



**BOLTON
& MENK**

Bolton & Menk, Inc.

Project 1054113/CR23-04
January 2026

Pooled Fund #TPF-5(479)
www.clearroads.org

Prepared by:

Douglas R. Klimbal
Water Resources
Bolton & Menk, Inc.

Carolyn J. Dindorf
Water Resources
Bolton & Menk, Inc.

January 2026

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

This guide is a deliverable of Clear Roads Project 23-04, “Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation”. The project webpage includes links to this Guide, the Final Report, the Shadowcast Model workbook and Technical Specifications Document, and a recording of the final project webinar. Visit <https://www.clearroads.org/project/23-04/>.

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation, Bolton & Menk, Inc., or the University of Minnesota. This report does not contain a standard or specified technique.

The authors, the Minnesota Department of Transportation, Bolton & Menk, Inc., or the University of Minnesota do not endorse products or manufacturers. Trade or manufacturers’ names appear herein solely because they are considered essential to this report.

Acknowledgements

The research team would like to thank the Clear Roads Technical Advisory Committee for their time and expertise in providing project input, document review, and comments on the tasks and deliverables.

- Aidan Neely (CT), co-chair
- Jessica Andrews (UT), co-chair
- James Morin (WA)
- Doug McBroom (MT)
- Joe Thompson (NY)
- David Gray (NH)
- Steve Kohler (AZ)
- Dan Whetzel (PA)
- Joe Huneke (MN)
- Rick Nelson (AASHTO)
- Tom Peters (MN)

We would also like to thank Jim Plemon (Senior Manager, Road Maintenance) and Matt Herzog (Highway Maintenance Foreman) with the Anoka County (MN) Highway Department for providing road sites to review and assistance in permitting the monitoring stations, as well as providing AVL data that enhanced our analysis.

The research team would like to thank the agencies that participated in the survey of vegetation management sites. Their willingness to provide information and data helped to expand the project findings.

- Gabriel Alvarado, Operations Superintendent, Arizona Dept. of Transportation
- Todd C Law, Director- Fleet, Vermont AOT
- Michael Russell, Asst. Snow and Ice Engineer, MassDOT
- Jason Allen, Maintenance Review/ Maintenance Noxious Weed Coordinator, Montana DOT
- Ryan, Maintenance Supervisor, Washington State Dept. of Transportation
- Gustave Nothstein, Vegetation Manager, Maine Department of Transportation
- Ryan Succheralli, Roadside Vegetation Specialist, PennDOT District 10
- Jessica Andrews, Winter Maintenance Methods Engineer, UDOT
- Carl Fedders, Transportation Systems Management & Operations, Michigan DOT
- Mindy B. Foresman, Maintenance Services Manager, PennDOT
- Todd Howard, Assistant County Engineer, Dakota County Highway

Thank you also to Hafiz Munir, project coordinator with MnDOT; and Greg Waidley, Clear Roads Administrator with CTC & Associates.

Table of Contents

Chapter 1: An Introduction to Winter Road Maintenance and Roadside Vegetation.....	1
1.1 Sustainable Operations: A complicated balance	2
1.2 Benefits of Solar Radiation	2
1.3 Where to Prioritize Sun Exposure.....	5
1.4 Other Benefits of Vegetation Management	6
1.4.1 Storm Resilience	6
1.4.2 Windbreaks	6
1.4.3 Enhanced Airflow	7
Chapter 2: Vegetation Management & Shade	8
2.1 Canopy Considerations for Winter Roads	8
2.1.1 Growth Habit	8
2.1.2 Seasonal Leaf Retention and Shade	9
2.2 Vegetation Management Practices for Winter Benefits	10
2.2.1 Sizing Management Zones	10
2.2.2 Clearcutting and Replanting	11
2.2.3 Selective Removal	11
2.2.4 Pruning	12
2.2.5 Timing Vegetation Management	13
2.3 Examples of Vegetation Management	14
Chapter 3: Methods for Prioritizing Vegetation Removal.....	20
3.1 Finding Shade-Prone Sites	20
3.2 Site Characterization & Data Collection	21
3.2.1 Direct Observation and Measurement	21
3.2.2 Digital Reality Capture using LiDAR or Photogrammetry.....	22

3.2.3 Public-Sector Elevation Data	23
3.3 Analysis Tools.....	24
3.3.1 Simple Methods	24
Geospatial Methods	29
3.3.2 Shadowcasting Model Workbook	30
3.4 Site Assessment Examples.....	30
3.4.1 US 395 in Washington, from MP 184-202.....	31
3.4.2 Pennsylvania Route 147, Segment 400.....	33
3.5 Conclusions.....	34
References.....	35
Appendix A Technical Specification for Shadowcast Spreadsheet Model.....	A
Appendix B Fundamentals of Shadowcasting Calculations	B

List of Figures

Figure 1. Example of pavement temperature differences and solar radiation differences observed during CR 23-04 field measurement.	3
Figure 2. A vegetation removal site in Montana, indicated by the operations staff during CR 23-04 research process.	6
Figure 3 growth habit of trees.	9
Figure 4 illustration of various pruning outcomes.....	12
Figure 5.Vegetation Management Example in Goshen	14
Figure 6. Vegetation management Example on Route 181 South.....	15
Figure 7. Vegetation Management Example on Route 181 North	16
Figure 8. Vegetation Management Example on Route 20 West	17
Figure 9. Vegetation Management Example from 606 Stafford Road, Mansfield	18
Figure 10. Vegetation Management Example from 10 Stafford Road, Mansfield	19

Figure 11. An image of a shade-prone road segment showing important measurements.....	21
Figure 12. World map of magnetic field declination.	22
Figure 13. Shadow lengths at latitude 47.5° N	25
Figure 14. Shadow lengths at latitude 45.0° N	26
Figure 15. Shadow lengths at latitude 42.5° N	27
Figure 16. Shadow lengths at latitude 40.0° N	28
Figure 17. Shadowcast modeling tool example of vegetation thinning and canopy setback.	32
Figure 18. Shadowcast modeling tool example for proposed clearcut from roadway.	33

List of Tables

Table 1. Pavement temperature differences between unshaded ($T_{unshaded}$) and shaded (T_{shaded}) sites from CR 23-04 field measurements.....	3
Table 2. Potential salt application rate differences based on pavement temperature differences between shaded and unshaded road segments during snowfall.	4
Table 3. Mean time to dry at the study sites during CR 23-04 field measurements.	5
Table 4. Canopy shade and shadow distance from the left and right side of the road in Washington.	31
Table 5. Monthly outcome summary of energy conditions blocked by canopy.....	32
Table 6. Canopy and shadow distance to the right of the road bearing in Pennsylvania.	33
Table 7. Monthly outcome summary for energy blocked by canopy.....	34

Chapter 1: An Introduction to Winter Road Maintenance and Roadside Vegetation

Forested regions of the United States are known for their beauty, their economic importance, the character they add to communities, and their vital role in supporting ecosystem integrity. A wide variety of wildlife lives in the forests, and some find roadside forests particularly useful. Large species such as deer use roadside vegetation for grazing and as a corridor for traveling. Small mammals such as wood mice use the vegetation as corridors and for refuge (Galantinho et al., 2022). In addition, trees and other plants provide habitat for bees, birds, and bats which help pollinate a variety of plants (Federal Highway Administration, 2016).

People living in, working in, and recreating in forested landscapes rely on road infrastructure. A 2003 study on ecological impacts from roads suggests that 5% of forests in the United States were within 42 meters (137.8 feet) of a roadway (Riitters and Wickham, 2003). A 2019 communication published by USGS suggests that among all the land cover changes that took place from 2001 – 2016, approximately half involved forest (USGS, 2019). Roadways are essential for supporting communities and regional economies in these landscapes, but they may also be seen as a disruption. As a result, maintenance programs that extend beyond the road shoulder and into the vegetation may be opposed.

Vegetation management is a decades-long process which looks disruptive at times, especially early on. Opponents may advocate for the trees but miss the benefits to the forests. Taking an informed approach to vegetation management near roadways results in more sustainable operations, safer roadways, and improved resilience of trees and shrubs near the roadway.

Much of the United States experiences freezing rain and snow during winter. Seasonal road maintenance in these regions means removing the snow and ice from pavement areas to support the flow of traffic. Whether the road cuts through miles of forest or runs briefly along a vegetated riverbank, certain aspects of snow removal are made dramatically more difficult in areas where the vegetation casts deep shadows onto the roads. The presence of slopes and curves through a wooded area makes it even more important to use whatever means necessary to remove ice and provide sufficient friction for drivers to maintain control. Deicing chemicals, especially road salt, are commonly used to provide safe driving conditions. Deicing materials are more effective in warmer temperatures, and allowing less moisture on the pavement reduces the need for deicers. These chemicals are generally reapplied many times throughout winter, which can create issues with corrosion and toxic effects on natural resources. Since tall vegetation growing close to the roads can limit pavement temperatures and promote moisture retention on the pavement, managing the roadside is an important sustainability and safety topic.

1.1 Sustainable Operations: A complicated balance

Winter operations, especially the use of deicing chemicals, can have a high cost to forests and natural areas as well as the communities connected to them. The materials themselves can be expensive. According to the Clear Roads Annual Winter Maintenance Survey, there were 6.7 million tons of solid rock salt used annually on state-maintained roadways over the 5-year period of winters beginning in 2019-2020. Most agencies also reported increasing per ton cost for purchasing salt during that time. Salt also has impacts on water resources, vegetation, soils, and infrastructure. Chloride toxicity to vegetation may have the most visible impact on roadside vegetation. Salt toxicity inhibits growth, browns leaf tissues, and causes cell death in plants (Deicing Products User Guide, 2025). The sodium content can also degrade soil mineral structure. The combined damage to vegetation and soil stability can increase rates of erosion on the road shoulder.

Chloride and other chemical deicers can also have impacts on aquatic ecosystems. The USEPA recommends a chronic exposure limit of 230 mg/L (EPA, 2024) which is commonly communicated as one teaspoon of salt contaminating five gallons of water. In waterways with chloride content above that concentration, freshwater organisms are likely to grow more slowly and have lower populations. As chloride accumulates in the water table, local wells may also become too salty to drink. The infrastructure costs detailed in “The Real Cost of Salt Use” estimate that damages related to corrosion, pavement weathering, and vegetation range from 10 – 50+ times greater than the per-ton cost of salt (Minnesota Pollution Control Agency, 2014).

1.2 Benefits of Solar Radiation

The sun’s energy reaching a pavement surface has a substantial effect on the temperature and, as a result, the persistence of moisture. The findings detailed in this section are based on field measurements taken as part of the Clear Roads project 23-04. The measurements show that road conditions improve quicker on road segments with good sun exposure compared to shaded areas. They also show an opportunity for reducing the need for maintenance materials like salt. A significant part of the difference between shaded and unshaded areas can be explained by the sun’s influence on pavement temperatures. Figure 1 shows the difference in solar radiation and pavement temperature over two days between a shady site and an unshaded site on an asphalt paved County highway in Minnesota. Pavement temperatures in the sun were as much as 20°F higher than in the shade. Pavement temperature differences were most apparent between about 11:00 a.m. and 2:00 p.m. While no maintenance was being done on these days, the implications for deicer use between the two segments is substantial. If crews were called out to spot treat in these conditions, as an example, the effective types and amounts of deicers used would be dramatically different depending on sun exposure.

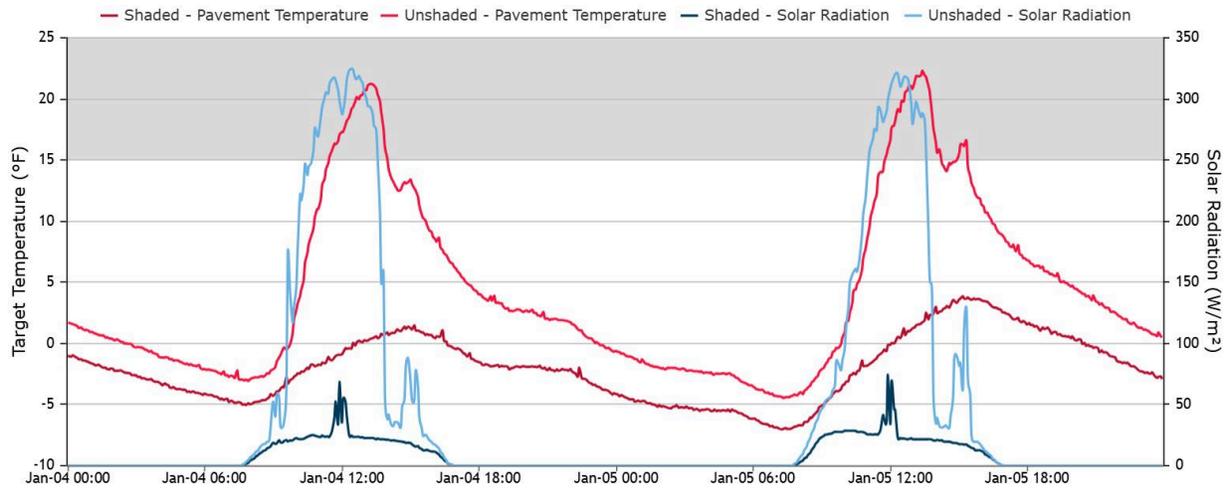


Figure 1. Example of pavement temperature (left y-axis) differences and solar radiation (right y-axis) differences observed in early January at unshaded and shaded sites during CR 23-04 field measurement.

A warm pavement will transmit energy into its surroundings, including compacted snow. This transfer of heat creates a thin film of meltwater along the contact area between ice and pavement. The formation of that film can undercut compacted snow, loosen the compaction, and allow traffic action or snow removal equipment to clear the road. This effect is enhanced by deicer residuals already on the road surface, making maintenance operations more effective in areas where sunlight reaches pavement.

Table 1. Pavement temperature differences between unshaded ($T_{unshaded}$) and shaded (T_{shaded}) sites from CR 23-04 field measurements.

Month	All Winter Days			Days with Snowfall		
	Median Difference (°F)	Mean Difference (°F)	# Days $T_{unshaded} > T_{shaded}$	Median Difference (°F)	Mean Difference (°F)	# Days $T_{unshaded} > T_{shaded}$
December	1.04**	1.64	25/25	1.44**	2.22	4/4
January	2.99**	4.59	31/31	1.91**	3.47	4/4
February	4.57**	7.21	28/28	3.00**	4.62	6/6
March	5.76**	8.74	31/31	2.76**	6.14	3/3
April	0.94**	1.11	12/28	1.26	1.55	2/2

** Indicates statistically significant differences.

Table 2. Potential salt application rate differences based on pavement temperature differences between shaded and unshaded road segments during snowfall.

<u>Salt Rate Difference</u> (lbs. per lane-mile)*	<u>Time %</u>	<u>Duration</u> (hours)	<u>Note</u>
200	0.10%	0.5	<p>More than one third of the time when maintenance operations are taking place, salt savings may be achieved in unshaded areas based on pavement temperature comparisons. When this was the case, the average rate difference was more than 50 pounds per lane mile.</p> <p>These findings are based on field measurements taken on a rural highway in central Minnesota during the 2024-2025 winter maintenance season.</p> <p>Pavement temperature is less likely to differ when clouds and precipitation prevail.</p>
175	0.25%	1.3	
150	0.29%	1.4	
125	6.0%	29.7	
75	2.8%	13.8	
50	12.1%	59.6	
25	12.5%	61.3	
0	65.9%	324.4	

***Based on Pre-Wet NaCl Recommendations in “Material Application Methodologies Guidebook” Table 1. Application Rate Guidelines for Light Snow (<1 in/hr., <4" in 24 hrs.)**

In addition to potentially limiting the need for salt use while maintenance operations are taking place, sun exposure of the pavement has also been linked to improving the safety performance of pavements passively. Following snowfall, shaded areas can remain slippery because of traffic compacting snowfall and bonding the ice to pavement. During the same study period referenced in Table 1, comparisons in road condition were made visually between unshaded and shaded road segments.

The study findings suggest that pavements in **unshaded areas typically cleared 5.3 hours sooner than shaded areas** after snowfall, with no difference in maintenance activity between the two locations set one mile apart on the same stretch of road. A slight difference was also observed after rain events.

Overall, the impact on pavement temperature is consistent and significant whether looking at the whole winter season or just looking at snow events. While the differences may seem small, they are significant and add up.

Table 3. Mean time to dry at the study sites during CR 23-04 field measurements.

	Number of Events	Mean Time to Dry (hours)		Additional time to dry for shaded sites (hours)
		CR01 (unshaded)	CR02 (shaded)	
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

1.3 Where to Prioritize Sun Exposure

All across the nation, road maintenance agencies and forested communities must find the balance between aesthetically pleasing roadways and safe travel conditions in winter. A survey of winter agencies showed that there was substantial interest in using the benefits of sunlight in a variety of regions – not only forests, but in the mountain deserts and plains as well. That said, some of the most well-represented cover types were curving roads through forested hills in the Mountain West and Northeastern United States. The agencies participating in the survey conducted roadside vegetation removal and recognized areas where more could be done to enhance road conditions.

Among respondents to our survey about vegetation removal:

- More than 90% reported that improved winter performance was an intended outcome of vegetation removal.
- 57% of sites were located in deciduous cover, 31% were located in mixed canopy cover, and 12% were in evergreen cover. This is despite the fact that studies show the deepest shade is cast by evergreen cover.
- Most of the vegetation removal efforts took place in late fall or early winter.

Among respondents to our survey about problematic, shade-causing vegetation:

- The most common location reported for problematic vegetation was for eastbound traffic on the right shoulder, where vegetation blocks the southern sky. The next most common responses were southbound right and northbound right shoulders.

Note that all respondents operate in the United States. These findings should translate well across the global northern hemisphere, and north would be swapped for south when evaluating a site in any latitudes south of the equator.

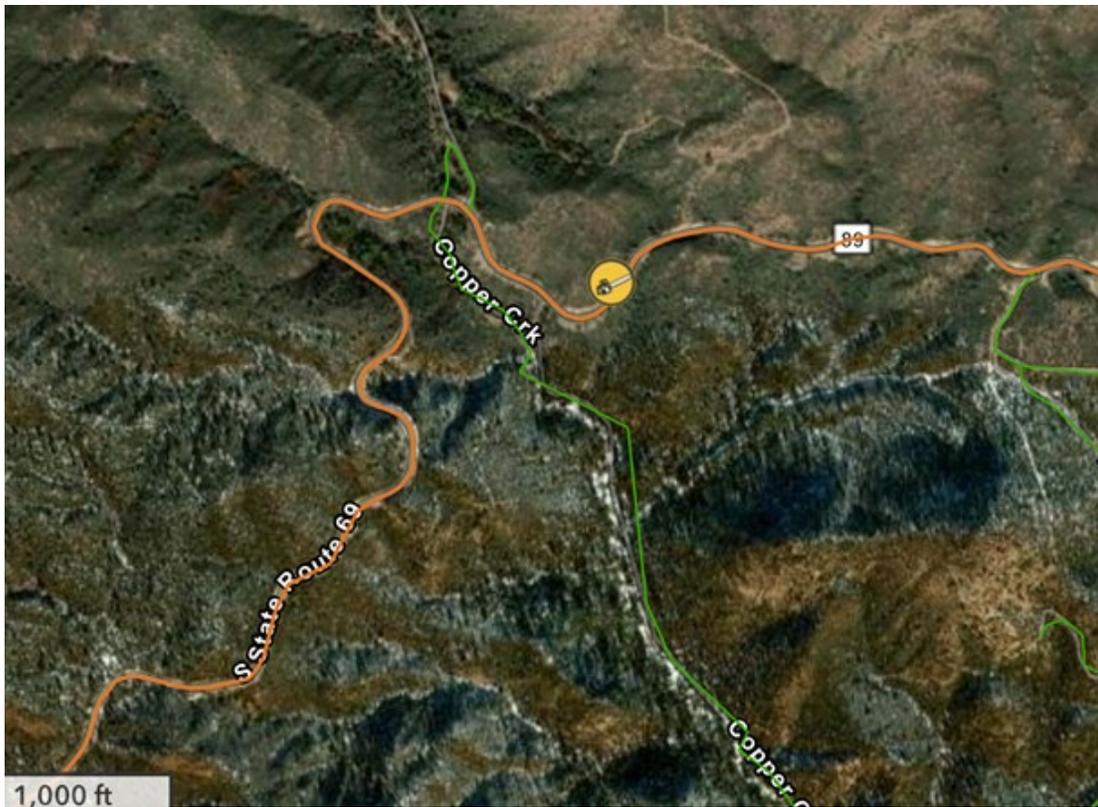


Figure 2. A vegetation removal site in Montana, indicated by the operations staff during CR 23-04 research process.

1.4 Other Benefits of Vegetation Management

Not all winter condition benefits that may be observed because of vegetation management are caused by increased sun exposure. Researchers have identified other areas which operations professionals suggest can lead to increased safety, reduced cost, and more sustainable practices.

1.4.1 Storm Resilience

Managing vegetation to prevent blowdowns and improve ice storm resilience is already a widespread practice along transportation and utility corridors. Consider how “[Stormwise](#)” management programs can be included in the type of vegetation management discussed in Chapter 2 and Chapter 3.

1.4.2 Windbreaks

When the wind hits vegetation, the wind is slowed. The vegetation acts as a windbreak. Windbreaks can be intentionally planted as living snow fences or can be structural fences (Kocur-Bera & Dudzinski, 2015) or a managed natural area. Large trees and vegetative screening are valuable ways to reduce wind across roadways. Decreasing the wind speed at the surface reduces debris and particles blowing across roads and impairing driving conditions. At the same time, tree and shrub plantings too near to roadways

can create unintentional catch points for airborne particles like snow to drop onto the roadway or shoulder and accumulate. Many design tools, such as the Minnesota Drift-Free Roads Design Tool, exist to aid in drift-free roads design.

Blowing snow is particularly important to consider where large open fields or ice-covered bodies of water become a source of friable snowpack during high wind conditions. Vegetation management strategies discussed in Chapter 2 should take this into account when determining an appropriate clear zone size. If the vegetation stand is thin, it may create substantial shading while not inhibiting blowing snow. If it is too close to the roadway, the drifts may accumulate on the pavement.

1.4.3 Enhanced Airflow

Air mixing can be healthy for vegetation growth, reducing the chance for mold growth that commonly afflicts trees where air stagnates.

Anecdotal evidence supports the idea that enhanced circulation may also benefit the pavement surface during winter. Where air at the pavement surface does not mix, it can become more saturated with moisture. Cold air has limited water content, so if the air above a wet or icy surface is saturated the moisture on the surface is much more likely to stay put. This not only results in lower surface friction on wet or icy pavement, but chronic moisture retention on pavement can also accelerate weathering from freeze-thaw and dissolution of the pavement materials.

Chapter 2: Vegetation Management & Shade

To realize the benefits of solar radiation on winter roads, it is essential to maintain a zone along the roadway where vegetation is managed to promote sunlight penetration and airflow. Maintaining this zone may mean using a combination of approaches to vegetation management (clearcutting, replacement planting, selective removal, pruning) over a planned multi-decade period. The appropriate management practices to implement will vary based on the location and layout of the roadway, the variety of vegetation present, and the width of right of way.

A note on vocabulary: the verbiage in this section breaks trees into four categories based on the seasonality of leaf drop and the overall shape of the crown. These terms are:

- Excurrent Growth – strong central trunk/leader with side branches, creating a narrow, conical shape.
- Decurrent Growth – trunk splits into spreading leaders with not clear dominance, creating a spreading crown shape.
- Evergreen – leaf shedding is not seasonal.
- Deciduous – leaf shedding is seasonal, and the whole canopy is shed.

While phrases like “conifers” are commonly used to describe pine, spruce, and fir, this manual would describe these species as excurrent evergreens because these terms will directly relate to the methods that might be employed for healthy roadside vegetation management.

Vegetation management also presents an opportunity for long term operations sustainability by controlling the age distribution of trees in the right of way.

2.1 Canopy Considerations for Winter Roads

The role of vegetation near roadsides is well-understood by many professionals in the industry. Ground cover supports soils and prevents erosion by intercepting precipitation and holding soil in place with roots. Most of this section will focus on tall vegetation which can cause shade.

2.1.1 Growth Habit

Tree growth is influenced by its species and age, as well as response to its environment. Most immature trees have a strong central tendency. A leading shoot will develop lateral branches, and, over the course of multiple growing seasons, those laterals will grow their own branches. However, as a tree matures it may develop lateral branches which are equal in stature to the original leader. If these codominant branches define a tree’s canopy shape, the growth habit is called “decurrent.” Decurrent growth is often seen as characteristic of mature deciduous canopy, though some species of deciduous trees will retain a

EXCURRENT



DECURRENT

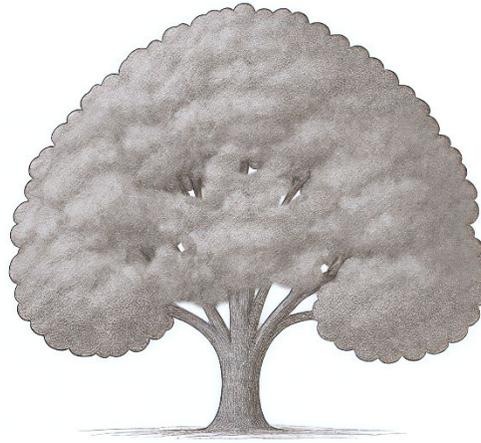


Figure 3 growth habit of trees.

strong central tendency through maturity. Wherever that central tendency can be observed and lateral branches are less prominent than a tree's leader and trunk, the growth is known as "excurrent."

Trees with excurrent growth have a central leader and are often evergreens or conifers. When a leader is pruned on a tree with excurrent growth it is much more likely to develop codominant stems and suffer disease and premature failure. Notable deciduous trees with excurrent growth habits include Pin Oak and Birch.

Retaining the overall tree shape is important for proper pruning of any tree, especially when mature, for both aesthetics and tree health.

2.1.2 Seasonal Leaf Retention and Shade

A tree species' tendency to retain leaves through winter will be a key factor in understanding how much light and airflow is allowed through the canopy, both of which have an influence on winter pavement conditions. The field measurements taken in this study, as well as evaluations done for an ongoing UMN/MnDOT study on Trunk Highway 34, have found that dense evergreen canopy can block 50% or greater of sunlight compared to unshaded sections of roadway (UMN & MnDOT, 2025). In this study, segments where the shade-causing canopy was mixed or deciduous had greater light penetration by roughly 10% and 20%, respectively. As a result, anticipate that vegetation management in evergreen forests will demand somewhat higher priority than in deciduous forests along an otherwise similar road segment.

2.2 Vegetation Management Practices for Winter Benefits

Maintaining a roadside for more than just safety is already widely practiced for preventing wind damage from severe storms in the warm season ([Ward et al, 2017](#)) or enhancing sight lines for drivers. Practices include clearcutting, selective removal, and pruning. This section will discuss each of these primary methods, as well as considerations to sun angle, dimensions of the roadway, and potential winter outcomes.

There are many published guides that include recommendations for vegetation management practices, and you may learn more from local transportation agencies, forestry associations, or arborists. One such publicly accessible guide is “Best Practices Handbook for Roadside Vegetation Management” published in 2008 by Minnesota Department of Transportation. The handbook suggests developing an integrated roadside vegetation management plan to justify operations by quantifying a range of potential benefits.

2.2.1 Sizing Management Zones

One widespread practice in roadside management is establishing a clear zone where obstructions that may be a hazard to runoff vehicles are removed. A 2015 benefit-cost study focused on managing safety options on low volume roads determined that tree removal was the safest and most beneficial option to improve safety compared to leaving the obstructions or installing a guardrail (Lichtenberg et al, 2015). There are many technical guidelines used to evaluate clear zone sizing for crash prevention purposes, especially in high speed or high traffic volume area.

At the time of publication, there are not established practices regarding how wide zones for clearcutting, selective removal, thinning or pruning ought to be for the purposes of enhancing winter road conditions. Tools presented in Chapter 3 may provide some insight, but operations decisions are likely to change agency-to-agency based on conditions, resources, and priorities.

For improving winter road conditions, we may also consider establishing a clear zone (or, where vegetation is selectively removed or thinned, a management zone) for enhancing light penetration through the canopy. A few important considerations for determining an appropriate clear zone width for benefiting winter maintenance may be:

- sun angle in winter
- orientation of the roadway
- overall height and density of canopy
- obstruction from local terrain, such as hills

In combination, these factors determine the potential for solar radiation to influence pavement conditions. For example, a 2025 study of vegetation shading in Minnesota selected a 75-foot clearcutting zone width from the road centerline and an additional 90-foot width of vegetation thinning (U of M & MNDOT, 2025). A traditional clear zone for safety alone on this stretch of road would be 65

feet from the road edge. These enhanced dimensions were based on a target solar elevation angle of 26°. Considering the right-of-way width on this road segment was 250 feet, there is substantial opportunity to fine-tune operations on this ENE-bearing road segment.

For more discussion of determining appropriate management zone size and priority through observation and analysis, go to Chapter 3.

2.2.2 Clearcutting and Replanting

In densely grown roadside forests where little vegetation management has taken place, there is a tendency for trees of similar age to compete by growing tall and slender. This growth is less resilient to severe weather than a tree which has been allowed to branch out and stands grow thick with trunks that completely block light.

Clearcutting unmanaged stands of trees when they encroach on the desired clear zone will improve safety, sight lines, and light penetration. Clearcutting will also provide a disturbance which promotes the growth of weedy species, including vines and invasive shrubs. Mechanical and chemical control of these species may be required. New cover should be established intentionally to reduce dominance of those weedy species, prevent soil loss, and plan for long-term ease of maintenance.

The growth of smaller trees, shrubs, and grasses can be emphasized to limit the long-term need for tree removal near the roadway, but retaining the forest cover likely will mean reintroducing some larger tree species. Species selected should be reflective of the region, though maintenance professionals should consider the potential benefit of introducing deciduous trees to develop a mixed forest cover next to the roadway rather than wholly evergreen canopy. The Stormwise program suggests young stands should be introduced at a rate of 75 – 100 trees per hectare, though a target for a sustainable mature stand of trees is half as dense.

2.2.3 Selective Removal

Beyond the clearcut zone, it may be beneficial to thin a stand of trees by identifying individuals to remove. One of the best reasons to do this may be making room for younger trees in the stand to develop stout growth and wider roots, making them more wind-firm, and reducing the overall stand height and density over time. For a mature stand, 30-50 trees per hectare is recommended in the Stormwise guidance. In a stand grown from replanting, selective removal should be done every 10-20 years as the stand matures.

Selective removal is a useful approach to keep existing trees in a mature stand, even if age and height are homogenous. If a dense mature stand is thinned in a single step to the target 30-50 trees per hectare, trees left standing are much more likely to blow down. The Stormwise guidance suggests a generational approach when keeping mature trees. First remove trees with cavities or other structural defects, trees with small crowns, or those suffering from perennial disease. The next round of selective

removal may occur as much as 10-15 years later, which allows the mature trees to have developed more wind-firm growth.

2.2.4 Pruning

Pruning is a well-developed field in forestry and there is already a wealth of literature on the topic. This document will only provide a summary of how common pruning approaches may be used to enhance the benefits of solar radiation on the roadway. The Federal Highway Administration's "Vegetation Control for Safety" (Eck & McGee, 2008) recommends *at a minimum* that dead limbs and overhanging branches be removed in the fall so that snow and ice accumulation does not cause them to fall on the roadway.

Pruning live wood on existing trees can lead to more resilient growth, promote light penetration, and increase airflow. When timed appropriately, pruning can also be used to slow the growth of trees to reduce the time needed for maintaining the clear zone in the long term. Pruning should always be done in a way which preserves the overall shape of the tree, so it's important to understand the stand's age and the growth habit of the trees present.

- "Heading back" a limb results in compact growth creating dense shade but may be used to influence the location of lateral branching, repress less successful branches, or to encourage upright growth of spreading branches. It is better to practice heading back limbs only on young trees and branches.
- "Thinning," which involves removing whole branches at the collar, should be used in all other instances to retain a tree's natural aesthetic, promote airflow and light penetration, and more evenly distribute weight along branches or tree trunks to support resilient trees. Extensive thinning out can also be used to "drop crotch" a mature tree which reduces the canopy height in a healthy

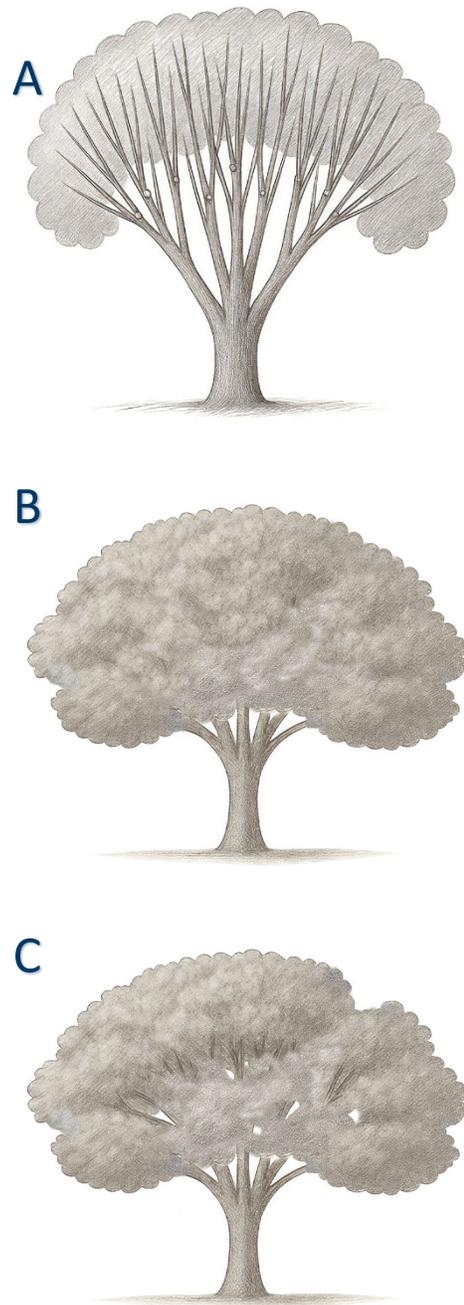


Figure 4 illustration of various pruning outcomes. A. Heading limbs on a mature tree induces dense regrowth with crossing limbs. B. A mature tree with dense canopy. C. The same tree with increased light penetration and airflow after intentional thinning.

manner (Harris, 1975). For proper development of stem taper, no more than half of a tree's foliage should be in the upper third of a tree's height.

- "Elevating" or "raising" canopy, or removing limbs up to a certain height, is a common approach to thinning to improve sight lines. It is especially common on excurrent evergreens where lower branches frequently die off after seasons of receiving too little light or airflow. This strategy may be successful if trees are mature enough. If elevating the canopy will result in more than 25% of the overall leaf area being removed, or if more than 50% of the tree's remaining leaf area will be in the uppermost 1/3rd of the tree, then the tree may not recover or may be prone to blow-down. If this is the case, consider less severe pruning or whole removal.

Pruning can get complicated but may be done efficiently by easing decision making. For example, since there are often multiple candidates for branch selection, remove ones with the most inwardly grown branches, those where shoots grow directly upright into the crown, or those where the bark has been rubbed through.

Pruning practices to avoid include "topping" trees to remove the entire upper portion, or "lion-tailing" where branches have all but the furthest laterals removed. These change the overall structure of the tree, and so are easy to see once learned. When removing limbs, cut just beyond a branch collar to avoid damaging a tree's trunk. If a limb is large, use the three-cut method (undercut, top cut through the limb, stub cut to finish) to prevent bark tearing. Also avoid using tools that are overdue for maintenance. Cutting tools should be sharp and cleaned with reasonable care both for worker safety and to avoid creating wounds to the tree that will be slow to heal.

2.2.5 Timing Vegetation Management

The timing of pruning can have a dramatic effect on how a tree responds. In general, pruning of live wood should be done at a time of year when the species present are not susceptible to disease. As a result, there is much guidance that focuses on pruning while vegetation is dormant, especially late fall and early spring.

Pruning near roadsides should target times of year where the growth of more vigorous trees, or evergreen species which cast more substantial shade, can be slowed. To slow the growth of plants and ease the burden on maintenance operations and reduce the leaf area for the longest time, pruning should be done in mid-to-late summer. However, this is also a time of year where some tree species are more susceptible to disease, so pruning should be targeted based on that restriction.

Proper vegetation management is not a once-and-done practice but, with proper planning and follow-through, maintenance efforts in a single corridor can effectively be spread out over years between major efforts.

2.3 Examples of Vegetation Management

The following pictures were submitted by Aidan Neely, Clear Roads project co-chair, to illustrate examples of roadside vegetation management. They are paired by location, with the first photo showing the outcome and the second photo showing initial condition.



Figure 5. Vegetation Management Example in Goshen. Note the selective removal of mature evergreens and thinning of understorey.

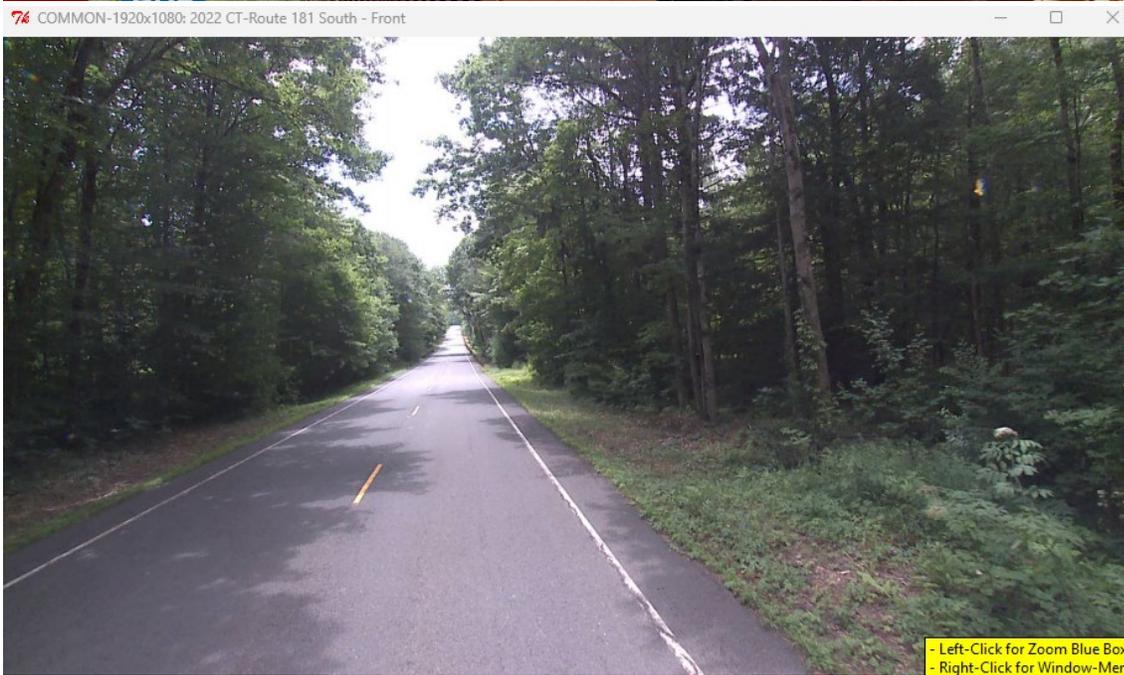


Figure 6. Vegetation management Example on Route 181 South. Note the consistent clear zone width.



Figure 7. Vegetation Management Example on Route 181 North. Note how the right shoulder shows a thinner understory, while the left shoulder was clear cut to a consistent width.



Figure 8. Vegetation Management Example on Route 20 West. Note the dramatic change in light penetration.



Figure 9. Vegetation Management Example from 606 Stafford Road, Mansfield. Note the removal of understory encroaching on the roadway.



Figure 10. Vegetation Management Example from 10 Stafford Road, Mansfield. Note how the removal of overhanging vegetation from the slope above the road surface benefit sight lines as well as light penetration.

Chapter 3: Methods for Prioritizing Vegetation Removal

Vegetation management along a whole corridor or highway network is no simple task. It will take substantial resources and time, so it is important to identify priority sites early in the process. As discussed in Section 1.3, shade-prone sites may have a variety of canopy types nearby, but typically they are shaded from the south during a significant portion of winter days. Hills, curves, and intersections make traction and braking capability even more critical, so these locations may take priority over locations where acceleration is less important.

Travelling along a transportation corridor during winter may be the most effective way to evaluate where shade is creating problems most frequently. Rather than driving every mile of a highway network, one approach may be to develop an inventory of shade-prone sites or sites prone to icy conditions due to shade based on the feedback of seasoned winter maintenance professionals. Once you have your list of sites to investigate, you will want to characterize and analyze these sites to prioritize them.

Determining priorities among multiple sites may prove to be a complicated task. To provide a consistent method for assessment using widely available software, **this manual is accompanied by a Shadowcasting workbook built in Excel** (see section 3.3.2). The workbook is designed to analyze a site's existing and proposed sun exposure conditions.

For technical documentation, refer to Appendix A.

3.1 Finding Shade-Prone Sites

Equipment operators with a few seasons of experience will be some of the most valuable sources of information for identifying route segments prone to shade. A wealth of sites can be collected if an organized effort is made. Using a paper map to have staff members markup sites for assessment will be one easy way to do this, but it may also be helpful to create a digital interface for staff to confirm the site location using aerial imagery.

Alternatively, agencies with well-organized records of winter operations may start with route-by-route analysis or hotspot analysis using Automated Vehicle Location (AVL) records. Shade-prone sites are likely to have an increased need for spot treatment. Calling up AVL records for the last 1-2 route completions after a season's worth of storms could provide a good indication of where extra spreading or plowing was not being done at intersections, which are easy to identify on a map. There are a variety of reasons why extra winter maintenance efforts may be done, so identifying these sites may be followed up by confirmation from winter maintenance staff.

3.2 Site Characterization & Data Collection

Important considerations when evaluating a road segment will be those which impact sun exposure of the pavement. The most static among these are: the local road orientation and width, site elevation, and geolocation. Latitude is of particular interest since it will determine the solar elevation throughout winter. National Oceanic and Atmospheric Administration has a variety of Solar Calculators available that calculate solar elevation based on date(s) and geolocation.

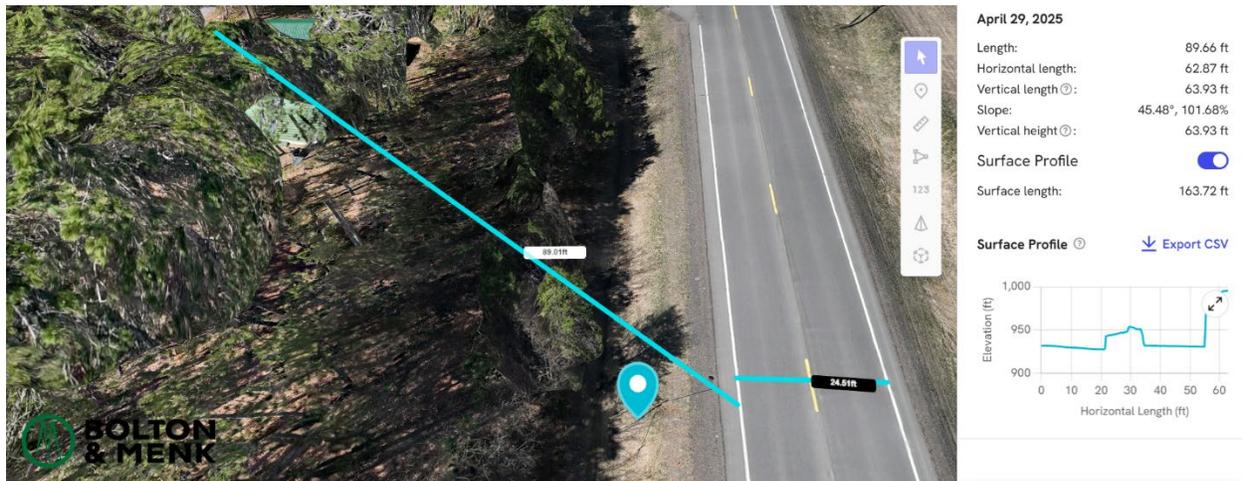


Figure 11. An image of a shade-prone road segment showing important measurements.

More dynamic factors will relate to the shade-causing canopy. Make an evaluation for each road shoulder, determining the distance from the fog line to the most prominent portion of the canopy. This may be the edge of canopy or some portion of the crown. You want to identify the height of the horizon created by the canopy relative to the pavement surface. If there is a topographic feature creating some horizon, you will want to note that separately since that may be an important consideration to set expectations of how helpful vegetation management can be in that location. It's helpful to imagine this road segment as being characterized by a single point. In reality, of course, roads often meander and a stand of trees will not create a sheer wall with a consistent height. Averages will be good enough during this exercise.

These measurements can be completed using a combination of the approaches detailed in the following subsections.

3.2.1 Direct Observation and Measurement

Determining many of these parameters of interest can be done with skill using common tools in forestry or surveying, especially a compass, inclinometer, or laser rangefinder, and measuring wheel, or even tablets or mobile devices which have distance sensing capabilities. Once the site is reached, take note of the road's general bearing. This can be done with a standard compass or even a mobile device. Be sure to account for magnetic declination (the angle between true north and magnetic north) which varies by +/- 15 degrees from 0 across the United States.

US/UK World Magnetic Model - Epoch 2025.0 Main Field Declination (D)

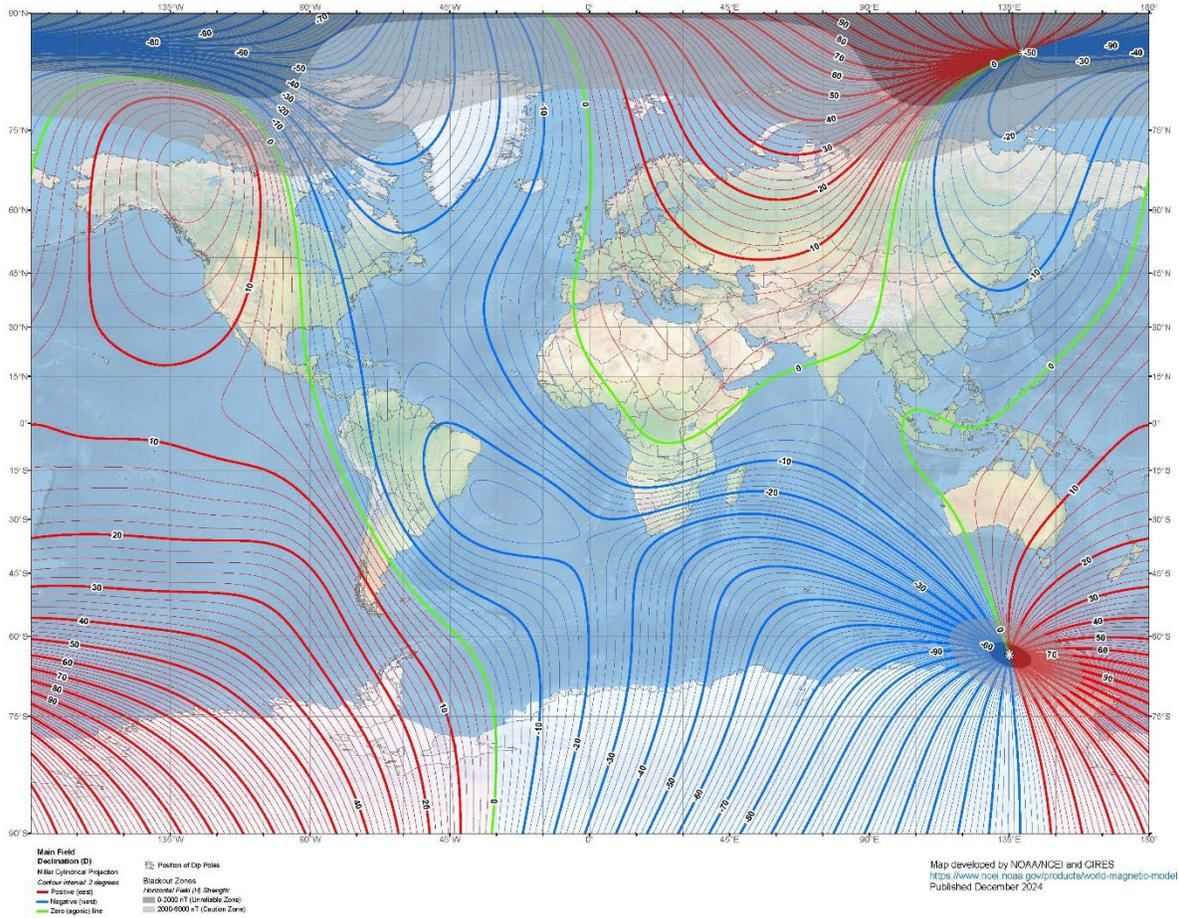


Figure 12. World map of magnetic field declination.

Next, use an inclinometer to measure (at a right angle to the road) the elevation angles of the highest portion of the canopy horizon, the angle from the road to the base of the trees, and, if applicable, the highest portion of the topographic horizon. You may have to sight through vegetation for the topographic measurement. Then, use a wheel or tape to measure the distance from the fog line or road edge to the base of shade-causing vegetation. Alternatively, a digital rangefinder can be used to approximate the horizontal distance which will make solving the shadowcasting problem much more straightforward. Finally, take note of the overall canopy type. At minimum, characterize the vegetation as deciduous, mixed, or evergreen.

3.2.2 Digital Reality Capture using LiDAR or Photogrammetry

Advancements in reality capture technology allow many of these measurements to be taken using Unmanned Aerial Systems (UAS, commonly known as “drones”) or by ground-based vehicle systems.

Either of these approaches can create high resolution, high precision datasets for analyzing solar radiation, as detailed in section 3.2.1.

While this may be the most powerful approach for creating a dataset to analyze, there are limitations and lessons yet to be learned. For example, aerial imagery may not resolve the height of treetops, especially in mixed or deciduous forests. Ground-based imagery will have great resolution for distances to lower portions of canopy, but true LiDAR systems may be required to resolve stand density further away from the road edge. In either case, the resulting point cloud may have gaps that lead to inconsistencies in analysis unless resolved, and having access to the right software packages or technical experts is a requirement. Regardless, the potential rigor of this approach should not prohibit agencies with the appropriate tools and expertise from trying it out. At the very least, the use of these tools can lead to high confidence in consistent measurement along road corridors.

3.2.3 Public-Sector Elevation Data

There are some opportunities to evaluate sites without directly visiting them. Agencies with their own survey programs may have elevation data products organized in their own databases. Short of that, consider exploring the United States Geological Survey 3D Elevation Program for high-quality topographic data extending throughout the United States, including Alaska, Hawaii, and some US Territories. Note the year/date of collection. Road alignments or local conditions may differ between the time of analysis and the time of collection. Even seasonal variations may be significant since the presence or absence of leaves in forest areas may affect the quality of data.

There are also many publicly accessible services where ground elevation assessment tools are accessible. These may be government agencies or private companies developed for a variety of purposes, including natural resources, conservation, and recreation. Examples shown in Section 3.3 utilize viewsheds and sightline analysis using a free webtool developed for backcountry exploration and mountaineering called “UpToWhere.” It is one example of many tools which can be used to fill the needs of evaluating terrain near a vegetation management site.

It is far less common for these tools to include non-ground heights. This is due to the ease of processing LiDAR data for ground elevation compared to more difficult canopy elevations. There have been methods developed for evaluating the height of structures based on images from services like Google Street View or other online mapping tools with ground-level images. Data collection and computational methods are changing frequently. Anyone relying on this approach should benefit from reviewing methods that are relevant at the time of assessment.

Referring to elevation data can provide powerful insights as to the distance and height of ground and non-ground objects that might affect the outcome of shadowcasting analysis. As long as non-ground surfaces (i.e., trees) are shown in the dataset, the analyst can approximate distance to and height of canopy from the road surface without sending any equipment or personnel to evaluate the site in person. Local topographic features can also be included to a reasonable extent.

3.3 Analysis Tools

Once measurements are collected, the vegetation manager(s) will have to decide what level of analysis is desired for the sites being evaluated. This may range from selecting representative date/time combinations to estimate shadow overlap on the roadway from existing or proposed vegetation to analysis of solar radiation accumulated by specific sections of the road segment during subsets of the season or the season as a whole. Comparing shadow overlap or solar radiation values can help quantitatively order the potential impact of shading across all sites identified in the highway network, making priorities much clearer and helping clearly communicate potential benefits with local residents.

3.3.1 Simple Methods

Take any given point on the globe, choose a specific date and time, and the approximate direction and height of the sun along the horizon can be determined. Solar calculations have been practiced since the times of Mesopotamians and Ancient Egyptians. Greek mathematicians and Islamic scholars were some of the first to formalize geometric understandings of the solar patterns. As a result, there are many accurate methods for predicting sun angles that are quite simple using modern tools.

Since solar radiation is greatest at the surface when the sun is at its greatest height, evaluating shadow overlap on the roadway during solar noon (or, for North-South oriented roadways, around 10am and 2pm) on a handful of days in winter may provide some understanding of how pervasive shade may be. Consider using a website or spreadsheet reference, such as NOAA's browser-based Solar Calculator or "Solar_Calculations_day" spreadsheet calculator, to determine solar elevation and direction at selected dates and times.

Determining the shadow overlap on a surface at a specific date and time is a short, multi-step process using straightforward trigonometry. It may be practical for getting a quick understanding of a site's potential or for communicating first principles, but the limitations of this approach make it impractical for program management. For a discussion of these fundamentals, review Appendix B. Geospatial Approach.

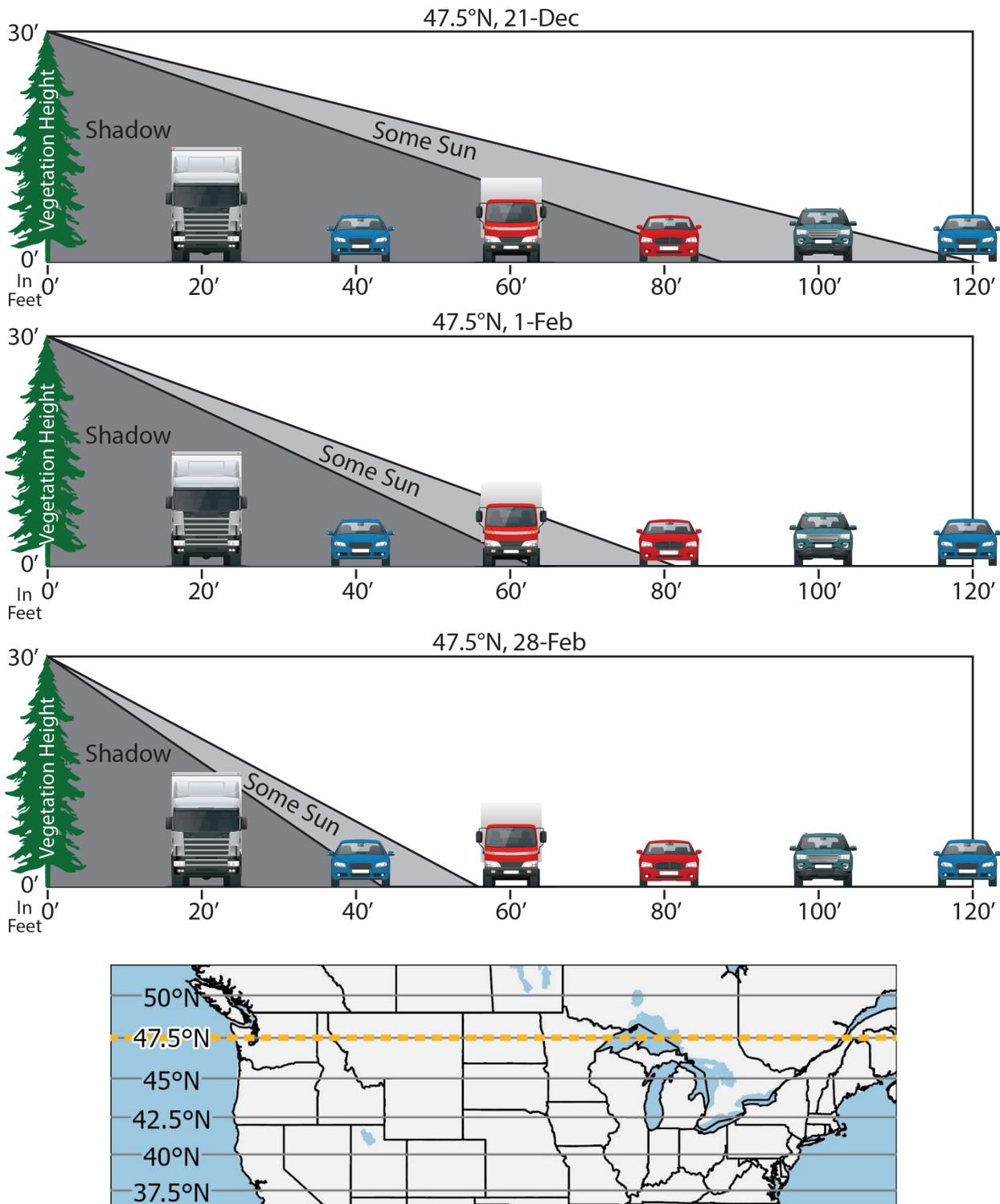


Figure 13. Shadow lengths at latitude 47.5° N on Winter Solstice, February 1, and February 28. The light, gray-filled section represents areas that are shaded in morning and evening but receive sun during midday hours. The dark, gray-filled section represents areas which receive no direct sun at any time of the day. The map shows the referenced latitude.

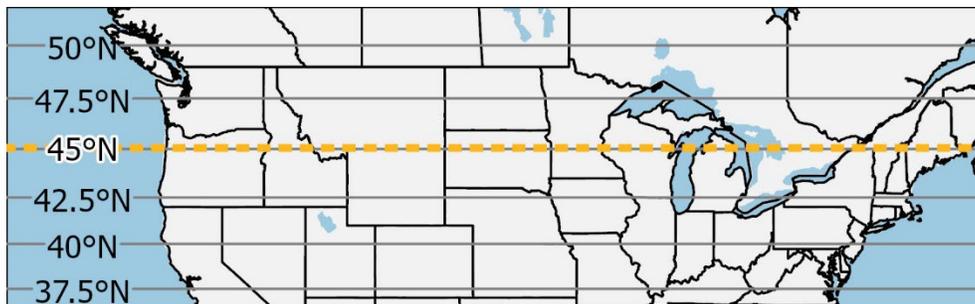
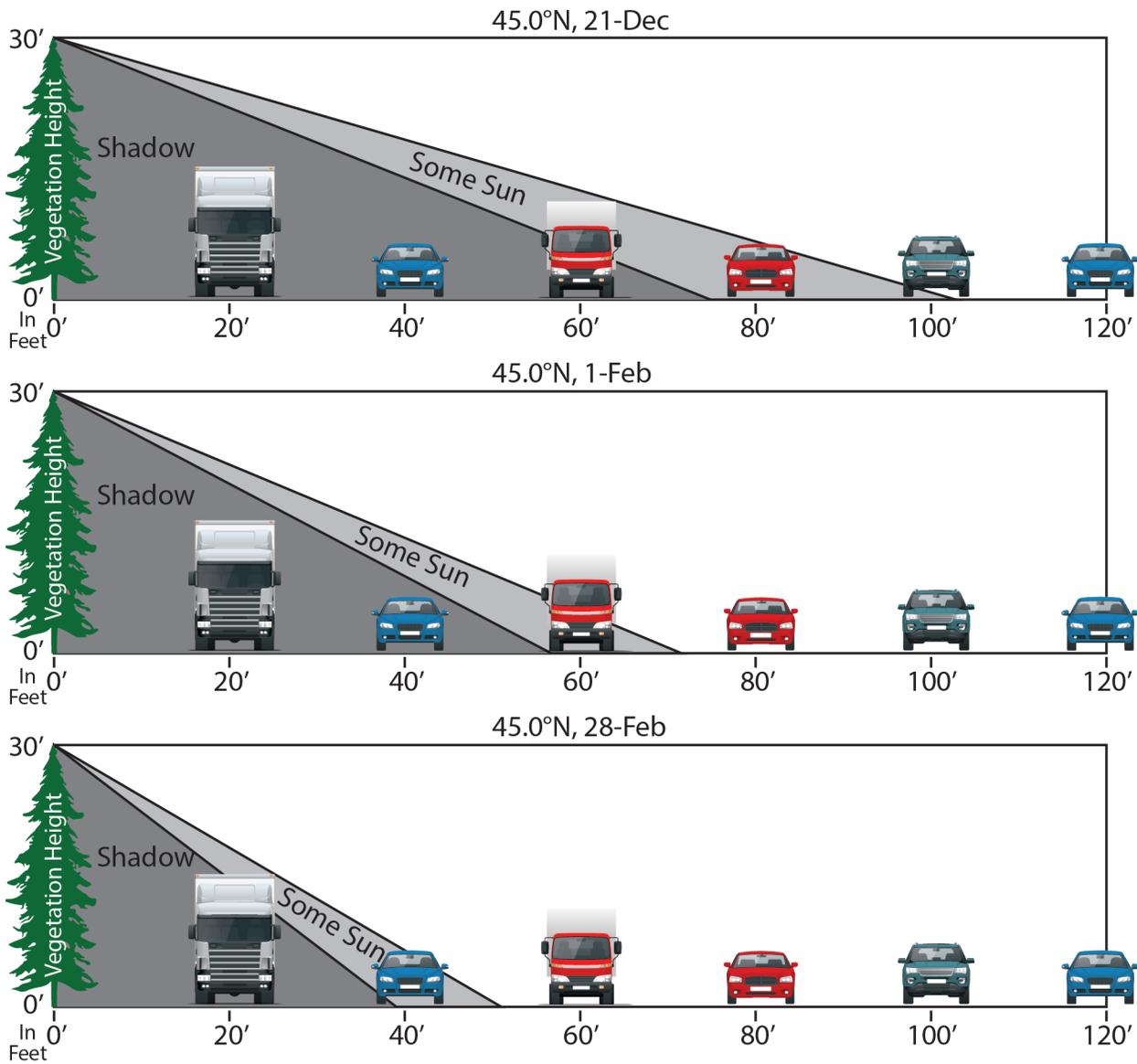


Figure 14. Shadow lengths at latitude 45.0° N on Winter Solstice, February 1, and February 28. The light, gray-filled section represents areas that are shaded in morning and evening but receive sun during midday hours. The dark, gray-filled section represents areas which receive no direct sun at any time of the day. The map shows the referenced latitude.

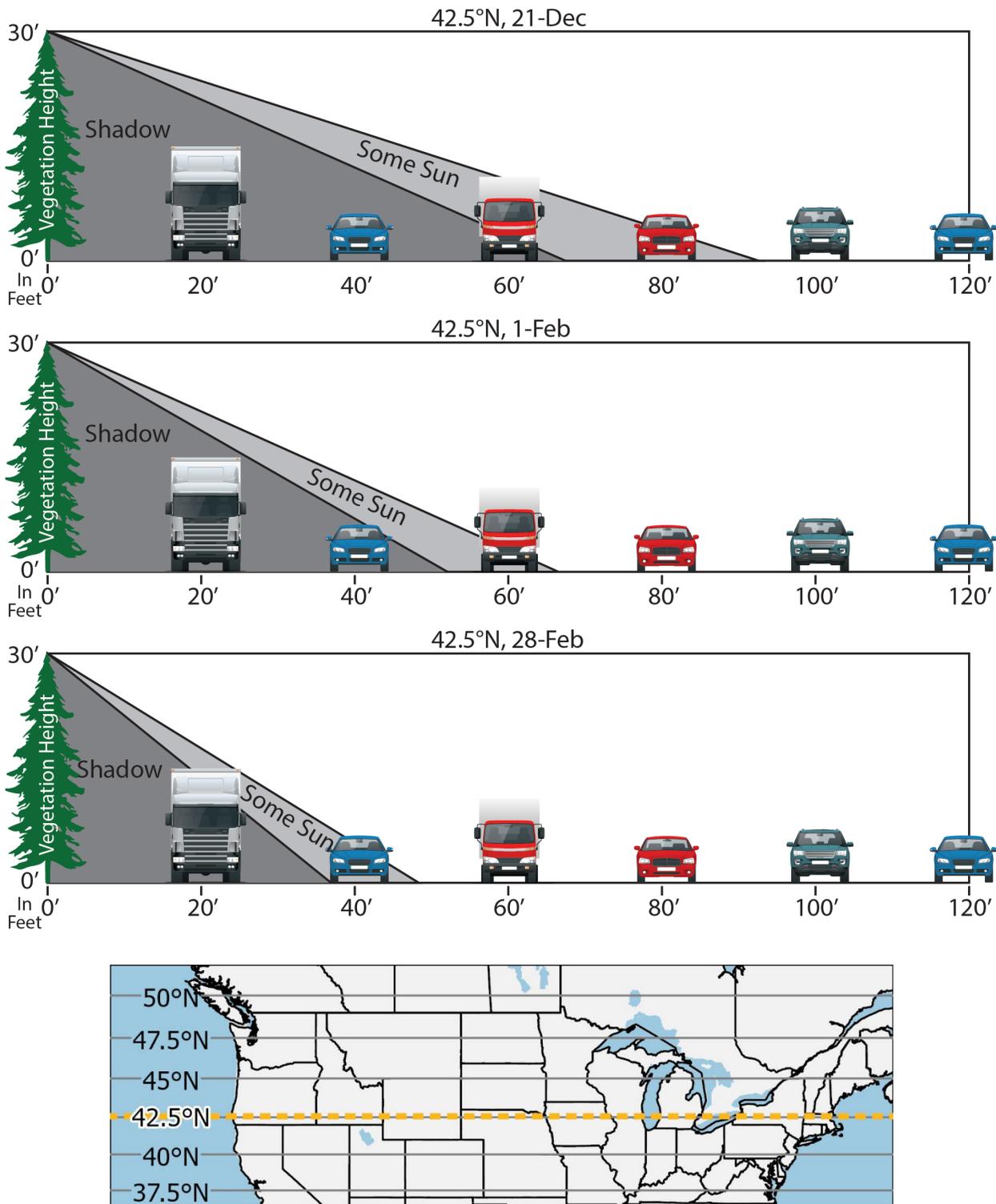


Figure 15. Shadow lengths at latitude 42.5° N on Winter Solstice, February 1, and February 28. The light, gray-filled section represents areas that are shaded in morning and evening but receive sun during midday hours. The dark, gray-filled section represents areas which receive no direct sun at any time of the day. The map shows the referenced latitude.

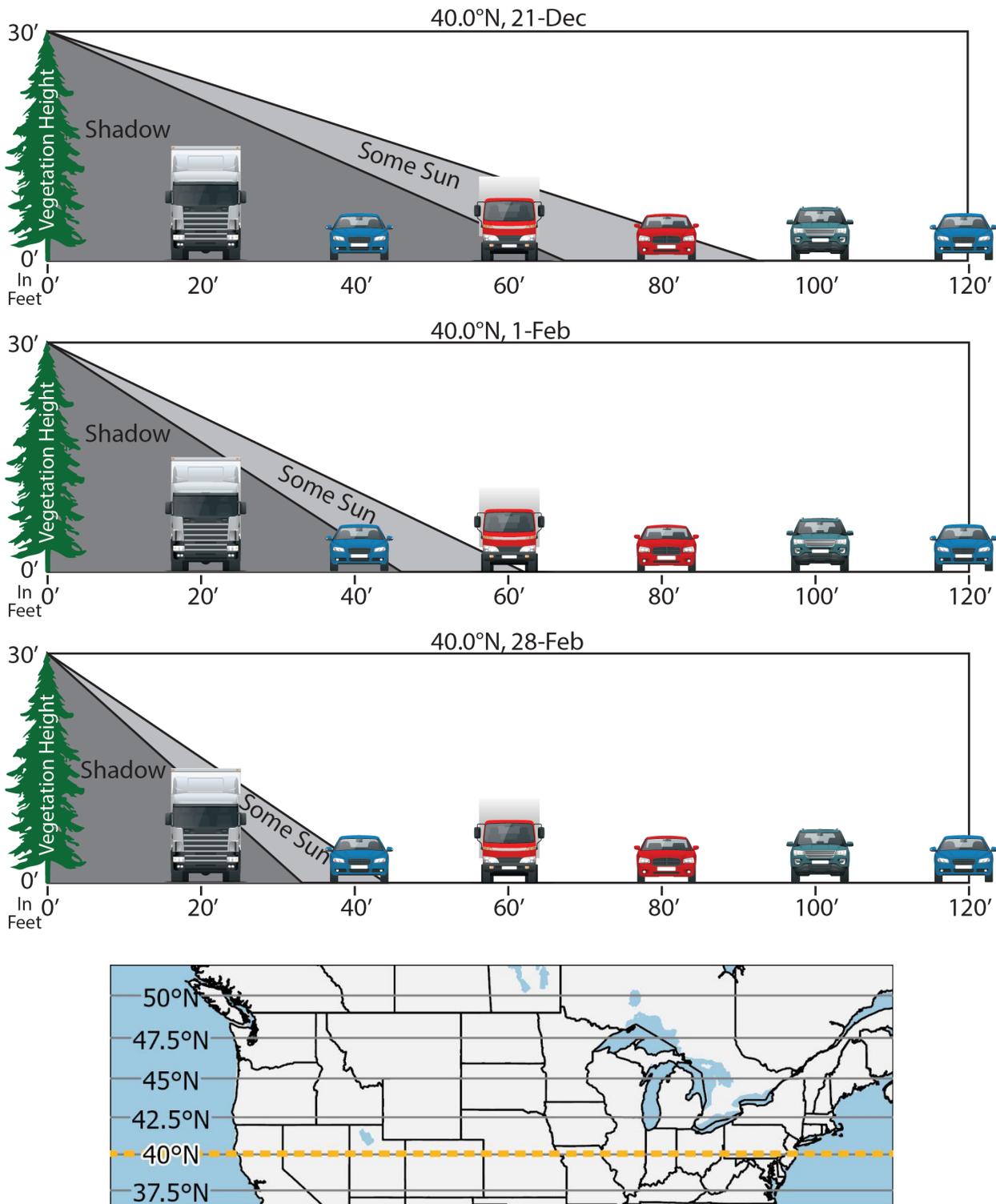


Figure 16. Shadow lengths at latitude 40.0° N on Winter Solstice, February 1, and February 28. The light, gray-filled section represents areas that are shaded in morning and evening but receive sun during midday hours. The dark, gray-filled section represents areas which receive no direct sun at any time of the day. The map shows the referenced latitude.

Geospatial Methods

There are a wide range of geospatial tools developed for desktop analysis to clearly delineate viewsheds, create astronomically-accurate 3D models of landscapes at specific dates and times, or analyze solar radiation at a location based on user-selected sky conditions and surface elevations. While many of these have been developed for site planning, streetscape visualization, or solar panel placement, these could all be adapted to evaluating a road segment's winter performance as it relates to potential benefits of sun exposure. Whole books are dedicated to documenting and critically assessing these methods, so this manual will only present a summary.

The most commonly used software tools for this approach rely on ArcGIS Geoprocessing Tools in the Spatial Analyst toolbox. The Solar Radiation toolset provides analysis tools that can be applied to feature classes (points or polygons) or raster (cell value-based) data.

At minimum, a digital elevation model and/or digital surface model must be prepared to make use of the solar radiation tools. While a digital elevation model is more readily available, these typically only represent the land elevation. A digital surface model should incorporate elevated elements, like tree canopies. The geoprocessing tools in the solar radiation toolset will allow the user to define a time period of assessment, frequency of assessment within that time period (such as hourly or daily) to allow for more refined analysis and assumed sky conditions. The software then considers the location and time periods to predict sun angles, and uses the landscape's slope, aspect, and surface elevations to predict solar radiation measured at the surface.

3.3.1.1 Considerations for using the Geospatial Modeling Approach

This method is powerful, readily scalable, and relatively easy to iterate. However, it's computationally intensive. Users unfamiliar with GIS tools may find the learning curve to be very steep. With that in mind, some recommended best practices are listed here. Keep in mind that these tools are supported by substantial development teams responding to user needs and issues that may arise as other hardware and software systems are updated over time, so guidance provided in this guide has been generalized.

- 1. Limit the scope of analysis.** A vegetation-shaded road segment may be dozens of miles long and suffer from impaired road conditions for many winter months. As the scope of evaluation adds up, the potential for errors to arise compound. In these scenarios, geoprocessing may make progress quickly at the beginning before slowing to a rate where the end of the evaluation is never reached.
- 2. Clearly define the evaluation area.** These tools are adaptable. It is likely necessary to use a digital surface model that covers a wide area, but keep in mind that the final output for solar radiation only needs to cover the extents of the road surface. For example, the Raster Solar Radiation tool for ArcGIS Pro includes a "Input Analysis Mask," which defines the location where analysis occurs. The tool still refers to the entire input surface to predict solar exposure, but it will only write output data values within the mask area. This can dramatically speed up or simplify the processing.

3. **Modify default or optional input values.** Some defaults will help the model run efficiently but may not provide the level of detail desired within the model output. Defining subset time intervals may be desired to see daily radiation changes, but this is likely to be nondefault. Other default values may cause the process to error if the hardware cannot support analysis. For example, these tools may be configured to rely on CPU or GPU. If insufficient resources are allocated from either CPU or GPU, the model will consistently error out.
4. **Be aware of data limitations.** Digital representations of physical objects and landscapes aren't perfect. Tree canopies are particularly complex, and one can expect data to be rougher or smoother than real world. While observed solar radiation values may differ from modeled values based on this exercise, road segments that have been observed and modeled using the same approach can be compared with great detail and high confidence.

3.3.2 Shadowcasting Model Workbook

The Shadowcasting Modeler is a specialized workbook designed to help users evaluate the benefits of vegetation management strategies. It works by allowing the user to simulate various scenarios for clear zone layout and density, then estimates solar radiation outcomes.

This tool is intended to provide a reference for roadway maintenance agencies to predict how vegetation management decisions may impact road conditions. The result is a data-driven discussion point that accounts for cleared right-of-way spacing, road orientation, elevation, local topography, and canopy height and density. An existing condition can be compared to a proposed condition based on estimates of solar radiation differences, and the likely difference can be tracked directly back to potential road surface benefits. This allows maintenance professionals and members of the general public to have a shared understanding of the benefits of vegetation management for solar radiation.

For more information, review the “Technical Specification for Shadowcast Model” in Appendix A.

3.4 Site Assessment Examples

Two examples of potential vegetation management sites have been used in this section. Each of these were contributed by road maintenance professionals to support Clear Roads Project CR 23-04. In these examples, the sites were assessed using the locations described in the survey. Each of these road segments are multiple miles long, but aerial imagery was used to assess specific points where shading was expected to be most severe. A combination of other tools was then used to identify appropriate site characteristics that could be used as inputs for the Shadowcasting Model Workbook. The section ends with a discussion of the results.

3.4.1 US 395 in Washington, from MP 184-202

Geolocation: 48.640410, -117.522295

Elevation: 2,463 ft

Approximate Road Bearing: 157.5°

Shade: Both Sides

Existing Conditions:

Table 4. Canopy shade and shadow distance from the left and right side of the road in Washington.

Shoulder A	(Right of Road Bearing)	Height of Canopy above Road Surface (ft)		Distance from Canopy Edge to near fog line (ft)	Sunlight Blocking Effect	Shadow is Longest When Sun Shines from...	Terrain Shadow Elevation (° from Horizontal)
			Thickness of Growth				
		80	Mixed Canopy	30	0.4	Western Sky	3
Shoulder B	(Left of Road Bearing)	Height of Canopy above Road Surface (ft)		Distance from Canopy Edge to near fog line (ft)	Sunlight Blocking Effect	Shadow is Longest When Sun Shines from...	Terrain Shadow Elevation (° from Horizontal)
			Thickness of Growth				
		80	Mixed Canopy	30	0.4	Eastern Sky	3

Results: While this road segment has some steep segments of road cut through soils, the slope likely will not obstruct sunlight. However, it does dramatically increase the height of the moderate density evergreen canopy, which is estimated to have a sunlight blocking effect of 0.4, similar to more dense stands of deciduous trees. A viewshed analysis was also done at this site to evaluate the likelihood of distant mountain ranges from blocking sunlight but, when evaluated from the road surface, none were more significant than the 3° horizon elevation provided by the road cut.

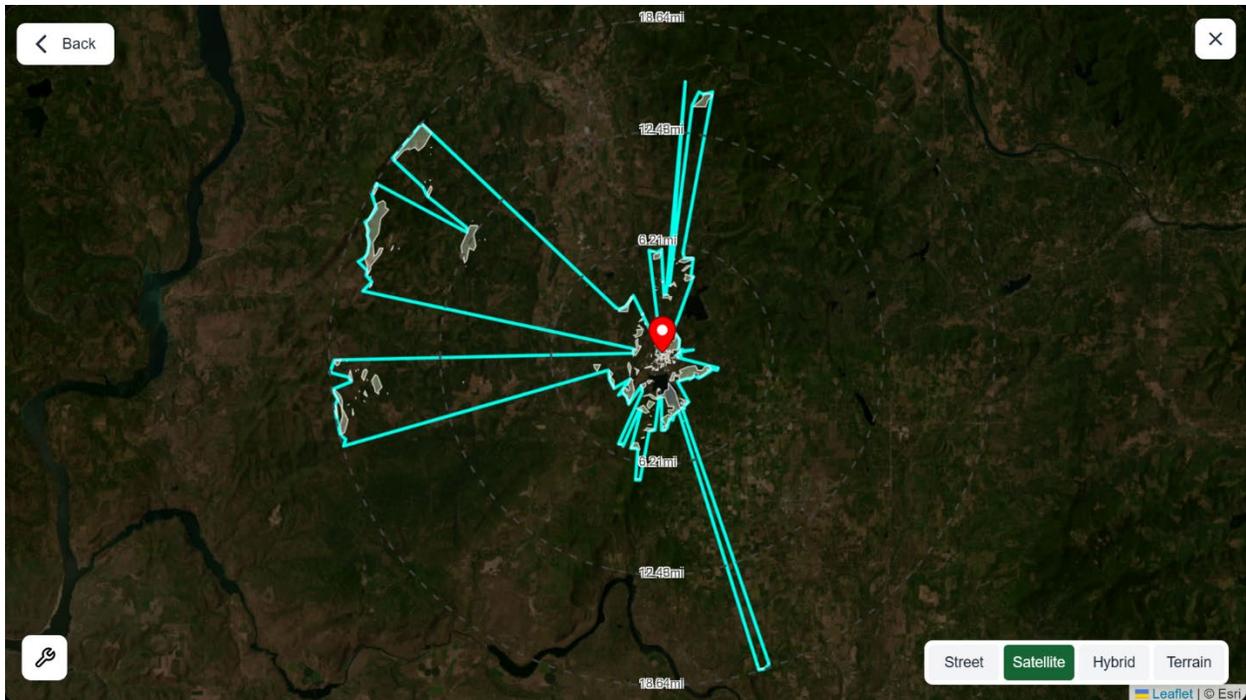


Figure 17. Shadowcast modeling tool example of vegetation thinning and canopy setback.

The results for existing conditions and proposed conditions have been modeled using the shadowcast tool. In this example, the proposed condition suggests both thinning of vegetation and increasing the canopy setback from 30 feet to 60 feet.

Table 5. Monthly outcome summary of energy conditions blocked by canopy.

5. Monthly Outcome Summary	Solar Energy	Total Unobstructed Energy (Wh/m ²)	Existing Condition Energy (Wh/m ²)	Energy Blocked by Existing Canopy	Proposed Condition Energy (Wh/m ²)	Energy Blocked by Proposed Canopy
	December	40,540	32,150	20.7%	37,340	7.9%
January	51,710	41,790	19.2%	48,010	7.2%	
February	82,250	69,100	16.0%	77,590	5.7%	
Season Total	174,500	143,040	18.0%	162,940	6.6%	

The proposed condition change will increase sun exposure in all winter months and should lead to substantial improvements in safety and reduced need for winter maintenance.

3.4.2 Pennsylvania Route 147, Segment 400

Geolocation: 40.846504, -79.518807

Elevation: 447 feet

Approximate Road Bearing: 67.5°

Shade: One-sided

Existing Conditions:

Table 6. Canopy and shadow distance to the right of the road bearing in Pennsylvania.

Shoulder A	(Right of Road Bearing)	Height of Canopy above Road Surface (ft)		Distance from Canopy Edge to near fog line (ft)	Sunlight Blocking Effect	Shadow is Longest When Sun Shines from...	Terrain Shadow Elevation (° from Horizontal)
		Thickness of Growth					
		65	Deciduous Canopy	0	0.3	Southern Sky	35

Results: The site is located between a river and a steep escarpment. Web analysis of local elevation showed that the terrain itself would block sun angles lower than 35° above the horizon.

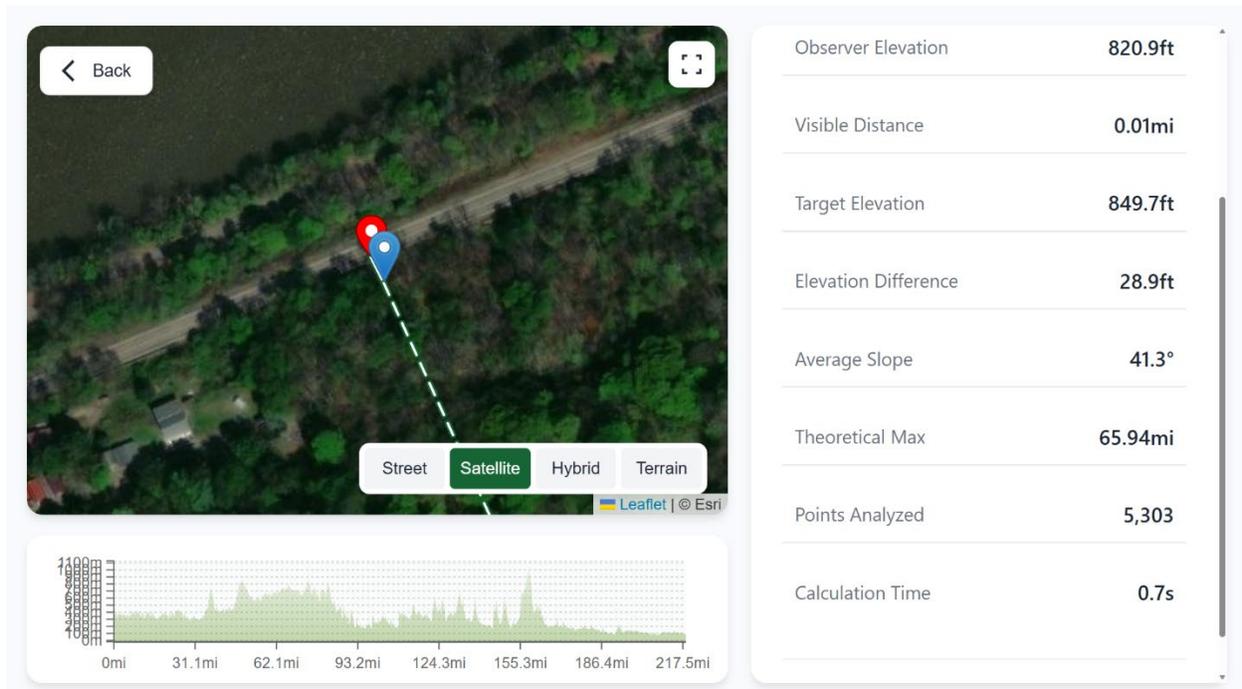


Figure 18. Shadowcast modeling tool example for proposed clearcut from roadway.

The results have been modeled using the shadowcast spreadsheet model. A proposed change is included, where the deciduous canopy which overhangs the roadway is clearcut to 50 feet from the edge of the road.

Table 7. Monthly outcome summary for energy blocked by canopy.

5. Monthly Outcome Summary	Solar Energy	Total Unobstructed Energy (Wh/m ²)	Existing Condition Energy (Wh/m ²)	Energy Blocked by Existing Canopy	Proposed Condition Energy (Wh/m ²)	Energy Blocked by Proposed Canopy
	December	-	-	-	Terrain Shade	-
January	-	-	-	Terrain Shade	-	Terrain Shade
February	33,660	33,660	27,140	19.4%	33,660	0.0%
Season Total		33,660	27,140	19.4%	33,660	0.0%

In this scenario, we see that the terrain obstruction will block sunlight during the months of December and January regardless of the vegetation management approaches used. The clearcutting distance will provide solar radiation enhancements in February. Vegetation management should still improve road conditions during December and January based on the close proximity of existing vegetation to the roadway, but the benefits will not be related to sun exposure.

3.5 Conclusions

Very little information on vegetation management related to solar radiation is available. This guide uses some existing information, information gained from an ongoing MnDOT study in northern Minnesota, and data collected for this project along with a literature search, to provide recommendations for vegetation management to increase solar radiation. The Guide was created in hopes of helping transportation agencies reduce shade and icy conditions and decrease potential crashes associated with those conditions. Both basic and more complex methods are presented for identifying problem shaded areas, determining the desired width of the clear zone, and identifying the strategy or strategies to use for managing vegetation in that area.

References

Clear Roads Project CR 23-04. In progress.

Clear Roads. (2025). *Annual survey of state winter maintenance data*. Retrieved from <https://www.clearroads.org/winter-maintenance-survey/>

Dindorf, C., Fortin, C., Asleson, B., and Erdmann, J. (2014). *The Real Cost of Road Salt Use in the Twin Cities Metropolitan Area*. Wq-iw11-06bbFortin Consulting, Inc. prepared for Minnesota Pollution Control Agency.

Eck, R. W., & McGee, H. W. (2008). *Vegetation control for safety: A guide for local highway and street maintenance personnel* (Rev. Aug. 2008, Report No. FHWA-SA-07-018). U.S. Department of Transportation, Federal Highway Administration, Office of Safety. Retrieved from <https://highways.dot.gov/media/14381>

EPA. (2024). *National Recommended Water Quality Criteria – Aquatic Life Criteria Table*. Environmental Protection Agency. Accessed July 03, 2025. <https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table>

Federal Highway Administration. (2016). *Noteworthy practices: Roadside tree and utility pole management* (Section 3). Washington, DC: U.S. Department of Transportation. <https://highways.dot.gov/safety/rwd/provide-safe-recovery/noteworthy-practices-roadside-tree-and-utility-pole-management/3>

Galantinho, A., Santos, S., Eufrazio, S., Silva, C., Carvalho, F., Alpizar-Jara, R., & Mira, A. (2022). *Effects of roads on small-mammal movements: Opportunities and risks of vegetation management on roadsides*. *Science of the Total Environment*, 837, 155743. <https://doi.org/10.1016/j.jenvman.2022.115272>

Harris, R. W. (1975). *Pruning fundamentals*. *Arboriculture & Urban Forestry*, 1(12), 221–226. Retrieved from <https://doi.org/10.48044/jauf.1975.055>

Johnson, A. M. (2008). *Best Practices Handbook for Roadside Vegetation Management*, Minnesota Department of Transportation, St. Paul, MN, Report no. MN/RC 2008-20.

Klimbal, D., Fortin, C., & Payette, L. (2025). *Deicing Products User Guide*. Report 2025RIC09. Minnesota Department of Transportation. Retrieved from <https://mdl.mndot.gov/flysystem/fedora/2025-08/2025RIC09.pdf>

Kocur-Bera, K., & Dudzinska, M. (2015). *Roadside Vegetation – The Impact on Safety*. Engineering for Rural Development. Jelgave, 20.-22.05.2015. Retrieved from <https://www.researchgate.net/profile/Katarzyna-Kocur->

[Bera/publication/282680798_Roadside_vegetation_-_The_impact_on_safety/links/5620ccce08aed8dd19405dc5/Roadside-vegetation-The-impact-on-safety.pdf](#)

Lechtenberg, K. A., Stolle, C. S., Faller, R. K., & Schrum, K. D. (2015). *Cost-effective safety treatment of trees on low-volume rural roads*. *Transportation Research Record*, 2472(1), 194–202.
<https://doi.org/10.3141/2472-22>

National Oceanic and Atmospheric Administration. (n.d.). *Solar calculator*. NOAA Global Monitoring Laboratory. Retrieved from <https://gml.noaa.gov/grad/solcalc/>.

Riitters, K.H. & Wickham, J.D. (2003). *How far to the nearest road?* *Frontiers in Ecology and the Environment*, 1: 125-129. [https://doi.org/10.1890/1540-9295\(2003\)001\[0125:HFTTNR\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2003)001[0125:HFTTNR]2.0.CO;2)

University of Minnesota. (n.d.). *Minnesota drift-free roads design tool*. Blowing Snow Control Tools. <https://snowcontroltools.umn.edu/design-tool>.

University of Minnesota (UMN) & Minnesota Department of Transportation (MnDOT) (2025, April 25). *Effect of Tree Shade on Winter Maintenance Operations*. Webinar, Center for Transportation Studies. Retrieved from [CTS Webinar: Effect of Tree Shade on Winter Maintenance Operations - YouTube](#).

UpToWhere. (n.d.). *Online viewshed calculator*: Free line-of-sight analysis tool. Retrieved from <https://www.uptowhere.com/>

U.S. Geological Survey. (2019, May 20). *New land cover maps depict 15 years of change across America*. U.S. Department of the Interior. Retrieved from <https://www.usgs.gov/news/national-news-release/new-land-cover-maps-depict-15-years-change-across-america>.

Ward, J. S., Worthley, T. E., Degnan, T. J., & Barsky, J. P. (2017). *Stormwise: Integrating Arboriculture and Silviculture to Create Storm-Resilient Roadside Forests*. P. 119-132 in Proceedings of the 20th Central Hardwood Forest Conference. USDA Forest Service Gen. Technical Report NRS-P-167. Retrieved from <https://research.fs.usda.gov/treesearch/53765>

Appendix A

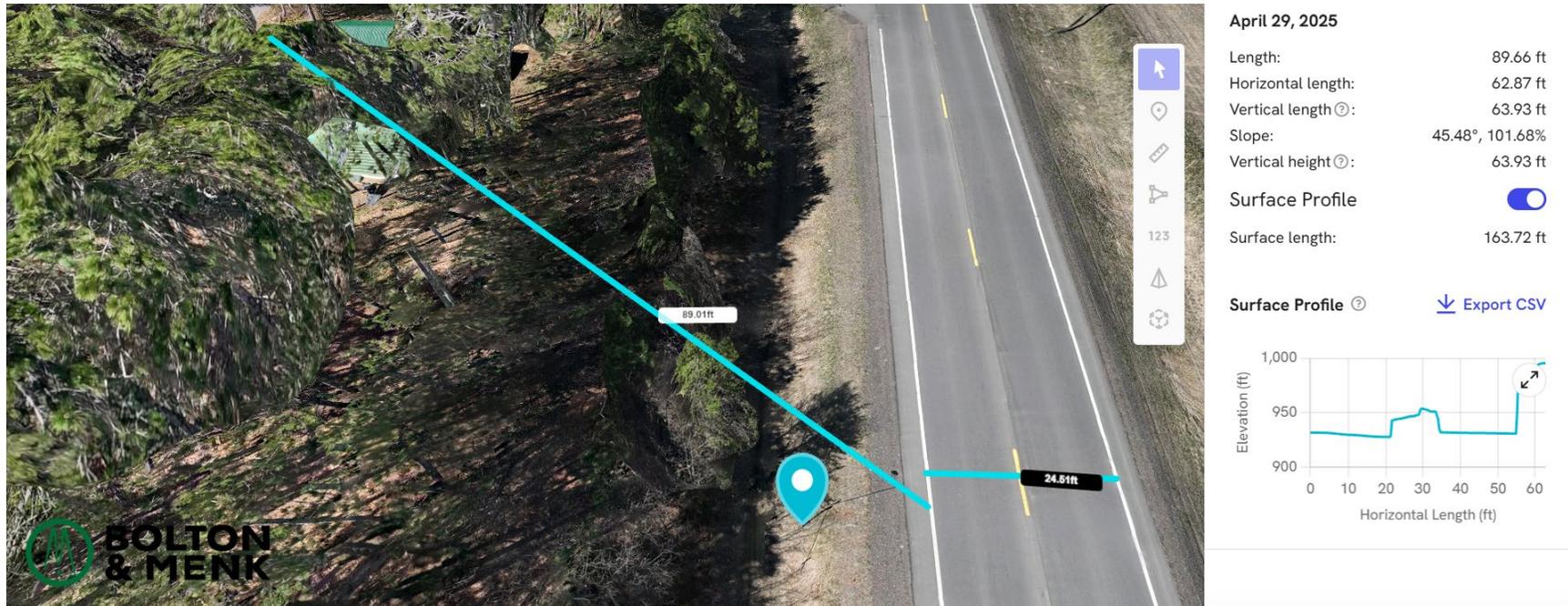
Technical Specification for Shadowcast Spreadsheet Model

Data Product of Clear Roads Project 23-04, “Using Vegetation Management Practices Near Roads to Leverage the Benefits of Solar Radiation”

Overview:

This Excel workbook is designed to model and approximate the effects of roadside vegetation and other structures on solar radiation reaching road surfaces. It integrates site-specific inputs, vegetation characteristics, and solar position calculations to estimate shading effects and energy loss due to obstructions.

Lat/Long: 45.3846680, -93.2915611
Northing: 1198217.3 US ft
Easting: 2806702.8 US ft
Elevation: 928.32 US ft
NAD83(2011) / Minnesota South (ftUS) (US survey foot)



A 3D visualization of a shade-prone site based on drone photogrammetry. The image is annotated with necessary inputs for the Shadowcast Model.

How to Use this Workbook

As you update the values in the “Setup” table, the workbook is automatically set to update the solar calculations. However, to get updated outputs for a shadowcasting scenario, you must refresh queries using the data tab. This allows for a series of more complicated computations to take place at a single time and keep the workbook from crashing.

Functionality:

The workbook supports dynamic updates via "Data > Refresh All" to recalculate shading and energy metrics based on updated inputs. Queries and formulas utilize the 'Params' table to simulate shading effects and quantify energy losses due to vegetation and terrain. Outputs include weekly and monthly summaries of shaded road proportions and net solar energy received.

Use Case:

Designed for transportation and environmental professionals to assess solar exposure and shading impacts on roadways. This workbook supports planning and evaluation of vegetation management strategies to optimize solar gain and road safety and is meant to be used to help communicate why vegetation management practices can help sustainable operations.

Setup Sheet

Contains five single-row input tables. Use the images below to assist with the example Setup page, based on study site CR-03. This is based on drone imagery taken on April 29, 2025.

Site Conditions:

- a. Site Name (descriptive only)
- b. Latitude – reported in decimal degrees
- c. Longitude – reported in decimal degrees
- d. Elevation – reported in feet above sea level
- e. Time Zone – this is the hour difference between local time and UTC.

Standard Time (UTC offset)								
Z-TIME	GUAM (+10)	HAWAII (-10)	ALASKA (-9)	PACIFIC (-8)	MOUNTAIN (-7)	CENTRAL (-6)	EASTERN (-5)	ATLANTIC (-4)

- f. Road Direction and Bearing – selected from a list of cardinal directions. Bearing is calculated from the pre-determined list of values and can be overwritten using values ranging from 0° to 180°.
- g. Road Width – the fog line-to-fog line width of pavement being maintained, reported in feet.
- h. Vegetation Presence (descriptive only)
- i. Pavement Type (descriptive only)

Example of Site Conditions:

The latitude, longitude, elevation are shown in a table in the upper right image. The road width is approximately 24.5 feet.

Existing Conditions A & B:

Characteristics of the road shoulder to the right (“A”) and left (“B”) of the road bearing shown in “Site Conditions”:

- a. Height of Canopy Above Road Surface (ft) –the average height of canopy along the corridor being assessed. Note that only the height above the pavement is important.
- b. Thickness of Growth and Sunlight Blocking Effect – the approximate amount of direct light able to break through canopy. Direct light is the most impactful to pavement temperature.
- c. Distance from Canopy Edge to Near Fog Line (ft) – the average horizontal distance from the edge of the canopy to the edge of the maintenance area. Note that this isn’t the distance to the nearest standing vegetation or the distance to the tallest tree trunks. This is best evaluated by drawing a line in 3D space between the nearest portions of the

shade-casting canopy and the edge of the pavement, then determining the horizontal distance covered between those points.

- d. Terrain Shadow Elevation (°) – the average angle of elevation for topographical features (hills, road cuts, buildings, etc.) which serve as permanent, unchangeable aspects of the landscape that block sunlight. This parameter is measured as the average angle from the horizontal at the road surface to the top of the terrain feature.

In the workbook, this parameter acts as a filter for potential solar radiation. Where a terrain shadow is included, sun exposure from that road shoulder which lies below the selected elevation is ignored. This should be considered when interpreting the Monthly and Weekly Outcome Summaries.

Example of Existing Conditions:

The image below shows an image taken by drone of the shaded study site CR-03 which demonstrates height of canopy above road surface (shown as “Vertical length”), distance from canopy edge to near fog line (shown as “Horizontal length”), as well as site conditions for road width. Note the Surface Profile shows the elevation at the near fog line. As horizontal length increases, the line passes over a short stand of vegetation which we ignore, then another gap before reaching the high portion of the canopy edge.

If the study site had a crest of hills to the south, Shoulder A would include a Terrain Shadow Elevation. Consider the hill crest height (H) relative to the road surface elevation being 300 feet, and a horizontal distance (D) of approximately 1 mile away. To determine an appropriate terrain shadow angle (θ):

$$\begin{aligned} \text{Tan}(\theta) &= \frac{H}{D}, \\ \theta &= \text{Tan}^{-1}\left(\frac{300}{5,280}\right) = 9.57^\circ \end{aligned}$$

If the study site were located along a road cut with 20 ft height and 45 ft from the edge of the roadway:

$$\text{Tan}^{-1}\left(\frac{20}{45}\right) = 26.6^\circ$$

Proposed Conditions A & B:

Apply the same input types to create a proposed condition for comparison purposes.

- a. Increasing Canopy Height and Sunlight Blocking Effect, or decreasing Distance to Near Fog Line. Making these adjustments could be used to simulate growth of a stand of trees and will result in more shade being cast on the road surface.
- b. Decreasing Canopy Height and Sunlight Blocking Effect or increasing Distance to Near Fog Line. Making these adjustments could be used to simulate the thinning of existing vegetation,

removal, and replanting of a stand of vegetation, and/or the expansion of a maintained clear zone.

Example of Proposed Conditions:

For illustrative purposes, the example uses a scenario where tree canopy is proposed to be cleared back to 100 ft from the pavement edge and thinned to a “Moderate,” approximately 50% sunlight blocking effect.

Monthly & Weekly Outcome Summary:

At the bottom of the Setup sheet provides estimated solar energy metrics including total unobstructed energy and incident energy on the pavement under existing and proposed conditions. These values assume clear sky conditions. The color-coded values demonstrate how much energy is being blocked by roadside vegetation. The net energy on the road’s surface accounts for the full road width, where the shaded portion is affected by canopy and the unshaded canopy receives the full potential energy under clear sky conditions.

The Weekly Outcome Summary provides greater temporal detail in order to show the gradual change of solar radiation throughout meteorological winter. The “Shaded Proportion of Road” reports the minimum daily shade coverage (the shortest shadow) estimated to take place during that week. If shaded proportion is 100%, the road surface is expected to receive no direct sunlight during that week. The “Daily Average Net Energy” and “Daily Average Potential Energy” are the sums of average hourly radiation per day within the week being assessed. The net value is affected by canopy characteristics, whereas the potential value would be representative of unimpeded sunlight.

Example of Outcomes:

In the example, the Monthly Summary shows that December is a dramatically impacted month by the adjacent vegetation. Inspecting the Weekly summary shows that the full month is entirely shaded based on existing conditions. Since the sunlight blocking effect is set to 95%, the full shade conditions still provide 5% of the sun’s energy. As the season goes on, there are instances of the sun reaching portions of the road’s surface, raising the net energy. By week 3 of February, minimum shadow lengths are reaching nearly the entire road surface.

Under the proposed conditions, these near-fully exposed conditions can be achieved an entire month earlier in Week 3 of January. This is due both to the increased setback and the 50% porosity canopy allowing more direct sunlight to reach the pavement. It’s also noteworthy that under the proposed conditions there are no portions of the winter where the entire road is shaded for the entire day. In fact, more than half of the road is exposed to uninhibited sunlight at some point of the day all through December.

Appendix B

Fundamentals of Shadowcasting Calculations

Site Characterization

Once you have collected these data for each road shoulder causing problematic shade, one of the last things you will need to do is use those angles and distances to calculate the vertical height of the horizons above the road surface. On level ground, the relationship here is simple:

$$\tan(\theta) = \frac{H}{D}$$

Where θ is the angle from road surface to canopy horizon, H is the vertical height of the canopy horizon above the road surface, and D is the horizontal distance from the road edge to the canopy edge. Digital rangefinders can be used to approximate the horizontal distance if the ground between the road surface and the base of the vegetation is not level. The same relationship holds true for the topographic horizon. Therefore, determining the vertical height of a horizon means solving for H .

$$H = D \times \arctan(\theta)$$

In practice, solving for the height of canopy relative to the road surface can get more complicated due to the topography of a landscape. This is where using more advanced forestry tools and survey equipment, or the use of digital reality capture, will be useful. Once all of these data are collected, the site can be assessed for shade impact using straightforward assessment of sun angles.

These measurements are adequate for making field assessments of shading on-site at one or two times of year at specific times of the day. There are many tools that can be applied to predict the sun's height above the horizon at times when it is at a right angle to the road or at its highest point in the sky, so long as particular days of assessment are selected beforehand. However, professionals seeking to expand the scope of analysis may find this approach limiting. Using more digitized methods can dramatically expand the scope of assessment.

Analysis using Simple Methods

A handful of inputs are essential:

- Solar Elevation – the angle of the sun above the horizon, measured in degrees. Shown below as $\theta_{elevation}$
- Solar Azimuth – the angle of the sun relative to true north, measured in degrees. Shown below as $\theta_{azimuth}$
- Height of Obstruction Above Road Surface – the vertical difference in elevation between pavement and the top of any structure casting a shadow onto the pavement, measured in any length unit. Shown below as H .
- Distance of Obstruction to Road Edge – the horizontal length directly from the base of the obstruction to the pavement edge. Shown below as W_{gap} .
- Road Bearing – the orientation of the roadway, measured in degrees from North. Shown below as φ_{road}
- Road Width – the length from one edge of the pavement to the other, measured in any length unit. Shown below as W_{road} .

First, use the solar elevation and the height of the obstruction to determine the length of the shadow, L_{shadow} . Apply the equation:

$$L_{shadow} = \frac{H}{\tan(\theta_{elevation})}$$

Second, calculate how much of the roadway is shaded. If the shadow is being cast directly toward the roadway, then the shadow overlap, $L_{overlap}$, is the difference between shadow length and obstruction distance from pavement. This is the case if solar azimuth is 90° from road bearing. If the solar azimuth does not extend directly toward the roadway, then the shadow's distance toward the road will be less.

$$L_{overlap} = W_{gap} - [\sin(|\theta_{azimuth} - \varphi_{road}|) \times L_{shadow}]$$

The difference in angle between the sun's azimuth and the road bearing should be a positive value for this calculation to work. The result, $L_{overlap}$, will be the length of shadow that extends onto the roadway. From there, calculating the percentage of road coverage is simple, where:

$$Shade \% = \frac{L_{overlap}}{W_{road}} \times 100$$

The shaded percentage of the roadway is an intuitive way to communicate the extent of shade at important times of day. This is a predicted value that a road user or maintenance professional can compare to their own personal experience and can be determined accurately with prepared foreknowledge of the site and a scientific calculator.