as animal corridors and can help to offset the negative impacts roads often have on biodiversity.

Jakobsson et al. (2018) reviewed 54 publications on the impact of roadside vegetation removal on plant and invertebrate diversity. Twenty-four of the studies were performed in North America and 29 in Europe; 48 investigated the impact of mowing. Overall, mowing effects were dependent on the interaction between hay removal and the frequency of mowing. There was more species richness in roadsides mowed one or two times per year with hay removal compared to roadsides that were not mowed. Mowing twice per year also had a more positive impact than annual mowing. There were, however, no statistically significant differences between mowing/not mowing, frequency of mowing, or the timing of mowing or hay removal. Mowing also negatively impacted the abundance of woody plants, and a higher mowing frequency had a negative impact on the abundance of grasses. Regarding the impact on invertebrates, there was not enough data to quantify the impact of the variables that were investigated.

1.6 Summary

While there is much literature on modeling pavement temperatures and many models incorporate the impact of pavement shading by buildings, topography, and trees, there is very little scientific literature on the direct impact of tree and vegetation shading on winter pavement temperatures and ice formation on pavement surfaces. Most information on this topic is anecdotal and/or merely based on the opinions of transportation personnel. While there is significant scientific literature on the impact of vegetation management on plants and animals there is little to none on ice formation on pavements. This project seeks to provide information to help fill this knowledge gap.

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Appendix B. Online Survey and Results

Online Survey and Results

An online survey of winter maintenance professionals within the network of Clear Roads member states was conducted to evaluate existing vegetation management practices. The survey was used to identify locations of vegetation management as well as the motivations, especially if enhancing winter performance of the road surface was an intended outcome. The survey generated 65 responses from 8 different state agencies responsible for winter highway maintenance, as well as 2 counties in Minnesota. The survey questions, maps of participants, and a summary of results are provided below.

Survey Questions

Page 1. About

This survey is part of Clear Roads project 23-04. If you have questions about the project or Clear Roads, contact Greg Waidley at greg.waidley@ctcandassociates.com

Our project focuses on evaluating the potential benefits of vegetation removal for improved winter performance of roadways.

The survey results will be important for helping us build a list of sites where performance benefits may be evaluated. Any sites can be helpful, but those where deicer use and pavement temperatures can be evaluated using RWIS or AVL data (or some other records) will be particularly useful.

To participate, please complete these 3 survey pages to the best of your ability. We may follow up with you to learn more about the sites you list. If at any point you have questions about the survey, email douglas.klimbal@bolton-menk.com or call 612-772-2429. Thanks for your help!

Add your contact information below.

1. Name:
2. Agency:
3. Role:
4. Phone Number:
5. Email:

Page 2. Add Vegetation Removal Sites

Use this next group of questions to add as many sites as you would like. If at any point you have questions about the survey, email douglas.klimbal@bolton-menk.com or call 612-772-2429. This survey is part of Clear Roads project 23-04. If you have quesitons about the project or Clear Roads, contact Greg Waidley at greg.waidley@ctcandassociates.com

It is not required that winter maintenance benefits are the intended purpose of vegetation removal. Any sites where vegetation removal has taken place are helpful for our study.The next page presents an opportunity to add problematic shade-prone areas you're aware of.

Complete the "Where", "When", and "Why" sections for each site you add.

Where?

1. What road is the vegetation removal site on?
   - Use the map to locate the site, or describe it in words in the text field below. You don't need to complete both.
   - Alternatively, write a description (use road names, exits, mile markers, etc.)
2. Select the placement(s) of vegetation removal:
   - Eastbound Right
   - Eastbound Left
   - Southbound Right
   - Southbound Left
   - Westbound Right
   - Westbound Left
   - Northbound Right
   - Northbound Left
   - Alternatively, if the placement options above don't make sense, please describe here:
3. What marks one end of the removal site? (ex. Mile marker, exit, etc.)
4. What marks the other end of the removal site? (ex. Mile marker, exit, etc.)
5. Approximately how many road miles were effected by this project?
6. What is the road surface material?
   - Asphault
   - Mixed
   - Concrete
   - Other
7. What is the predominant vegetation nearby?
   - Deciduous
   - Mixed
   - Non-Deciduous

When?

8. Date of Vegetation Removal (Past or Planned)

Why?

9. Was improved winter performance an intended outcome of vegetation removal?

IF YOU HAVE MORE SITES TO ADD, CLICK THE “+” ICON ABOVE. If you're all set adding sites, advance to the next page.

Page 3. Add Shade-Prone road segments

Use this next group of questions to add as many shade-prone segments as you would like. If at any point you have questions about the survey, email douglas.klimbal@bolton-menk.com or call 612-772-2429. This survey is part of Clear Roads project 23-04. If you have quesitons about the project or Clear Roads, contact Greg Waidley at greg.waidley@ctcandassociates.com

Complete the "Where", "When", and "Why" sections for each shade-prone segment you add.

Where?

10. What road is the shade-prone segment on?
    - Use the map to locate the segment, or describe it in words in the text field below. You don't need to complete both.
    - Alternatively, write a description (use road names, exits, mile markers, etc.)
11. Select the placement of problematic vegetation:
    - Eastbound Right
    - Eastbound Left
    - Southbound Right
    - Southbound Left
    - Westbound Right
    - Westbound Left
    - Northbound Right
    - Northbound Left
    - Alternatively, if the placement options above don't make sense, please describe here:
12. What marks one end of the removal shade-prone segment? (ex. Mile marker, exit, etc.)
13. What marks the other end of the removal shade-prone segment? (ex. Mile marker, exit, etc.)
14. Approximately how many road miles were effected by this project?
15. What is the road surface material?
    - Asphault
    - Mixed
    - Concrete
    - Other
16. What is the predominant vegetation nearby?
    - Deciduous
    - Mixed
    - Non-Deciduous
17. What is a typical change in application rate on this road segment?

IF YOU HAVE MORE SHADE-PRONE SEGMENTS TO ADD, CLICK THE "+" ICON ABOVE. If you're all set adding shade-prone segments, advance to the next and final page.

Page 4. Follow Up

We may select sites from this survey to evaluate winter performance. This would be more impactful if you can provide some of the following supporting information. If at any point you have questions about the survey, email douglas.klimbal@bolton-menk.com or call 612-772-2429. This survey is part of Clear Roads project 23-04. If you have quesitons about the project or Clear Roads, contact Greg Waidley at greg.waidley@ctcandassociates.com

Can you provide more data if requested?
Unsure
Yes
No

Road Surface Temp/Condition:
Unsure
Yes
No

If your responses feel incomplete, you can click the "Back" button and review them. If you're done, click "Submit".

Survey Responses

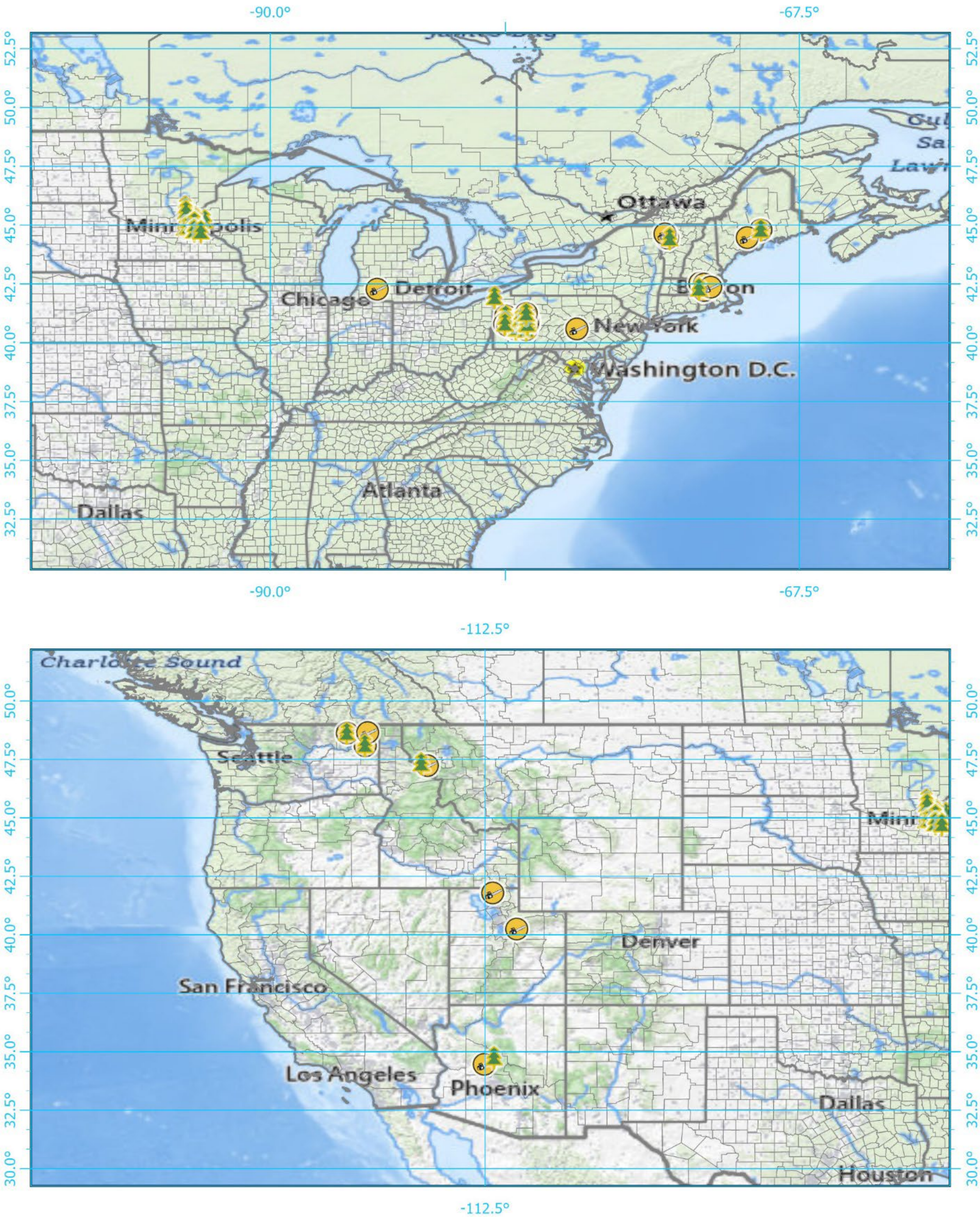
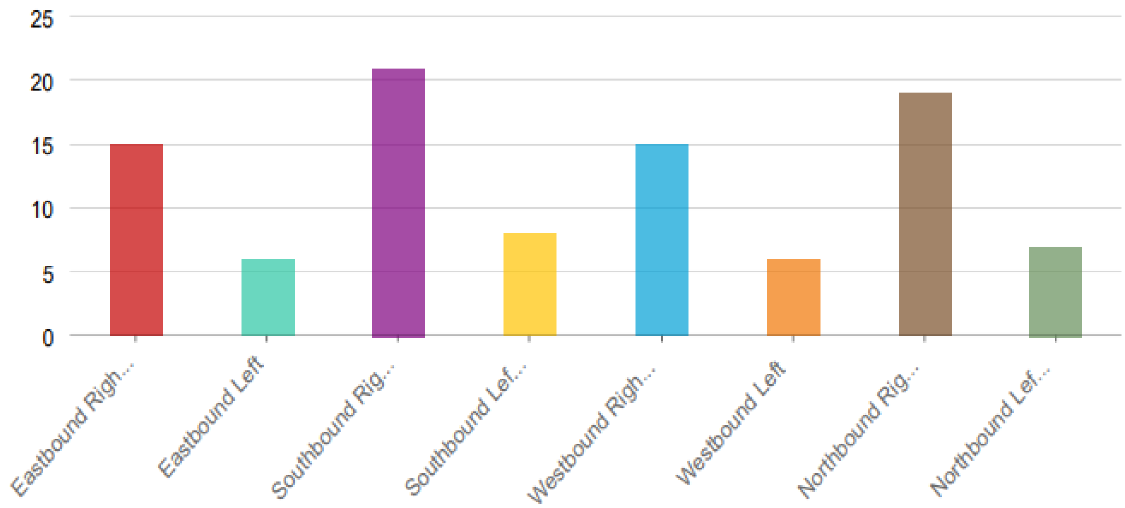


Figure 1: Maps of the Eastern (upper) and Western (lower) United States with locations of study participants.

Figure 2: Map of the United States with the locations of study participants.

CR23-04 Survey Results

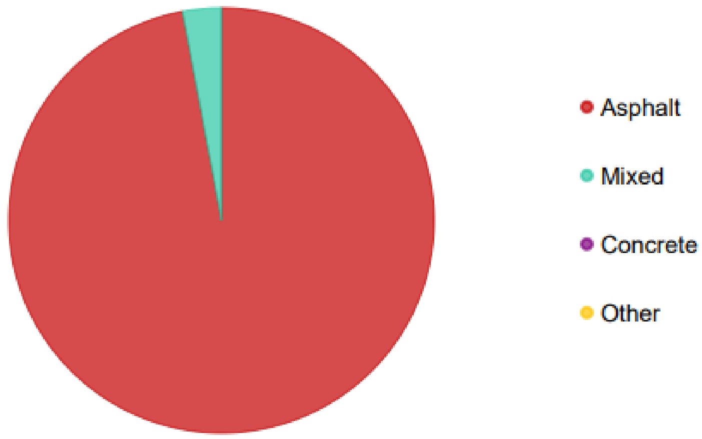
Page 2: Select the placement(s) of vegetation removal:



Answers	Count	Percentage
Eastbound Right	15	42.86%
Eastbound Left	6	17.14%
Southbound Right	21	60%
Southbound Left	8	22.86%
Westbound Right	15	42.86%
Westbound Left	6	17.14%
Northbound Right	19	54.29%
Northbound Left	7	20%

Answered: 34 Skipped: 1

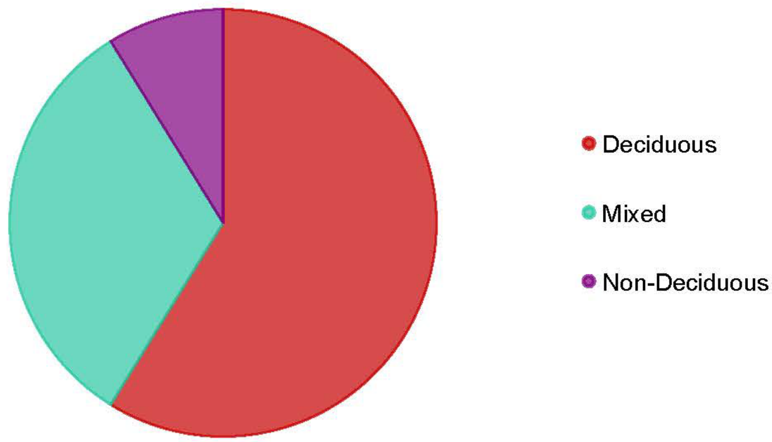
Page 2. What is the road surface material?



Answers	Count	Percentage
Asphalt	33	94.29%
Mixed	1	2.86%
Concrete	0	0%
Other	0	0%

Answered: 34 Skipped: 1

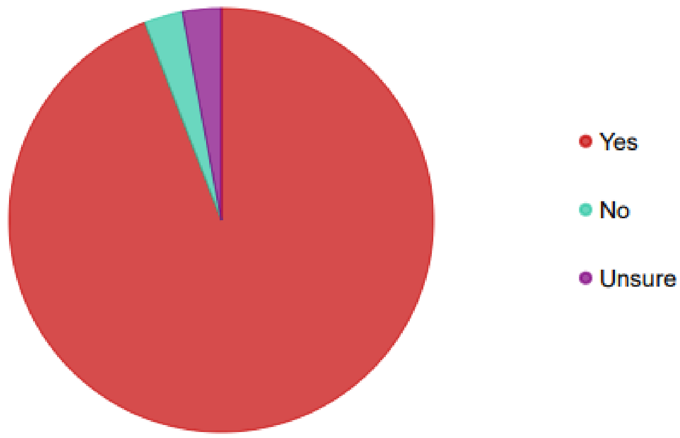
Page 2. What is the predominant vegetation nearby?



Answers	Count	Percentage
Deciduous	20	57.14%
Mixed	11	31.43%
Non-Deciduous	3	8.57%

Answered: 34 Skipped: 1

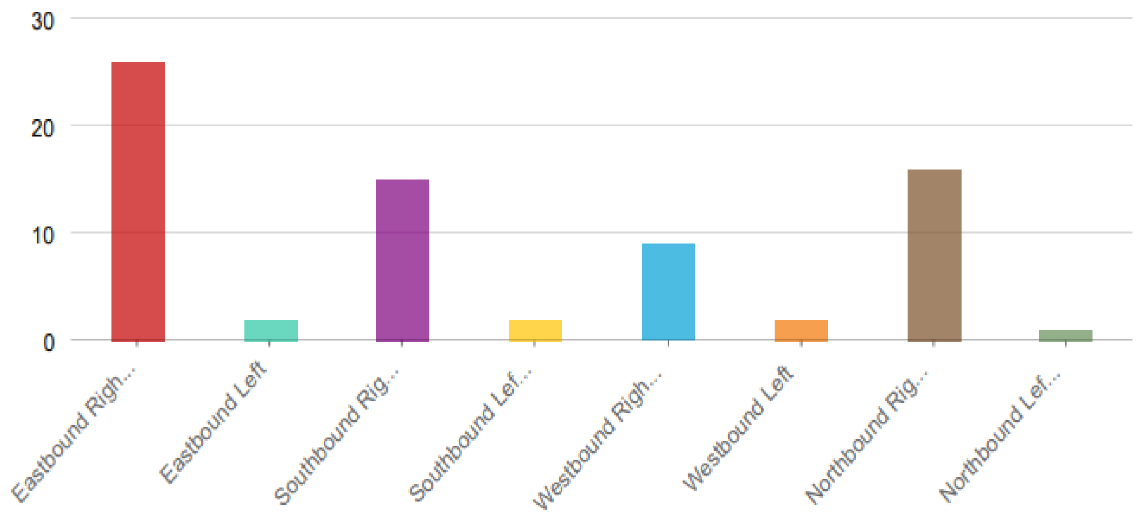
Page 2. Was improved winter performance an intended outcome of vegetation removal?



Answers	Count	Percentage
Yes	32	91.43%
No	1	2.86%
Unsure	1	2.86%

Answered: 34 Skipped: 1

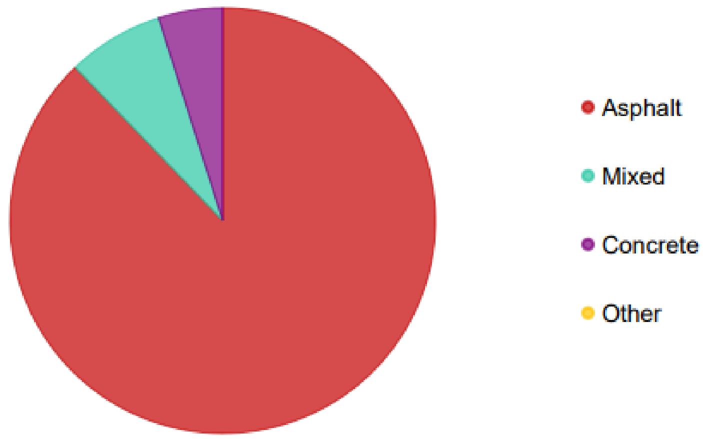
Page 3. Select the placement of probleatic vegtation.



Answers	Count	Percentage
Eastbound Right	26	57.78%
Eastbound Left	2	4.44%
Southbound Right	15	33.33%
Southbound Left	2	4.44%
Westbound Right	9	20%
Westbound Left	2	4.44%
Northbound Right	16	35.56%
Northbound Left	1	2.22%

Answered: 42 Skipped: 3

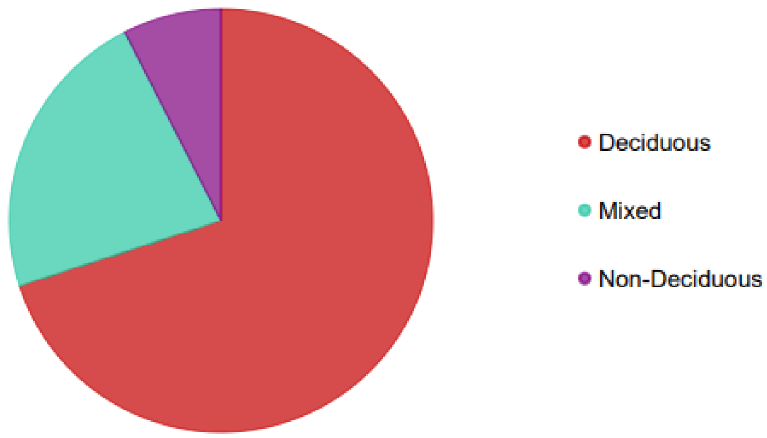
Page 3. What is the road surface material?



Answers	Count	Percentage
Asphalt	36	80%
Mixed	3	6.67%
Concrete	2	4.44%
Other	0	0%

Answered: 41 Skipped: 4

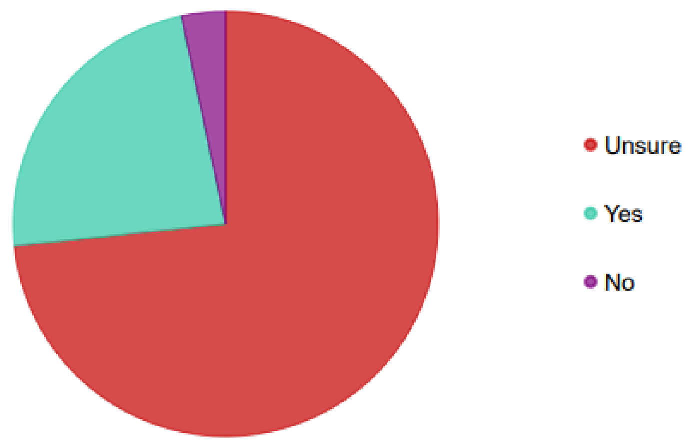
Page 3. What is the predominant vegetatation nearby?



Answers	Count	Percentage
Deciduous	28	62.22%
Mixed	9	20%
Non-Deciduous	3	6.67%

Answered: 40 Skipped: 5

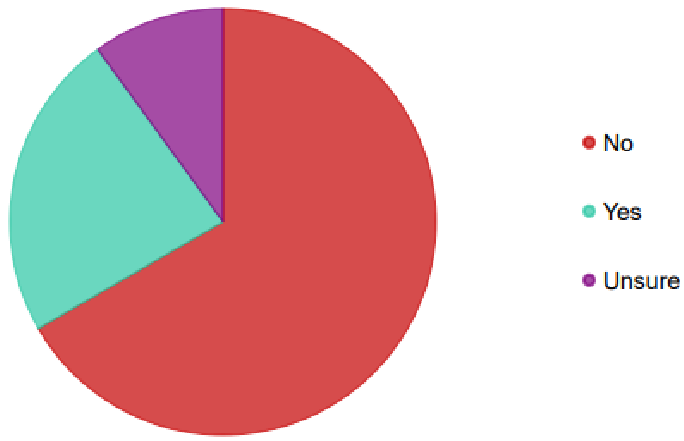
Page 4. Can you provide more data if requested on: Material use?



Answers	Count	Percentage
Unsure	22	73.33%
Yes	7	23.33%
No	1	3.33%

Answered: 30 Skipped: 0

Page 4. Can you provide more data if requested on: Temp/condition?



Answers	Count	Percentage
No	20	66.67%
Yes	7	23.33%
Unsure	3	10%

Answered: 30 Skipped: 0

Appendix C. Data Analysis

Data Analysis for "Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation"

Task 3 Report

November 2025

Douglas Klimbal; Bolton & Menk, Inc. – Executive Summary, Chapter 1, Chapter 3

William R. Herb, Andrew J. Erickson, and Levi J. Burrows; Saint Anthoy Falls Laboratory, University of Minnesota – Chapter 2

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Executive Summary

Winter road safety can be enhanced wherever leveraging natural solar heating through strategic roadside vegetation management. This Clear Roads research project evaluated how removing or trimming trees near roadways affects winter pavement conditions and maintenance needs. This report presents data analysis and key findings: differences in pavement temperature between shaded and open areas, the impact on snow/ice clearance times, and implications for salt application.

We conducted field monitoring at shaded and unshaded road segments in Minnesota and data analysis to document the process and findings. A key result of field monitoring is that pavement surfaces clear snow and ice significantly faster without shade. In our field study, an unshaded road segment warmed more under sunlight and dried ~5 hours faster after snow events compared to an adjacent shaded segment.

We also received survey data, primarily from state DOT staff across the United States, to better understand the distribution and characteristics of sites across the nation which are shade-prone or where vegetation removal has taken place to mitigate issues with shade. Respondents described wide-ranging geography, including Washington, Montana, Arizona, Minnesota, Michigan, Pennsylvania, Vermont, Mayland, and Maine. Analyses in this report compare the climate of these locations to that of our field site.

Findings underscore that sunlight is a valuable asset in winter maintenance. Shaded pavements in our field sites remained colder and icy longer, whereas sun-exposed pavement reached higher temperatures and achieved bare pavement conditions sooner. This effect was most pronounced after snowfalls – our camera analysis showed shaded pavement staying wet or icy ~26% longer than sunlit pavement. In practical terms, road sections beneath heavy tree cover may require more deicer and take hours longer to return to safe conditions. By contrast, increased solar radiation on clear roads can reduce the time and materials needed to achieve bare pavement.

Introduction

In cold regions of the United States, road maintenance means removing snow and ice from roadways to allow for safe travel. Professionals in the field of winter maintenance suggest that ice is more difficult to remove from pavement surfaces in heavily shaded or forested environments, compared to sunlit pavements. This is due in part to tall and close stands of vegetation casting shade onto the roadways. Shade reduces the exposure of pavements to sunlight, causing lower pavement temperatures. The presence of thick canopy close to the road may also limit the mixing of air, leading to higher relative humidity, and interception of snowfall can lead to snow continuing to fall onto the roadway even on days without snowfall. All of which make the maintenance of highways in forested regions more intensive regarding labor, equipment, and materials.

The sustainability of winter maintenance operations in forest regions may be dramatically improved by vegetation management initiatives that reduce these complications, but supporting those initiatives means having data to inform proper management practice development. A thorough understanding of the potential benefits of thinning forests or expanding clear zones is required, since the perceived drawbacks (loss of the scenic of forested roads, cost of management, impacts on property, etc.) are so readily apparent. This study is designed to quantify the impacts of shade on pavement temperatures.

In this report on data collection and analysis, we will present a discussion of how the study was conducted, as well as how findings may translate to other portions of the United States.

1.1 Identify, Monitor, and Evaluate Sites

This was the core research task. We first conducted a survey of Clear Roads member agencies and other contacts to identify candidate locations where significant roadside vegetation removal had occurred or was planned during the study period. The survey yielded few active vegetation removal project sites within our timeframe, so the team pivoted to selecting a controlled field site. We chose a two-lane county road that offered adjacent road segments with and without tree cover, allowing a direct side-by-side comparison of shaded and unshaded. We then deployed field instrumentation at that site to continuously monitor conditions over the winter. Data collected included pavement surface temperatures, weather variables, and time-lapse photos of the roadway. This task also involved acquiring and analyzing any existing data ("before" conditions) and any available maintenance logs (e.g., salt usage) for those sites. Details on the selected site and instrumentation are in Section 2.2. The guiding question for this task was: "What are the before-and-after differences in road surface temperature, ice coverage, and deicer use at locations with vegetation management?" (Note: In absence of a live before/after tree removal event, our analysis compared simultaneous shaded vs. unshaded conditions as a proxy for "with vs. without vegetation.")

We obtained and deployed the necessary instruments in Fall 2024 and removed them in Spring 2025 after data collection, as detailed below.

1.1.1 Site Selection and Description

After reviewing candidate sites, we selected 229th Avenue NW (County Road 13) in Anoka County, Minnesota as the primary field study location. This site was chosen for its convenient natural experiment setup: along this rural road, one stretch is flanked by dense trees (creating persistent shade in winter), while a nearby stretch has an open south side with no significant trees (full sun exposure on the pavement). The two stretches have similar road geometry, pavement material, and traffic, making them ideal for comparison. Importantly, no new tree removal was performed by the project – instead, we took advantage of existing conditions to simulate "with vs. without trees" influences.

1.1.2 Shaded vs. Unshaded Segments

The shaded segment is a portion of CR 13 passing through a wooded area (mixed deciduous trees) that towers close to the roadway on the south side. In winter, even without leaves, the tree trunks and branches cast substantial shade, especially during morning and afternoon low-sun-angle periods. The unshaded segment is a more open area of the same road where roadside vegetation is set back far enough that the pavement receives direct sunlight most of the day (particularly on the south-facing lane). Figure 1 illustrates the site layout: Site CR02 (shaded) near Unity St. intersection, and Site CR01 (unshaded) near Ibis St. The distance between CR01 and CR02 is only about 0.5 miles, ensuring that weather conditions (snowfall, air temperature, etc.) are virtually identical at both.

1.1.3 Geography and Orientation

The road runs east-west in this area, meaning the south side tree line at CR02 directly shades the south lane (eastbound direction) during the low winter sun from the south. At CR01, the south side is open (fields), so the south lane gets ample sun. This orientation was advantageous to maximize detectable solar effects – south-side shade in winter has the largest impact on solar energy reaching the pavement (in the northern hemisphere). The pavement is asphalt on both segments, and the terrain is flat, eliminating slope or aspect differences as factors.

1.2 Data Collection

We note that no controlled vegetation removal was done (we did not cut trees as part of the project, due to permitting and timing constraints). The shaded vs. open comparison effectively simulates the difference of vegetation removal. To strengthen confidence in our comparisons, we ensured both sites were as alike as possible aside from vegetation cover. Also, both sites were on the same segment of a single county highway route, so differences in winter maintenance were minimized.

1.2.1 Field Site Monitoring Equipment

We deployed a suite of instruments at the two monitoring sites in late November 2024, before the first significant snowfall, and collected data until late March 2025 (covering the core winter season):

- Infrared Pavement Thermometers: Each site (CR01 and CR02) was equipped with an Apogee SI-421 infrared radiometer pointed at the road surface. These sensors measured the pavement surface temperature continuously (at 5-minute intervals) without physical contact. They were mounted on poles ~3 feet above the road edge, angled to capture the pavement in the center of the lane. The measurement spot covered roughly a 1-ft diameter circle on the asphalt. Accuracy is within ±0.5 °C, and they provide a direct read of surface skin temperature, which is critical for detecting freezing vs melting conditions.
- All-in-One Weather Stations: At both CR01 and CR02, we installed METER ATMOS 41 compact weather stations. These recorded air temperature, relative humidity, wind speed and direction, atmospheric pressure, solar radiation, and precipitation. Note that the rain gauge on these units is unheated, so it recorded rainfall but not snowfall amounts. However, solar radiation (sunlight intensity in W/m^2) was a key parameter – it allowed us to confirm how much sun each site was receiving and correlate that with pavement temperatures. Data were logged every 5 minutes in sync with the IR thermometers using cloud-connected ZL6 data loggers, which transmitted data in near real-time for remote monitoring.
- Supplemental Winter Sensor: At a third location (CR03, very close to CR02 in the shade), we placed a Campbell Scientific "WinterSense" road sensor (infrared) with its own logger. This unit served as a backup and provided additional pavement temperature points at 15-minute intervals. It helped verify that CR02 readings were representative of shaded conditions even if one sensor had gaps.
- Trail Cameras: To visually observe snow/ice coverage, each of the two main sites had a time-lapse camera mounted roadside, aimed at the pavement. The cameras (Wildlife trail-cams) captured images of the lane every 1 hour during daytime. These images allowed us to document when snow covered the road and when it had melted or been plowed away, and specifically to measure "time to bare pavement" after each weather event. Due to some technical issues (battery and cold affecting electronics), the cameras did miss some periods (no images from Dec 11, 2024 – Jan 30, 2025 at CR01, and Jan 9 – Jan 30 at CR02). Even so, we obtained dozens of before/after photo sets for snowfall events in February and March 2025, which proved very useful for analyzing differences in snow/ice persistence.

All instruments were powered by battery and some with solar chargers, and data was stored on-site with periodic cloud upload. We checked calibrations during installation. The temperature sensors were cross-checked on a clear day – the sunny site showed higher pavement readings, as expected, but when both were shaded at night their readings converged (within ~0.2°C), giving confidence in their relative accuracy.

1.2.2 External Data Sources

In addition to our site-specific instruments, we gathered data from nearby sources to enrich the analysis:

- A Road Weather Information System (RWIS) station operated by MnDOT was located ~5 miles away. We pulled its records for air temp, etc., as a comparison.

- Ten other sites (RWIS and RAWS stations) from the state of Minnesota were included in pavement temperature analysis.
- NOAA Climate data for the region provided context on whether the winter was typical.
- Maintenance Data: Crucially, Anoka County provided GPS/AVL records from their plow trucks for CR 13 during our study period. These records included the truck's pavement temperature sensor reading and the rate of salt being spread at each location and time. By mapping these data, we could check if the shaded area received more salt or had lower truck-measured temps than the open area. (The truck we used primarily drove a night route, meaning most pavement temperature points were at night or early morning when solar influence is minimal, but it still offered insight – see Section 3.3.)

1.3 Data Analysis Techniques

The analysis focused on quantifying differences attributable to shade vs sun. Key analysis steps included:

- Descriptive Statistics: We computed daily and monthly summary statistics of pavement temperatures at each site (mean, minimum, maximum) and the differences between sites. This established how much colder the shaded pavement was on average. We also tabulated frequency of sub-freezing pavement conditions at each site.
- Regression Analysis: To isolate the effect of solar radiation on pavement temperature, we performed regression modeling. We related pavement surface temp to the concurrent air temperature and solar radiation, for each site separately and combined. We also looked at R^2 values to see how well we could predict pavement temperature – this helps understand variance due to sun.
- Event-Based Analysis: For each notable precipitation event (snow or rain), we examined the time-lapse photos and sensor data to determine the time to achieve bare pavement after precipitation stopped. We then compared these times for the shaded vs. unshaded sites under similar weather. This directly addresses the key metric for maintenance: when maintenance practices are held constant, is road recovery noticeably quicker in unshaded areas?
- Maintenance Log Analysis: Using the truck AVL data, we identified when the plow truck passed through our sites and how much salt it dispensed. We also used this data to separate pavement temperature readings between periods when maintenance operations were active from when they were not.

Data was processed with standard tools: spreadsheets and statistical software. Quality control was performed to remove any spurious readings (e.g., a brief sensor dropout). We paid special attention to aligning the time stamps of all datasets (weather, photos, truck data) to analyze events coherently. By applying these methods, we aimed to distill clear evidence of shade's influence on winter road conditions, and to ensure the findings were statistically robust.

1.4 Considerations

The methods used in this study could be applied anywhere. The research team went to great lengths to find a study site with as few complicating factors as possible regarding environmental conditions that may make analysis or maintenance more complicated than absolutely necessary. However, a flat road with consistent canopy structure and without curves or roadcuts is not perfectly representative of many roadways where these findings may be applied. Members of the TAP have emphasized that many roadways have hills or mountains that may cast shade as well. And of course, many roads that may be affected by heavy shading in forests may have different canopy heights of makeups on either road shoulder, each of which may cast shade through the course of a day.

The methods used for data analysis in this project are robust and should provide a much greater empirical understanding of the role of sunlight in keeping roadways clear through increased pavement temperature as well as other phenomena which may be less understood. However, we caution users that the Regression Analysis methods presented in the next chapter are necessarily empirical and may not transfer to other environments. Differences in the material properties of pavement, the energy of the surrounding environment, the transmissivity of the atmosphere, and all manner of other complications mean that direct application of our findings may be a misuse of our research. Rather, we suggest that the principles introduced here add significantly to the story of how sustainable winter maintenance in forested areas extends well beyond the winter season.

Accompanying the team's Task 4 deliverable, the Vegetation Management Manual for Solar Radiation Benefits, is an excel workbook designed to estimate the amount of potential radiation reaching a road's surface in a range of environments. This calculator allows a user to identify a geocoordinate to be assessed, describe the road orientation and layout at that location, and characterize the adjacent canopy for both existing and proposed conditions. The scenario calculator accounts for the elevation of the site, sun angles from December through February, and allows users to approximate the setback and height of vegetation relative to the roadway. It also allows the user to identify the presence of structures along a linear corridor, such as road cuts or ridges, which will limit sun exposure regardless of vegetation management practices. The outcome does not directly predict pavement temperature differences or potential maintenance savings. This is because our research cannot explicitly predict how a roadway will respond to sunlight or how an individual maintenance professional will respond to complex weather and road conditions.

The Shadowcast Model is a simple workbook interface that will calculate how much solar radiation is likely to reach the road surface in existing and proposed conditions. Along with the clear findings of substantial benefits of sun exposure to road surface conditions at our study's specific monitoring locations, this tool is meant to provide a significant step forward in being able to quantitatively communicate the degree of potential benefits to stakeholders in the maintenance region.

Chapter 2: Field Site Monitoring Results and Discussion

Written by William R. Herb, Andrew J. Erickson, and Levi J. Burrows; St. Anthony Falls Laboratory at University of Minnesota

This section summarizes the data analyses performed on pavement temperature, weather data, and camera images from the Clear Roads project study sites, additional data from roadside weather stations (RWIS) and other climate stations in Minnesota, and winter maintenance truck data (road temperature, salt application rate). Analyses included monthly summaries of weather and pavement temperature parameters (emphasizing differences between shaded and unshaded roadways), regression analysis to relate pavement temperatures to air temperature and solar radiation, analyses of roadside camera images to determine the time required for roadways to dry after precipitation events, and analyses of maintenance truck data to look for relationships between road temperatures and deicer application rates.

For the purposes of this project, three roadside stations were installed on 229th Ave NW (County Road 13), in northern Anoka County, Minnesota. Two of the stations (CR01 and CR02) were equipped with Apogee SI-421 infrared radiometers, to remotely measure pavement temperature, and ATMOS 41 all-in-one weather stations, which measured air temperature, humidity, wind speed and direction, atmospheric pressure, solar radiation, and rainfall. The ATMOS 41 rain gauges were not heated, so that snowfall measurements were not possible. CR01 and CR02 used Zentra cloud-connected data loggers to record the radiometer and weather measurements at 5-minute intervals. A third station (CR03) used a Campbell Scientific Wintersense infrared radiometer coupled to an Aspen 10 cloud-connected data logger, recording the radiometer temperature data at 15-minute intervals. All three stations had trail cameras installed to photograph the roadway surfaces at 1-hour intervals during some or all of the study period. Due to camera malfunctions, images were available for only a portion of the study period, as summarized in Table 1.

CR01 was installed adjacent to an unshaded stretch of 229th Avenue, near the intersection with Ibis St. NW, while CR02 and CR03 were installed adjacent to sections of 229th Avenue with heavy tree shading (Figure 1), near the intersection with Unity St. NW. At each site, the radiometers were mounted on steel strut material at a distance and height from the roadway such that the measurement spot size of the radiometer approximately covered the south (eastbound traffic) lane of the roadway.

Table 1: Summary of instrumentation and available data for each measurement station.

Site	Radiometer	Weather Station	Install Date	Removal Date	Missing Data	Camera Image Dates
CR01	Apogee SI-421	ATMOS 41	11/22/24	4/29/25	none	12/6/24-12/11/24; 1/30/25-4/29/25
CR02	Apogee SI-421	ATMOS 41	12/6/24	4/29/25	none	12/6/24-1/9/24; 1/30/25-4/29/25
CR03	Campbell Scientific Wintersense	none	12/6/24	4/29/25	2/14/25-2/28/25; 4/10/25-4/29/25	1/30/25-4/29/25

Figure 1: Map of the locations of the three measurement stations installed adjacent to 229th Ave NW (Anoka County Rd. 13).

2.1 Summarized weather conditions during the study

Weather data were summarized for the study period for the shaded and unshaded stations (CR01 and CR02, respectively), and for several other data sources used to compare and extend the data record (Figure 2). Forest Lake 5NE is a cooperative (COOP) weather station reporting at a daily time step, MSP is the National Weather Service ASOS weather station at the Minneapolis-St. Paul airport, reporting at an hourly time step, and CAVM5 is a US Forest Service Remote Access weather Station (RAWS) located in the Carlos Avery Wildlife Management Area, reporting at an hourly time step. A reliable source of hourly precipitation data, including snowfall, for the study site was not found – daily precipitation at the Forest

Lake 5NE station was used to summarize rain and snowfall for the study period and for calculating long term averages (Table 2). Future studies would benefit from the installation of a heated rain gage at the study site to measure snow and rainfall over the winter season. The NREL (National Renewable Energy Lab) national solar radiation databased was used to obtain 30-year average (1995-2024) monthly solar radiation for the study site.

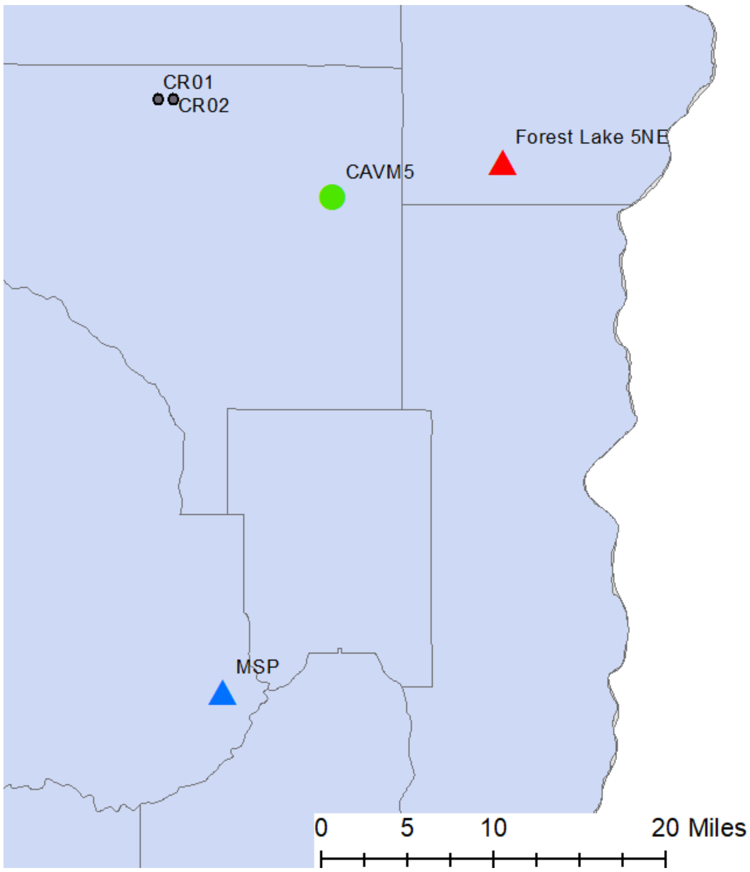

Figure 2: Locations of the weather stations used in the study with respect to the study sites (CR01 and CR02).

Table 2 and Figure 3 compare monthly total precipitation and monthly average air temperature for the study period (December 2024 – April 2025) and for a 30-year average (1995-2024). Compared to the 30-year average, the study period had low snowfall in December and January and relatively cold air temperatures in February (7 °F below normal). Table 2 also shows that the mean monthly solar radiation reported at CR01 (the unshaded study site) is up to 28% lower than solar radiation reported at CAVM5 RAWS station, which is about 11 miles from the study sites (Figure 2).

Table 2: Summary of monthly weather parameters for the study sites and other regional weather stations.

	Parameter and source	December	January	February	March	April
Local Station Data, 30-year Average (1995-2024)	All Precip (in)[1]	1.43	0.77	0.87	1.78	3.03
	Snowfall (in)[1]	12.1	9.1	8.4	9.0	3.2
	# Days with Precip[1]	8.4	7.6	5.9	7.3	9.8
	# Days with Snowfall[1]	7.9	8.5	5.8	4.6	1.7
	Air Temperature (°F)[1]	20.9	15.2	19.5	31.9	45.8
	Dew Point Temperature (°F)[2]	15.6	10.0	12.2	22.2	31.3
	Wind Speed (mph)[2]	9.0	9.0	9.4	9.9	10.8
	Mean Solar Rad. (W/m^2)[3]	54.3	71.4	115.8	161.5	199.2
	Mean Daily Max Solar (W/m^2)[3]	276.5	341.4	486.8	605.1	685.2
Local Station Data for Study Period	All Precip (in)[1]	1.1	0.3	0.89	3.11	2.53
	Snowfall (in)[1]	4.4	3.4	10.6	8.6	2.9
	# Days with Precip[1]	9.0	5.0	8	8	12
	# Days with Snowfall[1]	5	4	6	3	2
	Air Temperature (°F)[1]	21.9	12.2	12.4	35.0	44.3
	Dew Point Temperature (°F)[2]	18.0	4.6	7.1	24.3	31.7
	Wind Speed (mph)[4]	4.3	5.2	4.7	5.0	5.1
	Mean Solar Rad. (W/m^2)[4]	37.4	75.4	119.0	155.3	180.8
	Mean Daily Max Solar (W/m^2)[4]	195.1	353.5	489.4	565.2	623.3
CR01 Site Data	Air Temperature (°F)	24.3	13.4	15.0	35.9	44.8
	Dew Point Temperature (°F)	21.0	6.6	8.1	26.0	34.3
	Wind Speed (mph)	6.1	7.5	6.7	7.8	7.7
	Mean Solar Rad. (W/m^2)	26.8	53.9	92.0	132.3	167.1
	% Difference, CR01 – CAVM5	*-28.3%*	*-28.5%*	*-22.7%*	*-14.8%*	*-7.6%*
	Mean Daily Max Solar (W/m^2)	149.1	285.4	413.3	507.6	597.0
CR02 Site Data	Air Temperature (°F)	24.1	13.0	14.5	35.4	44.6
	Dew Point Temperature (°F)	21.2	6.9	8.5	26.6	35.0
	Wind Speed (mph)	5.4	8.4	7.7	7.7	7.1
	Mean Solar Rad. (W/m^2)	15.0	17.7	26.5	42.0	96.8
	Mean Daily Max Solar (W/m^2)	76.9	84.2	116.8	167.1	359.3

Data Sources: 1. Forest Lake 5NE. 2. Minneapolis-St. Paul International Airport. 3. National Renewable Energy Lab. 4. US Forest Service RAWS station CAVM5

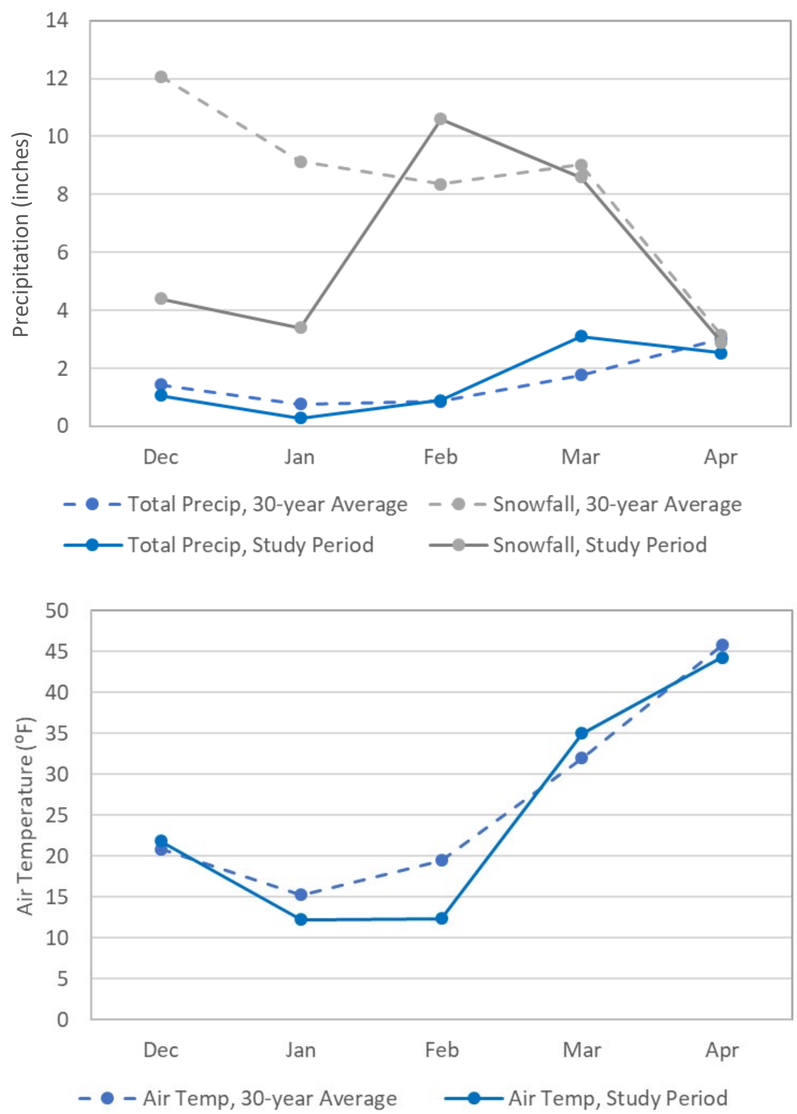

Figure 3: Comparison of total monthly precipitation (water-equivalent) and snowfall for the study period and for a 30-year average (upper panel), and comparison of mean monthly air temperature for the study period and for a 30-year average (lower panel).

2.2 Pavement temperature analysis

The unshaded site (CR01) and the first shaded site (CR02) had complete pavement temperature and weather records over their installation period (Table 1). CR02 and CR03 were designed to be redundant measurements for shaded pavement temperatures and the pavement temperature at the two sites were generally similar (within 1 °F) over most of the record. The shading conditions at CR02 and CR03 became slightly different in April due to higher sun angles. For the following temperature analysis, we chose to use the more complete CR02 record and excluded CR03.

2.2.1 Example Pavement Temperature Time Series

Figure 4 shows hourly-averaged time series of the pavement temperatures from CR01 (unshaded) and CR02 (shaded) sites. It is evident that the unshaded site has a much more dynamic temperature (i.e., more drastic changes) in January, February, and March, with similar minimum temperatures but much higher maximum temperatures at the unshaded site compared to the shaded site.

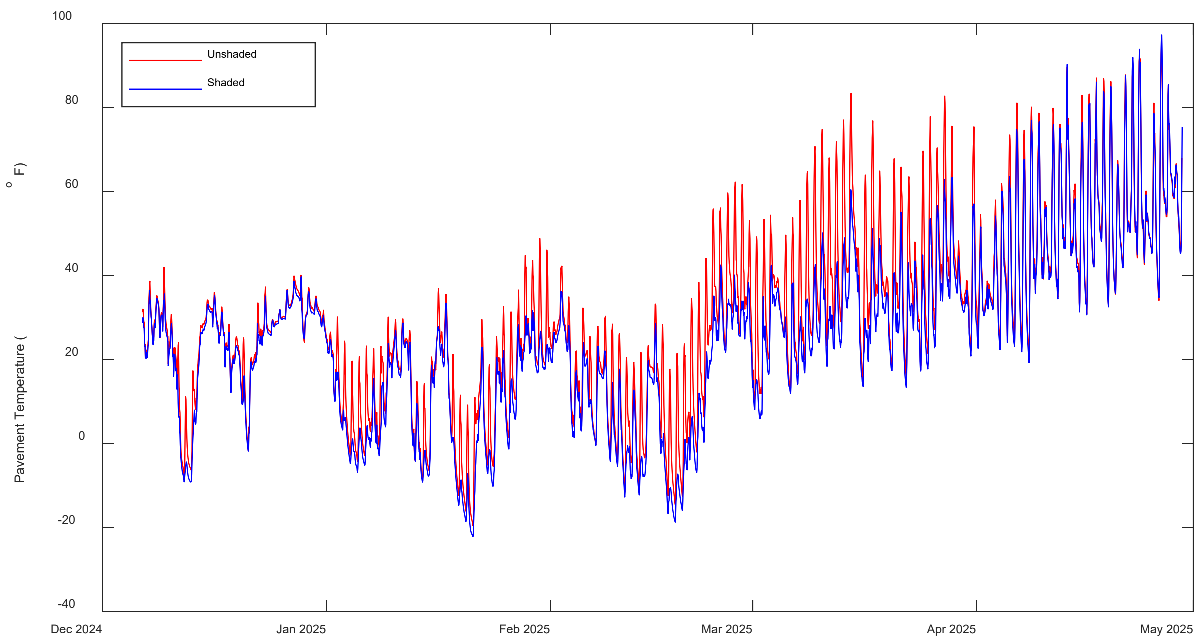

Figure 4: Time series of hourly-averaged pavement temperature from the unshaded (CR01) and shaded (CR02) roadway sites.

The behavior of the daily maximum, daily minimum, and daily average pavement temperatures is further explored in Figure 5, in comparison to air temperatures at the unshaded site. Note that 1) the daily minimum pavement temperatures at the shaded and unshaded sites are quite similar, and 2) the max, mean, and minimum daily pavement temperatures track max, mean, and minimum daily air temperature fairly closely. The differences in temperature between the two sites is more specifically quantified in the next section.

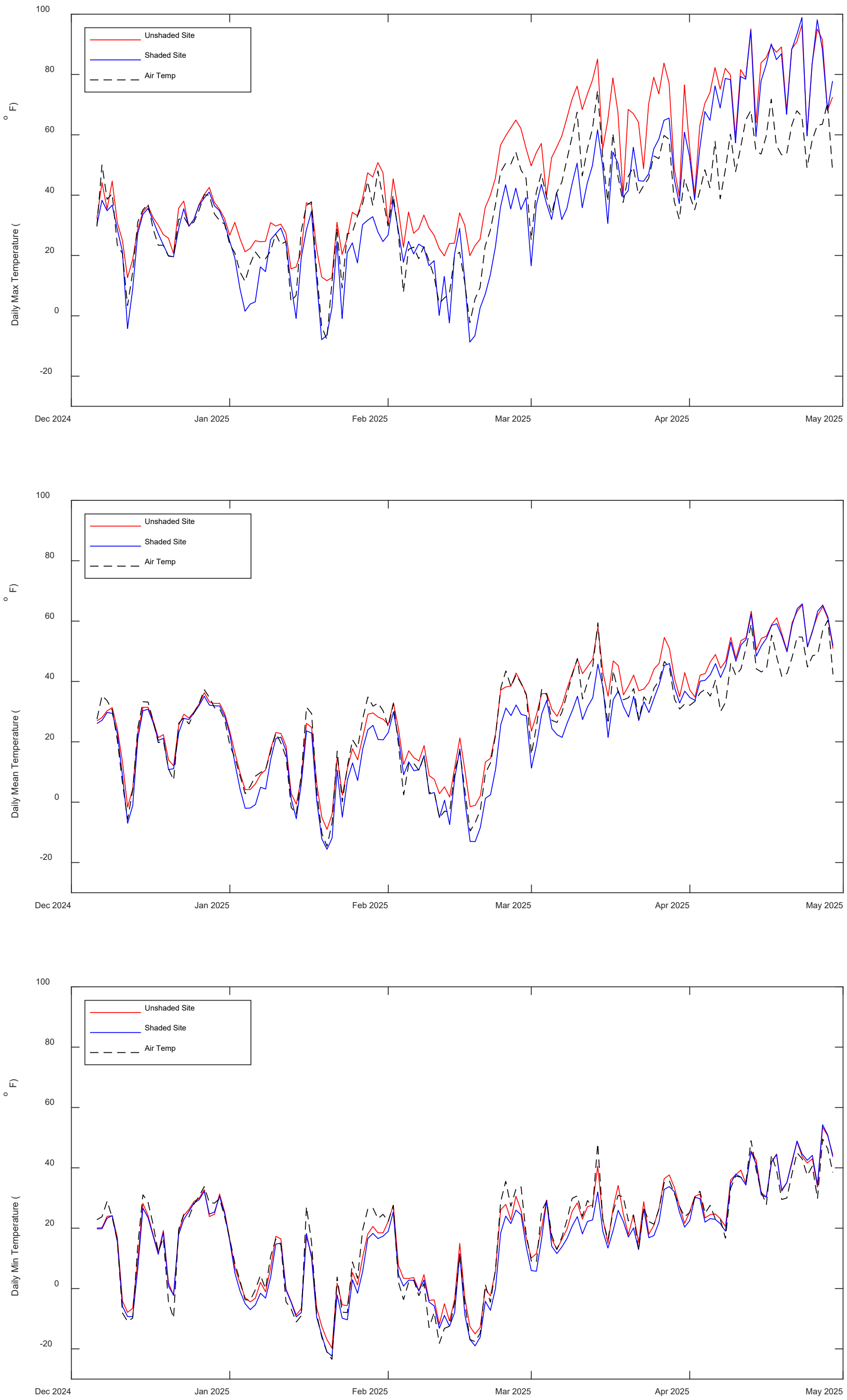

Figure 5: Time series of daily maximum (upper panel), daily average (middle panel), and daily minimum (lower panel) pavement temperature from the unshaded (CR01) and shaded (CR02) roadway sites, along with daily maximum, mean, and minimum air temperature from the unshaded site.

2.2.2 Quantifying the differences in pavement temperature between the unshaded and shaded roadway sites

The raw pavement temperature data from the CR01 (unshaded) and CR02 (shaded) sites were binned by month, and the mean, median, and standard deviation of the binned data were calculated (Table 3). These statistics were also calculated on the difference in temperature between the sites for all temperature data (Table 4) and for temperature on days with measurable snowfall (Table 5). For each month, a two-sided Wilcoxon rank sum test was used to test if the difference in median temperatures between the two sites was statistically significant, as reported in Table 4 and Table 5. The difference in monthly mean temperatures between the two sites was not tested, because the usual t-test used for this purpose requires the data to be normally distributed, and neither the temperature data for each site nor the temperature difference data are normally distributed.

Table 3: Summary of monthly mean, median, and standard deviations of the CR01 and CR02 pavement temperatures.

	Unshaded Mean (°F)	Unshaded Median (°F)	Unshaded Stan. Dev. (°F)	Shaded Mean (°F)	Shaded Median (°F)	Shaded Stan. Dev. (°F)
December	24.93	27.86	10.39	23.30	26.60	11.25
January	13.27	14.97	13.27	8.68	9.02	13.00
February	18.25	18.86	16.53	11.04	11.52	14.95
March	40.37	38.50	15.48	31.62	31.68	11.19
April	53.06	50.97	15.94	51.98	50.25	16.12

Table 4: Monthly summaries of the difference in pavement temperature between the CR01 (unshaded) and CR02 (shaded) sites. ** indicates significant difference in median temperature using a two-sided Wilcoxon rank sum test (see text).

Month	Median Difference (°F)	Mean Difference (°F)	# Days Unshaded Temp > Shaded Temp
December	1.04**	1.64	25 out of 25
January	2.99**	4.59	31 out of 31
February	4.57**	7.21	28 out of 28
March	5.76**	8.74	31 out of 31
April	0.94**	1.11	12 out of 28

Table 5: Monthly summaries of the difference in pavement temperature between the CR01 (unshaded) and CR02 (shaded) sites for days with measurable snowfall. ** indicates significant difference in median temperature using a two-sided Wilcoxon rank sum test (see text).

Month	Median Difference (°F)	Mean Difference (°F)	# Snow Days Unshaded Temp > Shaded Temp
December	1.44**	2.22	4 out of 4
January	1.91**	3.47	4 out of 4
February	3.00**	4.62	6 out of 6
March	2.76**	6.14	3 out of 3
April	1.26	1.55	2 out of 2

The monthly pavement temperature statistics were further explored using the box and whisker plots given in Figure 6 and Figure 7. Figure7, in particular, clearly shows how the difference in pavement temperatures between the two sites was distributed by month, with the greatest difference observed in March. The temperature difference rapidly decreased in April because the sun angle increased and the shade decreased at CR02. The distribution of the temperature difference is not substantially different for days with snow compared to all days (Figure 7), but the median and mean temperature differences are lower for snow days in January, February, and March (Table 4, Table 5). The box and whisker plots show a number of temperature outliers, which generally do not represent bad readings, but simply represent data in each month that are smaller or greater than standard thresholds (25^{th} percentile - 1.5 x (75^{th} percentile-25^{th} percentile) and 75^{th} percentile + 1.5 x (75^{th} percentile-25^{th} percentile).

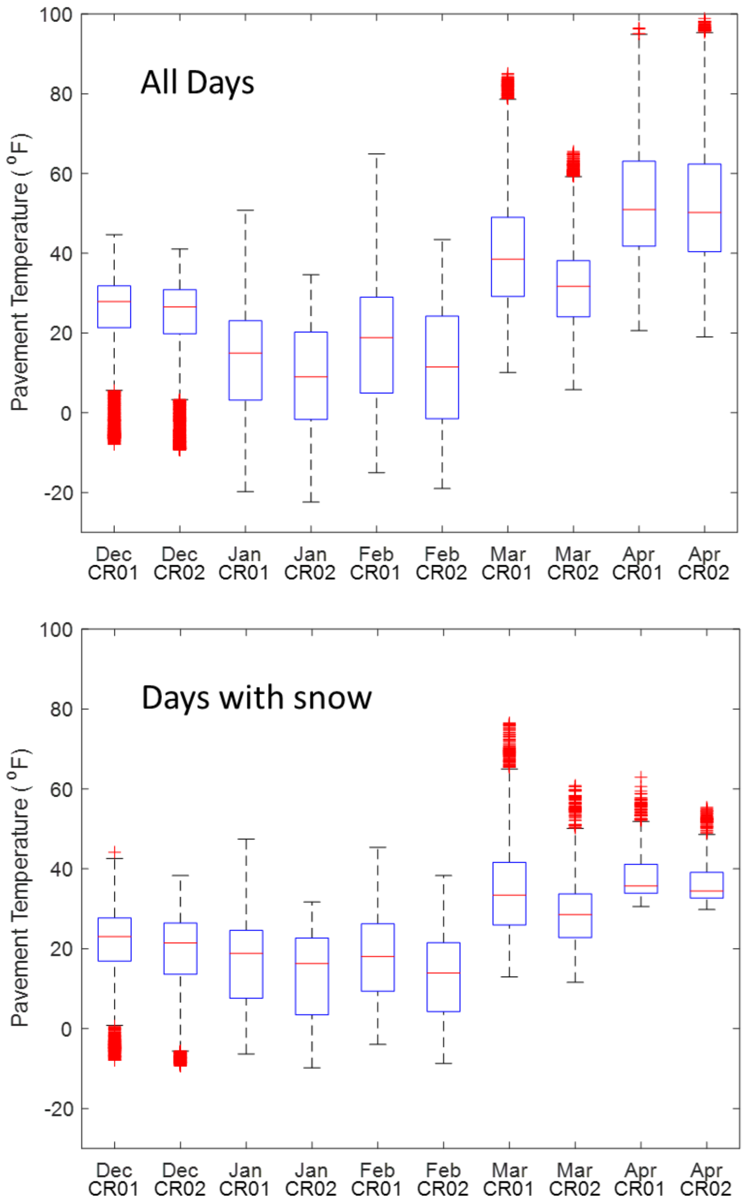

Figure 6: Box and whisker plot showing the distribution of the raw pavement temperature data for the unshaded (CR01) and shady (CR02) sites, by month. The upper plot gives the distribution of all temperature data, while the lower plot gives data only for days with measurable snow. The red lines represent the median, the upper and lower extent of the blue boxes gives the 25th and 75th percentile, the black whiskers give the upper and lower extremes of the data that are not classified as outliers, and the red crosses indicate outliers.

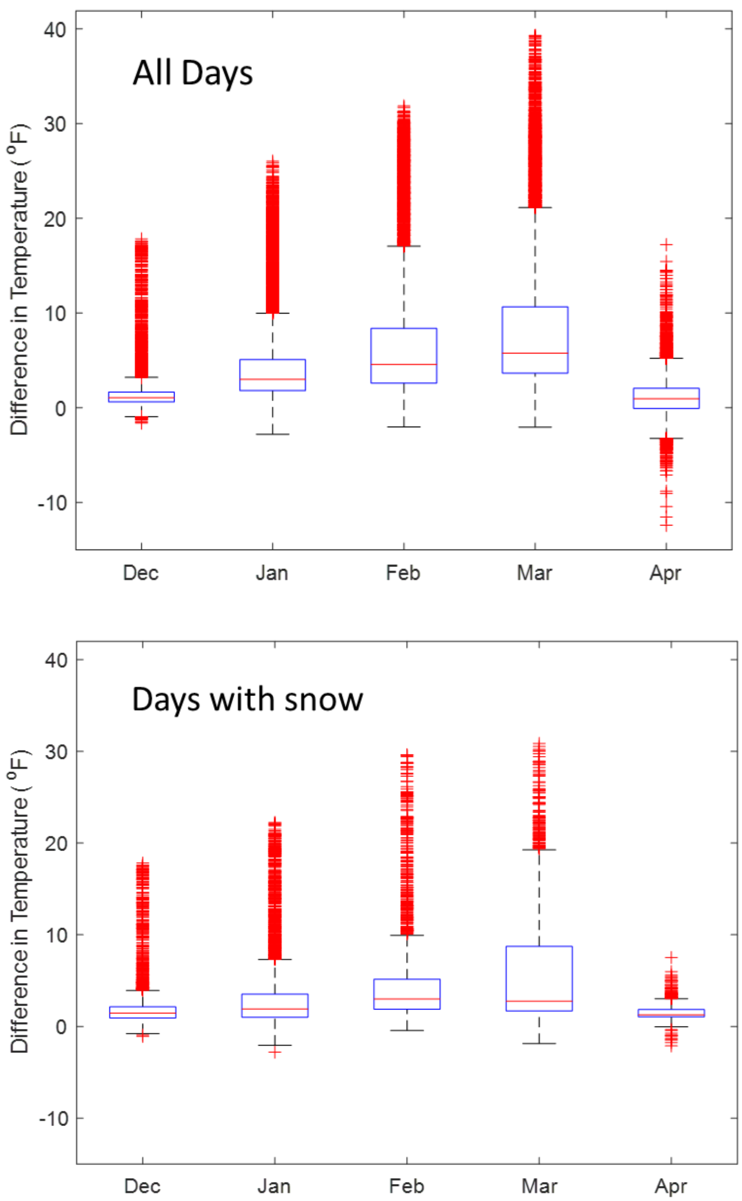

Figure 7: Box and whisker plot showing the distribution of the difference in pavement temperature (unshaded – shaded), by month. The upper plot gives the distribution of all temperature data, while the lower plot gives data only for days with measurable snow.

2.2.3 Regression Analysis of Pavement Temperature

The pavement temperature data were combined with the measured air temperature and solar radiation data to find relationships between pavement temperature, air temperature, and solar radiation. The main purpose of this analysis was to determine the sensitivity of pavement temperature to changes in solar radiation, which can then be related to changes in shading. This analysis was first performed with the pavement temperature and climate data collected during this study, but additional analyses were made using pavement temperature data from nine MnDOT RWIS stations (Figure 8). US Forest service climate stations (RAWS stations) were used as a source of solar radiation data, with RWIS stations chosen to be within 20 miles or less of a RAWS station. The air temperature reported by the RWIS station was used in the regression analysis. The raw pavement and air temperature were processed to calculate daily maximum, daily mean, and daily minimum, and the solar radiation data were processed to calculate daily maximum and daily mean.

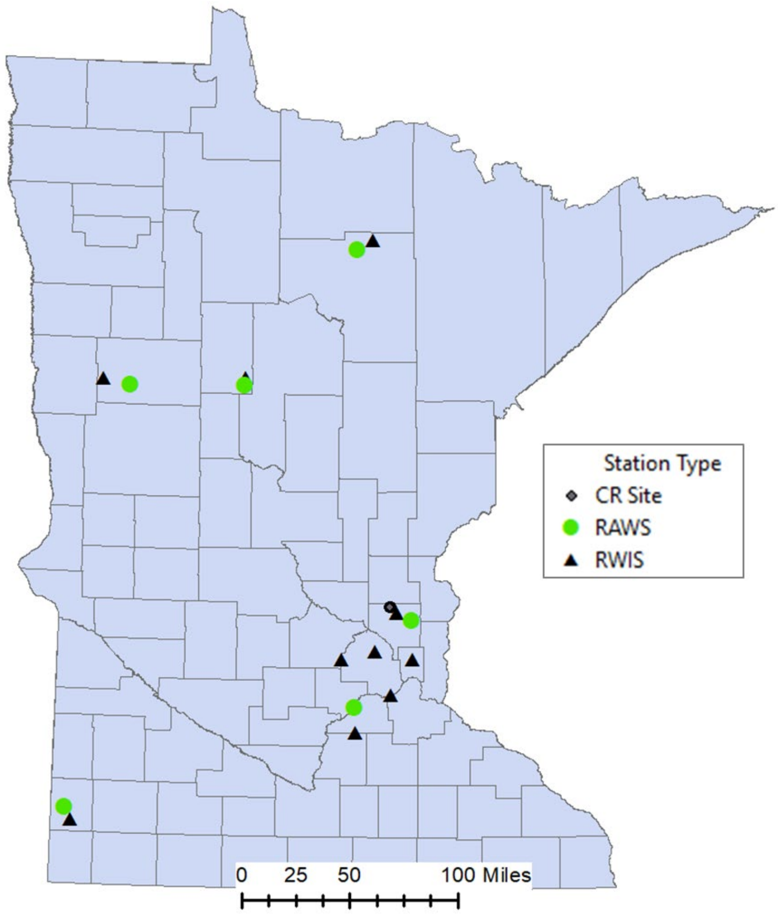

Figure 8: Map of the locations of the Clear Roads study sites (CR), RWIS and RAWS stations used in the pavement temperature regression analysis.

Figure 9 illustrates the relationships between 1) pavement temperature and air temperature, and 2) pavement temperature and solar radiation, using the mean daily values of all parameters. There is a strong correlation between pavement temperature and air temperature, but pavement temperatures at the shaded site are generally lower than those of the unshaded site. The relationships between pavement temperature and solar radiation are weaker and nonlinear, with different relationships for the unshaded and shaded sites.

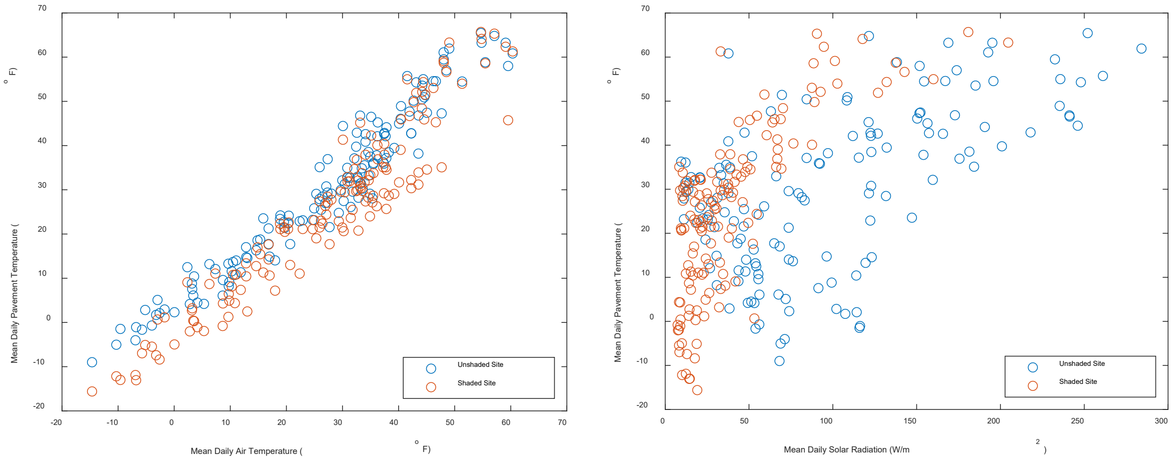

Figure 9: Relationships between mean daily pavement temperature and mean daily air temperature (left panel), and between mean daily pavement temperature and mean daily solar radiation (right panel), for the unshaded study site (CR01) and the shaded test site (CR02).

Multiple linear regression analysis was performed in Matlab using the *fitlm* function, to fit equations of the following general form:

$$Tp = c0 + c1 \cdot Ta + c2 \cdot Sr$$

where Tp is pavement temperature (°F), Ta is air temperature (°F), and Sr is solar radiation (W/m^2). More specifically, we analyzed daily maximum, minimum, and mean pavement temperature, daily maximum, minimum, and mean air temperature, and daily maximum and mean solar radiation. We found very good fits for the following relationships:

$$Tp_{max} = c0 + c1 \cdot Ta_{ave} + c2 \cdot Sr_{max} \quad (1)$$

$$Tp_{ave} = c0 + c1 \cdot Ta_{ave} + c2 \cdot Sr_{ave} \quad (2)$$

$$Tp_{min} = c0 + c1 \cdot Ta_{min} + c2 \cdot Sr_{ave,t-1} \quad (3)$$

where the max, min, and ave subscripts denote daily maximum, minimum, and average, respectively. $Sr_{ave,t-1}$ denotes mean daily solar radiation for the previous day. c0 has units of °F, c1 is dimensionless, and c2 has units of °F/W/m^2. For the Tp_{max} regressions, daily average air temperature did work slightly better than daily maximum air temperature. Figure 10 gives an example of the fitted daily mean pavement temperature (based on air temperature and solar radiation) versus the observed pavement temperature. Data for the unshaded (CR01) and shaded (CR02) sites are plotted with separate symbols, showing that the fit coefficients calculated for the combination of CR01 and CR02 work well for both sites.

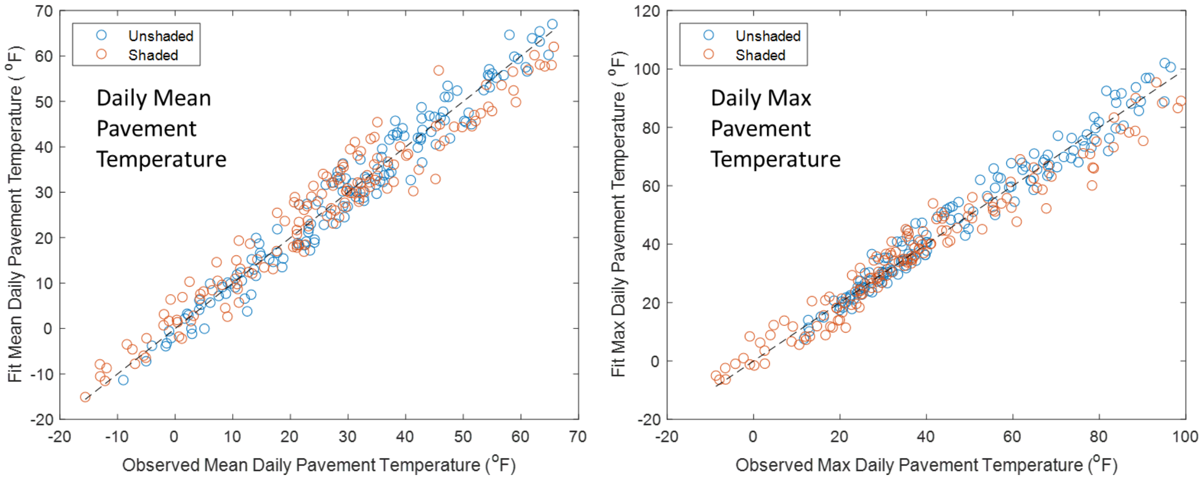

Figure 10: Predicted mean daily pavement temperature (Eq. 1) versus observed mean daily pavement temperature and predicted daily max pavement temperature (Eq. 2) versus observed daily max pavement temperature, for the unshaded (CR01) and shaded (CR02) study sites. The fit coefficients for Eq. 2 are based on the combined data set (CR01 and CR02). The dashed line represents a 1:1 slope.

Overall, very good fits between pavement temperature, air temperature, and solar radiation were obtained, with R^2 ranging from 0.94 to 0.988 (Table 6, Table 7, and Table 8 for equations 1, 2, and 3, respectively). The offset term (c0) had the most variability between sites, with the standard deviation on the same order as the mean (Table 6). Preliminary analysis suggested a relationship between c0 and traffic volume, but analysis of all eleven sites gave no relationship between c0 and traffic volume or c0 and latitude. We found daily minimum pavement temperature had a significant relationship to mean solar radiation on the previous day, but with a smaller coefficient (c2) compared to average and maximum pavement temperature.

Only one site, CR02, had significant shading. For the mean daily temperature fits, the solar radiation coefficient (c2) for CR02 was within one standard deviation of the mean for all sites, but for the minimum and maximum daily temperature fits, the c2 coefficient for CR02 was higher than any of the other sites. However, it was shown in the weather analysis section that the solar measurements at CR01 and CR02 may be biased low (Mean Solar Rad., % Difference, CR01 – CAVM5; Table 2), which would tend to increase the value of c2.

Table 6 also gives the mean coefficients for asphalt and concrete road surfaces (MN062, MN087 and MN088 are concrete, the other nine sites are asphalt). The mean c2 coefficients are lower for the concrete sites, e.g., 0.039 for concrete vs. 0.048 for asphalt for both daily mean and daily maximum pavement temperature. This implies that the temperature of asphalt road surfaces responds more to changes in solar radiation (and shading) than concrete. This is likely due to concrete road surfaces being more reflective than asphalt (Alleman & Heitzman, 2019). More data points for concrete road surfaces are needed to test the statistical significance of this difference.

Table 6: Summary of fit coefficients (c0, c1, c2) obtained for Equation 1, relating pavement temperature, air temperature, and solar radiation, for the two measurement sites on 229th Avenue (CR01 and CR02), nine RWIS stations, and five RAWS stations (US Forest Service climate stations). CR01+CR02 indicates the analysis of the combined unshaded (CR01) and shady (CR02) site data. c0 has units of °F, c1 is dimensionless, and c2 has units of °F/W/m^2. *indicates concrete pavement; all others are asphalt.

Pavement Temperature Site	Solar Measurement Site	Mean Daily Pavement Temperature			
		c0	c1	c2	R^2
CR02	CR02	1.636	0.884	0.049	0.953
CR01	CR01	0.069	0.939	0.051	0.968
CR01	CAVM5	-0.410	0.974	0.039	0.962
CR01+CR02	CR01+CR02	-2.221	0.947	0.069	0.952
MN049	BDRM5	5.645	0.844	0.064	0.957
MN052	EFFM5	4.884	0.849	0.052	0.960
MN062*	DMLM5	5.123	0.874	0.042	0.970
MN079	TS642	5.049	0.882	0.049	0.965
MN086	TS642	2.049	0.920	0.031	0.988
MN087*	CAVM5	2.771	0.885	0.044	0.986
MN088*	CAVM5	2.928	0.935	0.037	0.987
MN140	CAVM5	3.221	0.914	0.043	0.981
MN154	CAVM5	3.911	0.862	0.046	0.972
MN161	TS642	1.158	0.942	0.029	0.961
	Mean, All Sites	2.361	0.906	0.046	0.969
	Stand Dev	2.309	0.041	0.012	0.013
	Mean, Asphalt Sites	2.352	0.907	0.048	0.965
	Mean, Concrete (*) Sites	3.314	0.893	0.039	0.981

Table 7: Summary of fit coefficients (c0, c1, c2) obtained for Equation 2, relating pavement temperature, air temperature, and solar radiation, for the two measurement sites on 229th Avenue (CR01 and CR02), nine RWIS stations, and five RAWS stations (US Forest Service climate stations). CR01+CR02 indicates the analysis of the combined unshaded (CR01) and shady (CR02) site data. c0 has units of °F, c1 is dimensionless, and c2 has units of °F/W/m^2. *indicates concrete pavement; all others are asphalt.

Pavement Temperature Site	Solar Measurement Site	Max Daily Pavement Temperature c0	c1	c2	R^2
CR02	CR02	-0.752	0.868	0.065	0.957
CR01	CR01	1.636	0.884	0.049	0.968
CR01	CAVM5	-0.218	1.020	0.047	0.967
CR01+CR02	CR01+CR02	0.374	0.910	0.052	0.940
MN049	BDRM5	6.104	0.873	0.057	0.946
MN052	EFFM5	3.139	0.930	0.055	0.943
MN062*	DMLM5	5.684	0.937	0.042	0.950
MN079	TS642	4.819	0.947	0.049	0.951
MN086	TS642	2.405	0.944	0.034	0.973
MN087*	CAVM5	3.272	0.906	0.042	0.975
MN088*	CAVM5	3.346	0.997	0.040	0.983
MN140	CAVM5	2.794	0.961	0.043	0.977
MN154	CAVM5	1.607	0.969	0.043	0.956
MN161	TS642	0.792	1.029	0.036	0.952
	Mean, All Sites	1.851	0.939	0.047	0.961
	Stand Dev	2.763	0.055	0.009	0.014
	Mean, Asphalt Sites	1.671	0.941	0.048	0.958
	Mean, Concrete (*) Sites	3.787	0.929	0.039	0.966

Table 8: Summary of fit coefficients (c0, c1, c2) obtained for Equation 3, relating pavement temperature, air temperature, and solar radiation, for the two measurement sites on 229th Avenue (CR01 and CR02), nine RWIS stations, and five RAWS stations (US Forest Service climate stations). CR01+CR02 indicates the analysis of the combined unshaded (CR01) and shady (CR02) site data. c0 has units of °F, c1 is dimensionless, and c2 has units of °F/W/m^2. * indicates concrete pavement; all others are asphalt.

Pavement Temperature Site	Solar Measurement Site	Min Daily Pavement Temperature c0	c1	c2	R^2
CR02	CR02	-2.560	0.860	0.070	0.961
CR01	CR01	0.194	0.893	0.019	0.965
CR01	CAVM5	0.325	0.906	0.013	0.963
CR01+CR02	CR01+CR02	-1.253	0.888	0.032	0.959
MN049	BDRM5	7.862	0.773	0.022	0.950
MN052	EFFM5	7.684	0.768	0.012	0.950
MN062*	DMLM5	5.939	0.858	0.007	0.970
MN079	TS642	6.798	0.853	0.004	0.960
MN086	TS642	3.459	0.901	0.006	0.983
MN087*	CAVM5	3.750	0.872	0.013	0.980
MN088*	CAVM5	3.784	0.910	0.009	0.981
MN140	CAVM5	4.401	0.883	0.010	0.979
MN154	CAVM5	5.751	0.869	0.002	0.949
MN161	TS642	1.854	0.923	0.002	0.958
	Mean, All Sites	3.234	0.869	0.016	0.964
	Stand Dev	3.361	0.048	0.018	0.012
	Mean, Asphalt Sites	3.167	0.866	0.018	0.961
	Mean, Concrete (*) Sites	4.383	0.877	0.009	0.978

2.3 Camera Image Analysis

The measurement stations were equipped with trail cameras to record images of the road surface at 1 hour intervals. Some issues were encounted with the cameras, such that images are unavailable for the time period 12/11/24 to 1/30/25 at CR01 and 1/9/25 to 1/30/25 at CR02. The available camera images were manually analyzed at each site to look for either rain or snow events, and to record the time period needed for the pavement surface to dry (time to dry), starting from the event start time. Sample images are given in Appendix I. The time to dry times for analyzed for rain and snow events that were recorded at both the CR01 and CR02 stations. Table 9 summarizes the mean time to dry times for CR01 and CR02, for all precipitation, rainfall-only, and snowfall-only events. Considering all precipitation events, the time to dry was about 2 hours longer at the shaded CR02 site. For rain events, the mean time to dry was less than one hour longer (~7% longer) at the shaded CR02 site. For snow events, the mean time to dry was over 5 hours longer (~26% longer) at CR02, because less solar energy is available to evaporate (or sublimate) moisture from the road surface. The time to dry for CR01 and CR02 are further compared in Figure 11, which also illustrates that there is little difference in time to dry between the two sites for rain events, but a larger difference is observed for snow events.

Table 9: Mean time to dry at the CR01 (unshaded) and CR02 (shaded) study sites for all precipitation events and snow events only.

	Number of Events	Mean Time to Dry (hours) at CR01 (unshaded)	Mean Time to Dry (hours) at CR02 (shaded)	Additional time to dry for shaded sites (hours)
All Precip Events	24	13.1	15.2	+2.1
Rain Events	15	11.3	12.1	+0.8
Snowfall Events	9	20.2	25.5	+5.3

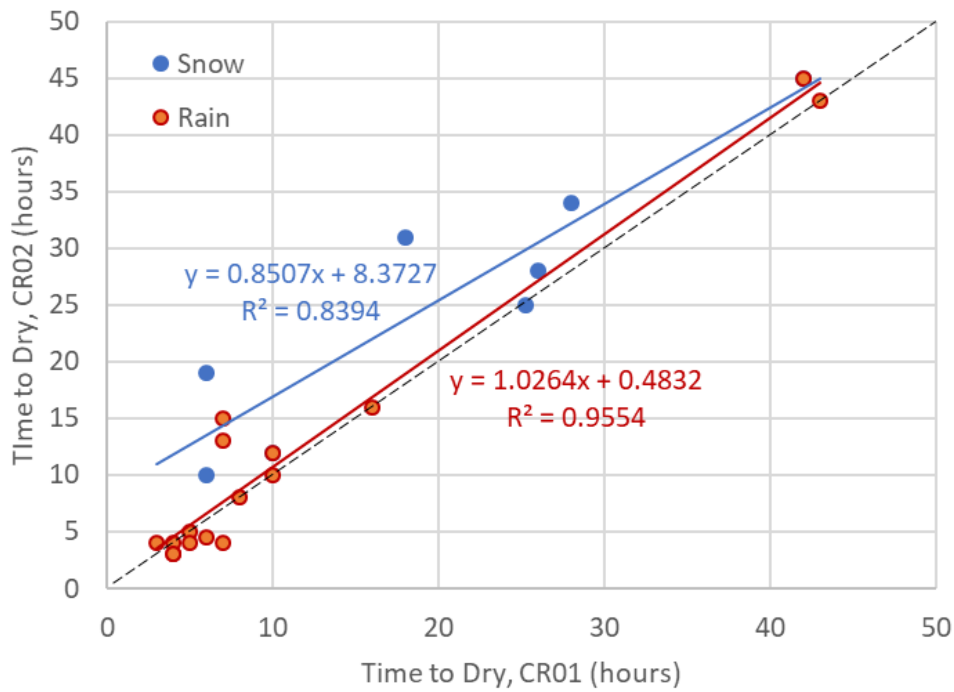

Figure 11: Time to dry for road surfaces at CR02 (shaded) vs. CR01 (unshaded), for snow events (blue) and rain events (red). The solid blue and red lines give separate linear regressions for snow and rain events, respectively, and the black dashed line gives a 1:1 slope (i.e., no difference in time to dry between sites).

2.4 Winter Maintenance Truck Data Analysis

Winter maintenance truck data was supplied by Anoka County for the truck route that included the study sites (Figure 12), for the period October 31, 2024 to April 2, 2025. The data included the truck locations (latitude-longitude) and times, road temperatures, and deicer application rates. Analysis of the truck data included 1) comparisons of truck-measured pavement temperatures and 2) analyzing relationships between pavement temperatures and deicer application rates. In addition to the raw truck data, Bolton & Menk supplied a list of winter maintenance event time windows over the study period (Table 10).

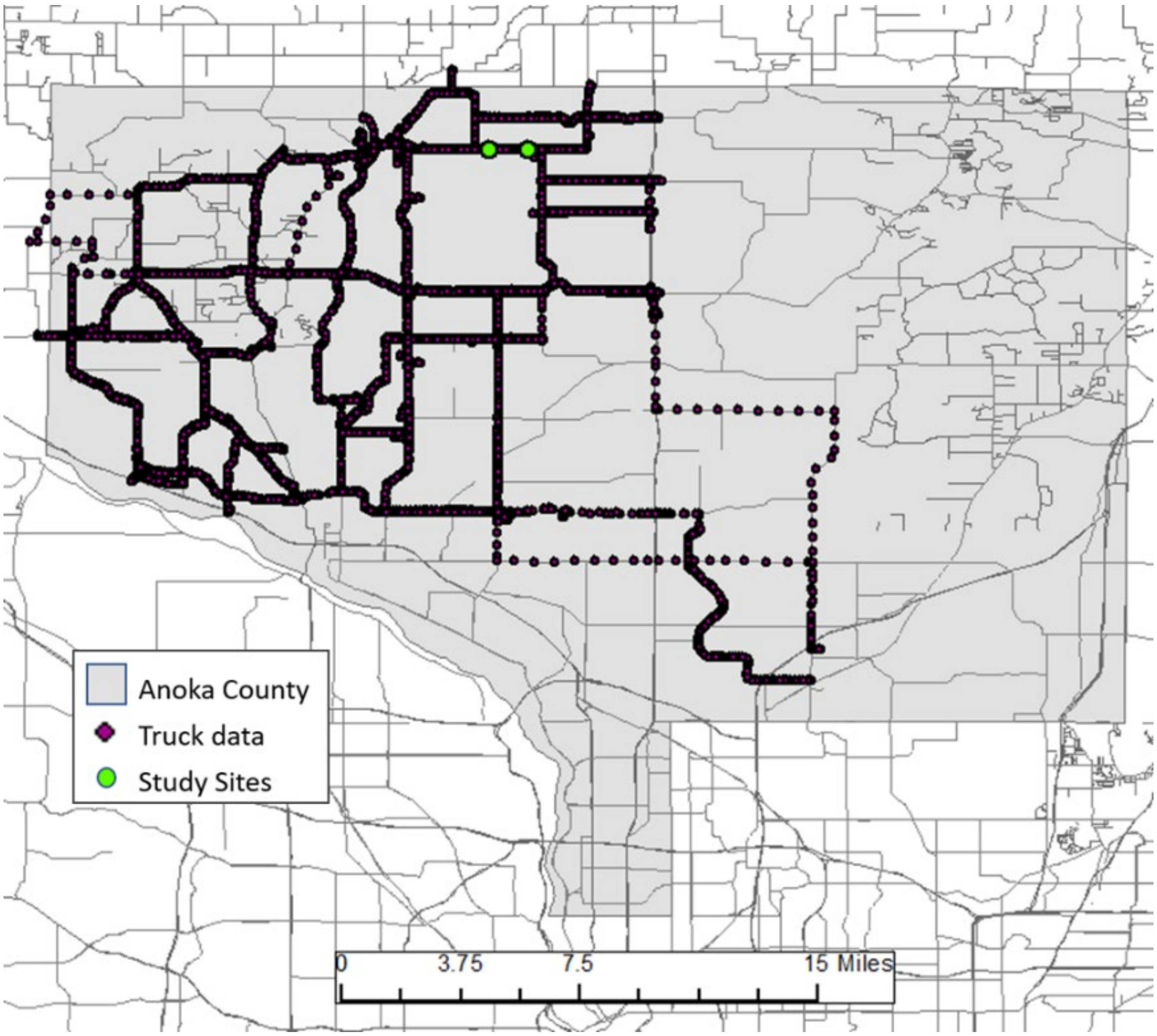

Figure 12: Map of the winter maintenance truck data supplied by Anoka County.

Table 10: Winter maintenance events extracted from the maintenance truck database.

Event Number	Start Date/Time	End Date/Time
1	12/10/2024 14:23	12/11/2024 11:30
2	12/14/2024 7:38	12/14/2024 13:13
3	12/16/2024 7:00	12/16/2024 14:35
4	12/19/2024 2:10	12/21/2024 13:42
5	12/30/2024 6:01	12/30/2024 10:30
6	1/9/2025 12:45	1/13/2025 14:23
7	1/15/2025 14:14	1/15/2025 14:49
8	2/1/2025 14:35	2/1/2025 18:48
9	2/3/2025 0:03	2/4/2025 13:49
10	2/5/2025 13:49	2/6/2025 20:43
11	2/7/2025 18:37	2/9/2025 1:01
12	2/14/2025 12:00	2/15/2025 10:01
13	3/4/2025 17:21	3/5/2025 20:39
14	3/30/2025 2:07	3/30/2025 18:34
15	4/1/2025 20:25	4/2/2025 8:30

2.4.1 Comparison of truck-measured pavement temperatures to the radiometer temperature data

Pavement temperature data were only available for the night route truck, so that the times of measured pavement temperatures are skewed towards night and early morning (Figure 13). To compare the truck-measured pavement temperatures to the radiometer-measured temperatures from the study sites, the truck data were parsed to find times when the truck was within specified shaded and unshaded windows near the study sites (Figure 14). The unshaded window does not contain the unshaded site, because the unshaded site is a short stretch of unshaded roadway surrounded by shaded roadway. The truck-based temperature readings within each window were then compared to the radiometer measurement closest in time to each truck measurement.

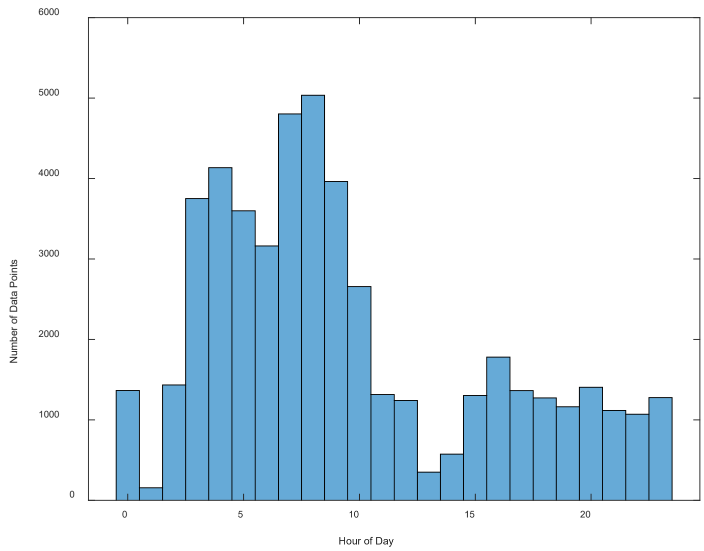

Figure 13: 24-hour distribution of truck-measured pavement temperatures (0=midnight, 12=noon).

Figure 14: Satellite photo of the unshaded and shaded windows (red squares) used to identify truck temperature data for comparison to the radiometer measurements (green circles).

The correlation between the truck-based temperature readings and the radiometer measurements is illustrated in Figure 15. The correlation is reasonably good at both the unshaded (r^2=0.93) and shaded sites (r^2=0.89), but the y-intercept is about +5 °F at both sites (i.e., truck temp > site temp). The slope is 0.93 for the shaded site, indicating the truck-based readings are biased high compared to the radiometer readings for all measurements. The slope is 0.87 for the unshaded site and the best fit line crosses the 1:1 line (truck temp = site temp), indicating that the truck temp may be biased greater than the site temp for low temps (< ~20°F) but may be similar to site temps for higher temps. The correlation was sufficiently good and bias minimal enough to use the truck-based temperature data in an analysis of application rates, which is described in the next section.

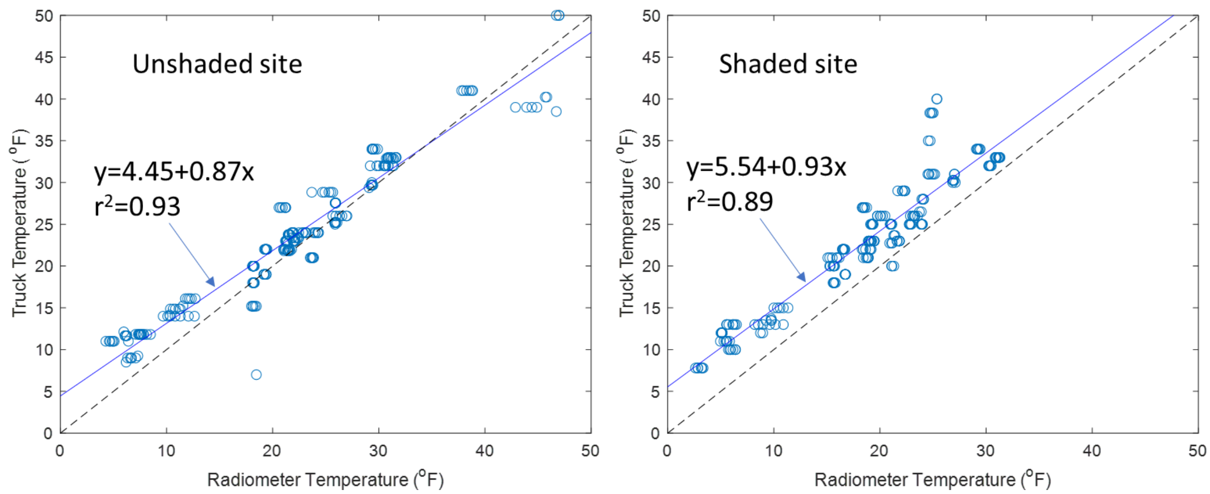

Figure 15: Scatter plots of truck-measured pavement temperature vs. radiometer-measured pavement temperature at the unshaded and shaded study sites. The dashed lines represent a 1:1 slope (i.e., truck temp = site temp).

2.4.2 Analysis of the relationship between pavement temperature and deicer application rates

The maintenance truck database was first used to compare rock salt application rates to pavement temperature at the two study sites, using the radiometer temperature data. The spatial windows shown in Figure 14 were used to parse the truck database to find application rate data near the study sites for each of 15 maintenance event time windows (Table 10). The application rates identified for each maintenance event time window were then averaged, and the corresponding pavement temperatures were also averaged.

Table 11: Summary of the mean and standard deviation of the deicer application rates at the unshaded and shaded study sites.

Site	Mean (lbs./lane- mile)	Standard Deviation (lbs./lane mile)
Unshaded (CR01)	265.1	75.4
Shaded (CR02)	270.8	76.0

Figure 16 gives a scatter plot of event-averaged application rates versus event-averaged pavement temperature for the unshaded and shaded sites. The relationships at both sites have a negative slope, but with low r^2 (0.069 and 0.162). At both sites, the negative slope of the regression is not statistically significant. For pavement temperatures above 20 °F, the application rates are higher than the Clear Roads recommended rates (Washington State University, 2019). The overall mean application rate was slightly higher at the shaded site (Table 11), but the difference in application rates between the unshaded and shaded sites was not statistically significant.

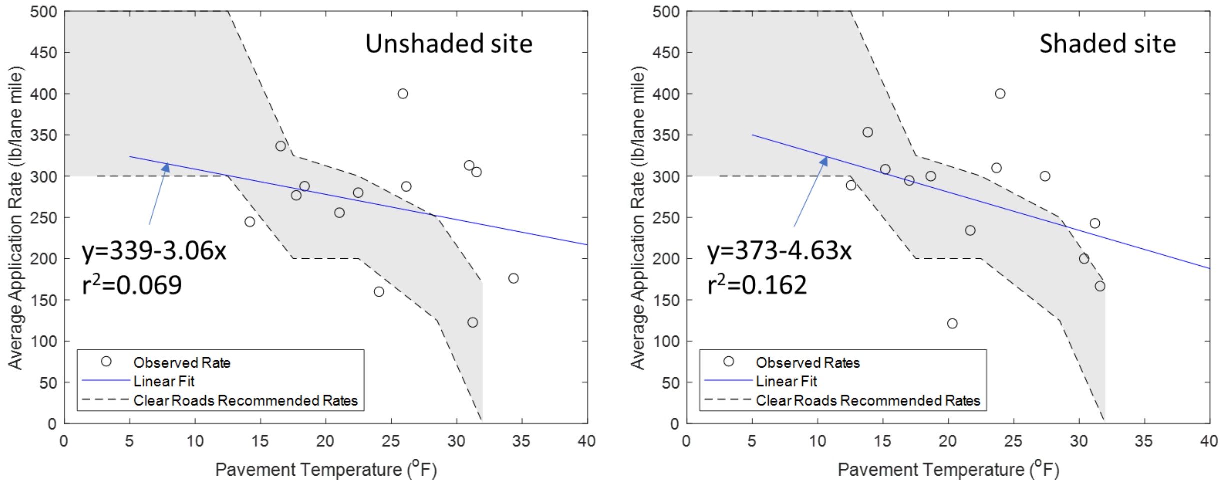

Figure 16: Deicer application rate vs. pavement temperature at the unshaded and shaded sites. The dashed lines and shading give the upper and lower bounds of the Clear Roads recommended application rates.

Following the application rate analysis at the Clear Roads study sites, a second, larger analysis was conducted using the truck-based pavement temperature measurements, as follows:

1) The road network covered by the Anoka County maintenance truck database (Figure 12) was broken up into approximately 100 road segments.
2) For each road segment and each of the 15 maintenance windows (Table 10), an average deicer application rate and an average road temperature were calculated. Since the truck-based pavement temperature readings were incomplete, the application rate-temperature data pairs were calculated for a subset of road segments and maintenance windows.
3) Regression analysis was performed on the application rate-temperature data.

The results of the application rate-temperature data regression analysis based on truck-based temperatures are given in Figure 17. The slope of the relationship is steeper (-5.7) than study site results given in Figure 16, and the slope is statistically significant. The fit to the reported application rates is about 100 lbs./lane-mile higher than the Clear Roads recommended rates.

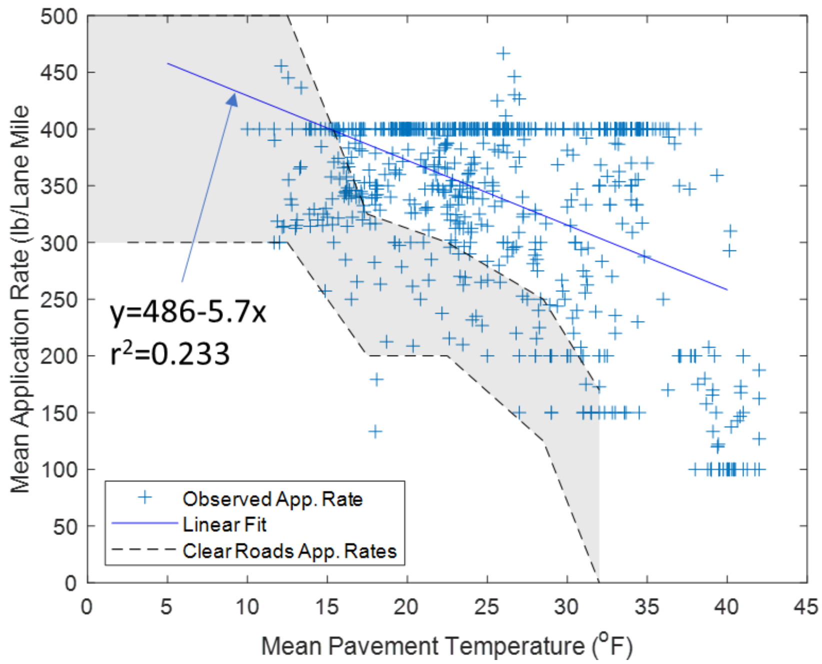

Figure 17: Deicer application rate vs. pavement temperature for road segments in Anoka County. The dashed lines give the upper and lower bounds of the Clear Roads recommended application rates.

2.5 Summary and Conclusions

The main purposes of the analysis presented in this report was to quantify the difference in pavement temperature between shaded and unshaded sites, and to develop relationships to estimate the change in pavement temperature for changes in roadway shading conditions. The pavement temperature data analysis showed that the monthly-mean pavement temperatures at an unshaded site were highest in March, and the unshaded site mean and median temperature was 8.8 °F and 5.8 °F higher than a shaded site on the same roadway, respectively. Cloud cover and precipitation tended to decrease this difference in pavement temperature – for days with snowfall, the mean and median differences in pavement temperature in March were 6.1 °F and 2.8 °F, respectively. The analysis of pavement temperature for different weather conditions was somewhat limited by a lack of good quality, hourly rainfall, and snowfall data for the study region.

Analysis of pavement temperature data along with air temperature and solar radiation found that daily maximum, daily mean, and daily minimum pavement temperatures are strongly related to the combination of air temperature and solar radiation. These relationships can be used to estimate the change in pavement temperature due to changes in roadway shading. For example, mean daily asphalt pavement temperature was found to be related to air temperature and solar radiation by $Tp_{ave} = c0 + c1 \cdot Ta_{ave} + c2 \cdot Sr_{ave}$, where the c2 coefficient was found to be 0.069 °F/W/m^2 for the study sites. For a difference in mean solar radiation of 65.5 W/m^2 (Table 2), this implies a modeled difference in pavement temperature between the unshaded and shaded sites of $0.069 \cdot 65.5 = 4.5$ °F. Using MnDOT RWIS pavement temperature data, the solar radiation coefficient c2 was found to vary between 0.029

and 0.069, but the mean value for concrete surfaces was lower (0.039) compared to asphalt surfaces (0.048). This suggests that the temperature of concrete roadways may respond less to changes in shading compared to asphalt roadways. Daily minimum pavement temperatures were less responsive to solar radiation, with average c2 coefficients of 0.018 for asphalt and 0.009 for concrete. The pairing of pavement temperature and air temperature data from DOT RWIS stations with solar radiation data from US Forest Service RAWS weather stations was found to be a useful way to relate pavement temperatures to solar radiation, and these analyses could be extended to other states to consider different terrains and climate.

Analysis of the trail camera images from the unshaded and shaded study sites found that the shaded roadway took on average about 2 hours longer to dry compared to the unshaded roadway for all precipitation events. This difference in time to dry for snowfall events was over 5 hours. An analysis of winter maintenance truck road temperature and application rate data found that mean salt application rates decreased with increasing pavement temperature, but the application rates tended to be higher than the Clear Roads recommended rates.

References

Alleman, J., & Heitzman, M. (2019). *Quantifying pavement albedo* (No. NCAT Report 19-09). Iowa State University. National Concrete Pavement Technology Center.

Washington State University (2019). *Material Application Methodologies Guidebook*, Clear Roads CR15.01 guidebook, 57 pp.

Chapter 3: Comparison of Field Site to Survey Response Locations

The survey, which was primarily distributed among Clear Roads members, generated 65 responses by 8 different state agencies responsible for winter highway maintenance, as well as 2 counties in Minnesota. Many of these agencies operate in areas where forested land cover combines with topography to create complicated maintenance areas.

3.1 Tabular Summary of Survey Sites

We prepared a summary of "typical" sites for these agencies, where the locations were compared to publicly accessible GIS data to evaluate the winter climate conditions. The data sources for these analyses include:

- Seasonal Snowfall Accumulation Analyses from National Operational Hydrologic Remote Sensing Center, which evaluates annual snowfall beginning September 2003.
- Monthly mean time-averaged daily surface-level air temperatures from MERRA-2 Retrospective Analysis, using 30-year Dec-February monthly averages.
- FLDAS Noah Land Surface Model Shortwave Downwelling Radiation, using 30-year Dec-February monthly averages.

Table 12: Climate Values Developed for "Typical" Shade/Vegetation Removal Sites by Agency

Agency	Number of Responses	Snowfall (m)	Air Temperature (°F)	Daily Average Shortwave Radiation (W/m^2)	Pavement Temperature Estimate (°F)
Minnesota Field Site*	6	1.08	18.3	79.7	22.7
Washington DOT	5	2.35	23.3	53.6	25.9
Montana DOT	3	1.68	22.5	57.9	25.4
Arizona DOT	2	0.5	44.2	139.4	48.82
Pennsylvania DOT	39	0.62	29.6	79.0	32.8
Vermont AOT	3	1.82	18.3	72.4	22.2
Massachusetts DOT	6	1.03	22.2	85.0	26.4
Maine DOT	3	1.82	16.8	76.5	21.1

*The Field Site metrics are representative of the other sites identified in Minnesota by Anoka and Dakota County Highway staff, so are reported here.
**These sites will be included in the final report data analysis but were missed during the initial data analysis stage due to early changes in the survey format.

3.2 Descriptive Summary and Comparisons to Test Site

These descriptions are for a climate-typical winter maintenance season based on 30-year records of air temperature and downwelling shortwave radiation, as well as 10-year records of snowfall. The expected daily average pavement temperatures are estimates made by using the regression-based method detailed in Chapter 2. These comparisons should help provide context for translating findings of this project to the regions identified in our surveys.

3.2.1 Field Site Climate & Other Sites from Anoka and Dakota Counties, MN

These sites are located in relatively flat regions relative to many of the other survey sites. Localized forest cover is mixed with residential and agricultural land use in these regions. For a discussion of observed weather at the field site for the season of observation, refer to Chapter 2.

Climate-typical snowfall is approximately 1.08 meters (42.5 inches). Among the 6 sites reported by county highway agencies in Minnesota, the average annual snowfall showed little variation, ranging from 1.03 meters to 1.22 meters. Annual snowfall across all sites evaluated ranged from 0.6m – 2.4m in the 10-year record used for analysis.

Daily average winter air temperature at the field site is estimated to be 18.3°F, though this is a high value among those contributed in the state, where the average is 15.6°F among all Anoka and Dakota County sites. Average daily downwelling shortwave radiation, on the other hand, is lower at the field site compared to the others, where values range from the field site's 79.7 W/m^2 – 81.4 W/m^2, a 2% increase.

Expected pavement temperatures at these sites, based on average daily air temperature and average daily solar radiation, is 22.1 °F with standard deviation of 0.49 °F across all sites.

3.2.2 Comparison to Other States

Other regions participating in the survey were compared to the Minnesota field site based on air temperature and average solar radiation values to estimate seasonal average pavement temperatures. States where sites may experience similar pavement temperature outcomes of vegetation management include Maine, Pennsylvania, Massachusetts, and Vermont. The combination of typical daily solar radiation and average daily air temperature among the sites reported by these agencies are similar to those at the study field site. Among those sites inventoried by our survey, Arizona is the most likely to observe even greater enhancements to road conditions following vegetation management. In Washington and Montana, benefits may be limited by low average air temperatures, although peak solar radiation should be greater at higher elevations and may increase the peak pavement temperature values as a result.

Overall, our findings suggest that pavement temperatures are strongly influenced by air temperatures. Therefore, the likelihood of vegetation management influencing road conditions more or less than our study site on a seasonal basis is generally based on average air temperatures. Because road conditions are generally established during short time periods relative to the length of an entire winter (operations take place over hours and days, not weeks and months) the short duration peak solar radiation and resulting pavement temperatures discussed in Chapter 2 may be more influential than this level of analysis can provide.

CLEAR ROADS
research for winter highway maintenance

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